Target reliability levels for the assessment of existing structures

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1 INTRODUCTION

1.1 *Motivation*

The reliability assessment of existing structures differs from structural design in a number of aspects including:

- Increased safety levels usually involving more costs for existing structures than for new structures.
- The remaining working life of existing facilities often different from the standard design working life of 50 years assumed for new buildings.
- Information on actual structural conditions that may be available for the assessment of an existing structure (inspections, tests, measurements).

At present existing structures are mostly verified using simplified deterministic procedures based on the partial factor method commonly applied in design of new structures. Such assessments are often conservative and may lead to expensive upgrades. More realistic verification of actual performance of existing structures can be achieved by probabilistic methods when uncertainties of basic variables are described by appropriate probabilistic models.

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 was recognised by (Vrouwenvelder, Scholten 2010) and (Zwicky 2010) that it would be uneconomical to specify for all existing buildings and bridges the same reliability levels as for new structures.

The target reliability levels recommended in (EN 1990 2002) related to consequences of failure, are primarily intended for new structures. More detailed classification is given in (ISO 2394 1998) 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 2010) 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.

The submitted paper attempts to apply this approach in conjunction with the criteria for safety of people in accordance with (ISO 2394 1998). The case study of an existing building with the remaining working life of 15 years, moderate costs of safety measures and moderate failure consequences (“model structure”) is considered throughout the paper to clarify general concepts.

1.2 *Present activities in standardisation*

Need for specification of the target levels for existing structures with respect to remaining working life, failure consequences and costs of safety measures, is indicated in (CEN/TC 250 & JRC 2009) . The European Committee for Standardization (CEN) - Technical Committee CEN/TC250, responsible for the preparation of European design rules for structures (Structural Eurocodes), has thus established the Working Group WG2 “Assessment of Existing Structures”. This initiative has been motivated by desired European technical rules to deal with the expanding construction activities in assessing and retrofitting of existing buildings and engineering works.

In order to support the technical work of CEN/TC250 WG2, the International Federation for Structural Concrete (*fib*) has established the Special Activity Group 7 “Assessment and Interventions upon Existing Structures” (SAG7). SAG7 is organized in four workgroups focused on:

– Reliability and safety evaluation,
– Modelling of structural performance,
– Assessment / evaluation procedures,
– Selection and implementation of interventions.

Operational guidelines for practical applications of probabilistic and semi-probabilistic methods in the assessment of existing structures are developed in the first workgroup. The submitted paper is a part of the background materials of this workgroup.

2 TARGET RELIABILITY LEVELS IN CODES

(EN 1990 2002) recommends the target reliability index for two reference periods (1 and 50 years), see Table 1. These target reliabilities are intended to be primarily used in design of new structures.

The couples of β-values given in Table 1 for each reliability class correspond approximately to the same reliability level. For a structure of RC2, the reliability index $\beta = 3.8$ should be thus used provided that probabilistic models of basic variables are related to the reference period of 50 years. The same reliability level should be reached when $\beta = 4.7$ is applied using the theoretical models for one year.

Note that the couples of β-values correspond to the same reliability level only when failure probabilities in individual time intervals (basic reference periods for variable loads) are independent.

Considering a reference period equal to the remaining working life, it might be understood from (EN 1990 2002) that the reliability level corresponding to an arbitrary remaining working life can be derived as follows:

$$\beta_{tref} = \Phi^{-1}\{[\Phi(\beta_1)]^{tr}\} \qquad (1)$$

where β_1 = target reliability index taken from Table 1 for a relevant reliability class and the reference period t_{ref} = 1 year. For the model structure, it follows that $\beta \approx 4.1$ should be considered for t_{ref} = 15 y.

A more detailed recommendation is provided by (ISO 2394 1998) where the target reliability index is given for the working life and related not only to the consequences but also to the relative costs of safety measures, see Table 2. For the model structure the target reliability $\beta \approx 3.1$ may be selected.

Table 1. Reliability classification for different reference periods according to (EN 1990 2002).

Reliability classes	Failure conseq.	Reliability ind. 1 year	50 y.	Examples
RC3	high	5.2	4.3	bridges, public buildings
RC2	medium	4.7	3.8	residences, offices
RC1	low	4.2	3.3	agricultural buildings

Table 2. Target reliability index (life-time, examples) in accordance with (ISO 2394 1998).

Relative costs of safety measures	Consequences of failure small	some	moderate	great
High	0	1.5	2.3	3.1
Moderate	1.3	2.3	3.1	3.8
Low	2.3	3.1	3.8	4.3

Similar recommendation is provided by (JCSS 2001). Recommended target reliability indices are also related to both the consequences and to the relative costs of safety measures, however for the reference period of 1 year.

(ISO 13822 2010) for the assessment of existing structures indicates four target reliability levels for different consequences of failure (the ultimate limit states):
– small consequences: 2.3,
– some: 3.1,
– moderate: 3.8,
– high: 4.3.

The related reference period is “a minimum standard period for safety (e.g. 50 years)”. For the model structure the target reliability $\beta \approx 3.8$ may be assumed.

In general (ISO 2394 1998) and (JCSS 2001) seem to provide a more appropriate reliability differentiation for existing structures than (EN 1990 2002) and (ISO 13822 2010) since costs of safety measures are taken into account. A clear link between the remaining working life and the target reliability level is not apparent from (EN 1990 2002) and (JCSS 2001) and thus it may not be obvious what target reliability should be used for different working life periods.

Recommendations on the target reliability levels are also provided in several national standards. For instance the reliability index for existing structures may be dropped in accordance with the Dutch standard (NEN 8700 2009) to 1.8, 2.5 and 3.3 for low, moderate and high consequences of failure, respectively. For the model structure the target reliability $\beta \approx 2.5$ thus may be accepted.

It is worth noting that several empirical models for the assessment of target reliabilities have been proposed in previous studies. Brief overview of these models is provided by (Sýkora, Holický et al. 2011).

3 COST OPTIMISATION

Lower target reliability levels can be used if they are justified on the basis of social, cultural, economical, and sustainable considerations, (ISO 13822 2010). (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 is to minimize the total working-life cost.

Based on previous studies concerning existing structures, see e.g. (Ang, De Leon 1997) and (Onoufriou, Frangopol 2002); 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.

In the present study the decision parameter is assumed to concern the immediate upgrade only while inspection, maintenance and future repair or upgrade strategies are influenced marginally. This may be a reasonable assumption 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.),
- Marginal cost C_m per unit of the decision parameter.

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

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

- Cost of repair or replacement,
- Economic losses due to malfunction,
- Societal consequences (costs of injuries and casualties),
- 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 important to include not only direct consequences of failure (those resulting from the failures of an individual component), but also indirect consequences (related to a loss of the functionality of a whole structure). Background information for consequence analysis can be found e.g. in (Faber, Kübler et al. 2004), (Janssens, O'Dwyer et al. 2011), (JCSS 2001), and (Kanda, Shah 1997).

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:

$$\mathrm{E}\left[C_\mathrm{f}\left(t_\mathrm{ref}, d\right)\right] = \int_{t_\mathrm{ref}} C_\mathrm{f}(t)\pi_\mathrm{f}(t,d)\mathrm{d}t \approx C_\mathrm{f} \int_{t_\mathrm{ref}} \pi_\mathrm{f}(t,d)\mathrm{d}t \tag{2}$$

where C_f = present value of the failure cost; and $\pi_f(t,d)$ = discounted conditional failure rate given by the relationship:

$$\pi_f(t,d) = [p_f(t,d)]' \,/\, \{(1+q)^t \times [1 - p_f(t,d)]\} \tag{3}$$

where $p_f(\cdot)$ = failure probability; $(\cdot)'$ = time derivative; and q = annual discount rate (for instance 0.03, an average long run value of the real discount rate in various European countries).

Based on these assumptions, the expected total costs can be expressed as follows:

In case of upgrade:

$$\mathrm{E}[C_\mathrm{tot}(t_\mathrm{ref};d)] = C_0 + C_\mathrm{m}\,d + C_\mathrm{f} \int_{t_\mathrm{ref}} \pi_\mathrm{f}(t,d)\mathrm{d}t \tag{4a}$$

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

$$\mathrm{E}[C_{\mathrm{tot}}(t_{\mathrm{ref}})] = C_{\mathrm{f}} \int_{t_{\mathrm{ref}}} \pi_{\mathrm{f}}(t, d_0)\mathrm{d}t \tag{4b}$$

where d_0 = value of the decision parameter before an upgrade. Previous experience shows that it is more convenient to analyse costs related to the reference initial cost C_{ref} (cost of a new structural member/structure identical to an existing member/structure to be assessed). Equations 4a and 4b can then be rewritten as follows.

In case of upgrade:

$$C_{\mathrm{tot}}(t_{\mathrm{ref}};d)/C_{\mathrm{ref}} = c_{\mathrm{tot}}(t_{\mathrm{ref}};d) = C_0/C_{\mathrm{ref}} + C_{\mathrm{m}}/C_{\mathrm{ref}}\,d + \frac{C_{\mathrm{f}}}{C_{\mathrm{ref}}} \int_{t_{\mathrm{ref}}} \pi_{\mathrm{f}}(t, d)\mathrm{d}t = c_0 + c_{\mathrm{m}}\,d + c_{\mathrm{f}} \int_{t_{\mathrm{ref}}} \pi_{\mathrm{f}}(t, d)\mathrm{d}t \tag{5a}$$

In case of no upgrade:

$$c_{\mathrm{tot}}(t_{\mathrm{ref}}) = c_{\mathrm{f}} \int_{t_{\mathrm{ref}}} \pi_{\mathrm{f}}(t, d_0)\mathrm{d}t \tag{5b}$$

The costs related to C_{ref} are hereafter denoted by small letters "c". Note that the symbol of expectation, used in Equations 2 and 4, is hereafter omitted for convenience of notation.

Apparently, the total costs C_{tot} and c_{tot} attain a minimum for the same value of the decision parameter. From Equation 5a, the optimum value of the decision parameter d_{opt} (optimum upgrade strategy) can be assessed:

$$\mathrm{minimum}_d\; c_{\mathrm{tot}}(t_{\mathrm{ref}};d)] = c_{\mathrm{tot}}(t_{\mathrm{ref}};d_{\mathrm{opt}}) \tag{6}$$

From an economic point of view, no upgrade is undertaken when the total cost according to Equation 5b is less than the total cost of the optimum upgrade. It follows from Equations 5a and 6 that d_{opt} is independent of c_0.

4 TARGET RELIABILITIES BASED ON COST MINIMISATION

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

$$\beta_{\mathrm{up}} = -\Phi^{-1}[p_{\mathrm{f}}(t_{\mathrm{ref}};d_{\mathrm{opt}})] \tag{7}$$

where $\Phi^{-1}(\cdot)$ = inverse cumulative distribution function of the standardised normal distribution.

However, the total costs given in Equations 5b and 6 should be compared to decide whether to upgrade the structure or not. The limiting value $d_{0\mathrm{lim}}$ of the decision parameter before the upgrade is then found as follows:

$$c_{\mathrm{f}} \int_{t_{\mathrm{ref}}} \pi_{\mathrm{f}}(t, d_{0\,\mathrm{lim}})\mathrm{d}t = c_0 + c_{\mathrm{m}}\,d_{\mathrm{opt}} + c_{\mathrm{f}} \int_{t_{\mathrm{ref}}} \pi_{\mathrm{f}}(t, d_{\mathrm{opt}})\mathrm{d}t \tag{8}$$

For $d_0 < d_{0\mathrm{lim}}$ 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 $d_0 > d_{0\mathrm{lim}}$ 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 unreliable and should be upgraded is thus obtained as follows:

$$\beta_0 = -\Phi^{-1}[p_{\mathrm{f}}(t_{\mathrm{ref}};d_{0\mathrm{lim}})] \tag{9}$$

5 REQUIREMENTS ON HUMAN SAFETY

The cost optimisation is aimed at finding the optimum decision from the perspective of an owner of the structure. However, society commonly establishes limits at human safety. General guidelines for the assessment of the target reliabilities with respect to human safety are provided in (ISO 2394 1998). The design of new structures and assessment of existing structures are not distinguished.

5.1 *Individual risk criterion*

Based on the concept of individual risk, the target failure probability $p_{\mathrm{ft,hs}}$ depends on the conditional probability of casualty p_1, given the structural failure:

$$p_{\mathrm{ft,hs}} \leq 10^{-6} / p_1 \tag{10}$$

With respect to the loss of human life, (EN 1990 2002) distinguishes among low, medium, or high consequences (Consequence Classes CC1-CC3, respectively). The Consequence Classes may be associated with the Reliability Classes indicated in Table 1.

Table 3. Probabilities of casualty given structural failure.

Conseq. class	Conseq. for loss of hum. life*	p_1**	Prob. of casualty p_1 given failure***	accepted in this study
CC3	high	0.3	0.03-0.055	0.05
CC2	medium	0.03	0.01-0.03	0.01
CC1	low	0.001	0.005	0.001

* (EN 1990 2002), ** (Steenbergen, Vrouwenvelder 2010), *** (Eldukair, Ayyub 1991).

Based on the qualitative definition of the Consequence Classes, (Steenbergen, Vrouwenvelder 2010) estimated the conditional probabilities p_1 given in Table 3.

Evaluation of the excessive database of structural failures by (Eldukair, Ayyub 1991) reveals probability of casualty given the structural failure provided also in Table 3. It is emphasised that these values should be considered as an upper bound on p_1. Given the structural failure, the probability of casualty of an individual person (whom risk is being assessed) is lower than the probability of at least one casualty of any user.

Based on this limited background information, it is rather tentatively assumed that the probabilities p_1 can be assessed by the values 0.001, 0.01 and 0.05 for CC1 to CC3, respectively. The annual target failure probabilities of a structural member then become from Equation 10:

$$\begin{aligned} &\text{CC1:}\quad p_{\mathrm{ft,hs}} \leq 10^{-3}\ (\beta_{\mathrm{t,hs}} \geq 3.1) \\ &\text{CC2:}\quad p_{\mathrm{ft,hs}} \leq 10^{-4}\ (\beta_{\mathrm{t,hs}} \geq 3.7) \\ &\text{CC3:}\quad p_{\mathrm{ft,hs}} \leq 2 \times 10^{-5}\ (\beta_{\mathrm{t,hs}} \geq 4.1) \end{aligned} \tag{11}$$

Apparently, it is highly desired to improve estimates of p_1 on the basis of additional empirical data.

The target failure probabilities related to a reference period are obtained as follows:

$$\begin{aligned} &\text{CC1: } p_{\mathrm{ft,hs}} \leq t_{\mathrm{ref}} \times 10^{-3} \\ &\text{CC2: } p_{\mathrm{ft,hs}} \leq t_{\mathrm{ref}} \times 10^{-4} \\ &\text{CC3: } p_{\mathrm{ft,hs}} \leq t_{\mathrm{ref}}\ 2 \times 10^{-5} \end{aligned} \tag{12}$$

5.2 *Societal risk criterion*

(ISO 2394 1998) indicates that in many cases authorities explicitly want to avoid accidents where large numbers of people may be killed. The additional societal risk criterion may thus be applied:

$$p_{\mathrm{ft,hs}} \leq A\, N^{-\alpha} \tag{13}$$

where N = expected number of casualties; and A and α = constants ((ISO 2394 1998) provides examples for values of A and α; A = 0.01 or 0.1 and α = 2).

Based on the analysis of more than 100 structural collapses (Tanner, Hingorani 2010) provide empirical relationships for the number of casualties N and a collapsed area A_{col}:

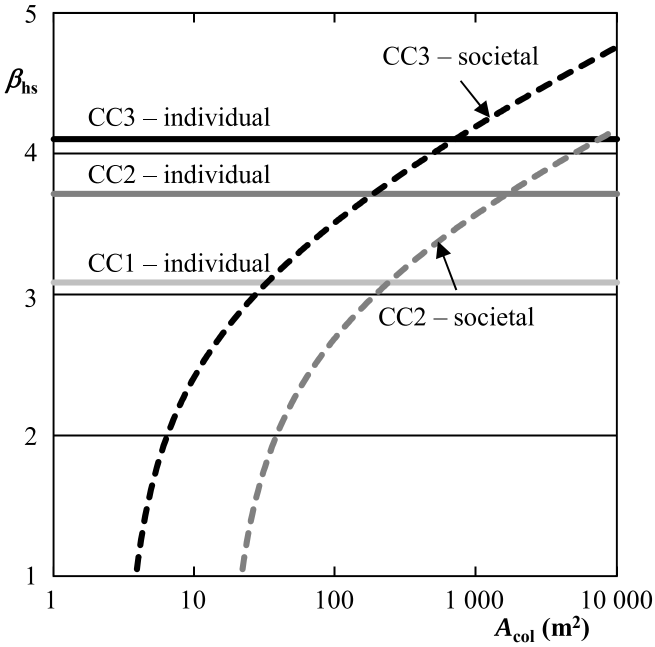

Figure 1. Target reliability indices based on the individual and societal risk criteria as a function of the collapsed area (for $A = 0.01$ and $\alpha = 2$).

CC1: no recommendation
CC2: $N = 0.27A_{col}^{0.5} - 1 \geq 0$ (14)
CC3: $N = 0.59A_{col}^{0.56} - 1 \geq 0$

Considering $A = 0.01$ and $\alpha = 2$, annual target reliability indices based on the individual and societal risk criteria in Equations 12 and 13 are shown in Figure 1 as a function of the collapsed area.

It follows from Figure 1 that individual risk is a governing criterion for $A_{col} < 1\,000$ m^2 for CC2 and CC3 (no data available to establish the societal criterion for CC1). The following annual target reliabilities are thus further assumed to comply with the human safety criteria:

– for small to medium collapsed areas ($A_{col} < 1\,000$ m^2): $\beta_{t,hs} = 3.1$ for CC1; $\beta_{t,hs} = 3.7$ for CC2; and $\beta_{t,hs} = 4.1$ for CC3;
– for large collapsed areas ($A_{col} \approx 10\,000$ m^2): $\beta_{t,hs} = 3.1$ for CC1; $\beta_{t,hs} = 4.2$ for CC2; and $\beta_{t,hs} = 4.8$ for CC3.

6 CASE STUDY

Application of the cost optimisation procedure and human safety criteria is illustrated by the example of reliability assessment of a generic member of the structure with the remaining working life of 15 years. The reference period is assumed to be equal to the remaining working life. The member is exposed to permanent and snow loads. No deterioration is assumed.

The decision parameter is the ratio of the member over resistance required by Eurocodes for newly designed structures.

Table 4. Models for basic variables.

Variable	X	Dist .	x_k	μ_X / x_k	V_X
Resistance before upgrade	R	LN	0.77	1.29	0.15
Permanent load	G	N	0.37	1	0.05
Snow load (50 y.)	Q_{50}	GU	0.37	1	0.15
Resistance uncertainty	K_R	LN	1	1	0.05
Load effect uncertainty	K_E	LN	1	1	0.1

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

Initially, reliability of the member is verified by the partial factor method. The deterministic verification reveals insufficient reliability of the member ($d_0 \approx 0.65$).

6.1 *Probabilistic reliability analysis*

The failure probability is obtained as follows:

$$p_f(d,t) = P\{K_R R(d) - K_E [G + Q_{tref}] < 0\} \tag{15}$$

where Q_{tref} = maxima of the snow load related to a reference period t_{ref}. The considered characteristic values and probabilistic models of the basic variables, based on recommendations of (JCSS 2001) and the recent paper by (Holický, Sýkora 2011), are given in Table 4.

For reference periods different from 50 years, the mean of the snow load is modified as follows:

$$\mu_{Q,tref} = \mu_{Q,50} + 0.78\sigma_Q \ln(t_{ref} / 50) \tag{16}$$

The standard deviation σ_Q is constant for any reference period and the coefficient of variation V_Q is adjusted accordingly. Using the FORM method, the reliability index $\beta = 1.9$ is low and reliability of the member seems to be insufficient.

6.2 *Input data for the cost optimisation*

The total cost optimisation is based on the following assumptions:

1 The failure costs can be estimated using the data by (Kanda, Shah 1997) as follows:
- c_f = 1 to 3 for CC1,
- c_f = 5 to 20 for CC2,
- c_f = 20 to 50 for CC3.

2 The upgrade cost independent of the decision parameter is dominated by the losses due to business interruptions while the other costs (surveys, design, and replacement of users) are insignificant. Assuming further:
- In accordance with (Eldukair, Ayyub 1991) a half-year period is needed on average to upgrade a structure,
- A return period of the investments into the structure of about 30 years,
- Net profit lost due to the upgrade, standardised by C_{ref}, estimated as the ratio of the period of the business interruption over the return period of the investments, 1/60,
- The ratio between the net profit and gross profit of about 10 %,

c_0 = 1/60 / 0.1 = 0.17 is further considered. In the case study c_0 is assumed independent of d and of the Consequence Class. Obviously this value needs to be updated for specific conditions of an assessed structure.

3 Marginal cost per unit of decision parameter c_m can be estimated as follows:

$$c_m \approx 1.12\, d / d_0 - 1.06, \quad \text{for: } 1 < d / d_0 < 1.5 \tag{17}$$

4 The discount rate is q = 3 %.

Concerning the second assumption, general economic experience indicates that a return period of the investments into structures is about 10 years for industrial structures, 15 years for office buildings and 30 years for residential houses. Consideration of the largest period in the present study is conservative as this reduces the value of c_0, and consequently increases β_0.

Equation 17, based on limited authors' experience with upgrades of existing steel members, is foreseen to lead a lower estimate of c_m for most of structures. Similarly as for c_0, this yields conservative estimates of β_0 and β_{up}. Some information on the assessment of c_m is provided by (Ang, De Leon 1997).

6.3 *Optimum upgrade strategy and decision on the upgrade based on the cost optimisation*

The total cost given in Equation 5a is optimised with respect to the decision parameter d, considering the failure probability given in Equation 15. Figures 2 to 4 shows variation of the total costs c_{tot} and reliability index β with the decision parameter d for the Consequence Classes CC1 to CC3, respectively.

Considering purely economic criteria, it can be concluded from Figures 2 to 4 that:
- No upgrade is advisable for the member classified in CC1 since the total cost when no upgrade is undertaken is lower than the total cost for any repair strategy,
- For the CC2 member the present state is accepted for $c_{f,min}$ while the upgrade to achieve β_{up} = 2.6 is carried out for $c_{f,max}$,
- The upgrade to achieve β_{up} = 2.6 or 2.9 is carried out for $c_{f,min}$ or $c_{f,max}$, respectively, for the CC3 member.

Using Equations 8 and 9, the following minimum target reliability indices β_0 are obtained for $c_{f,min}$ and $c_{f,max}$:
- $\beta_0 \approx$ 0.7-1.2 for CC1,
- $\beta_0 \approx$ 1.4-1.9 for CC2,

– $\beta_0 \approx 1.9\text{-}2.2$ for CC1.

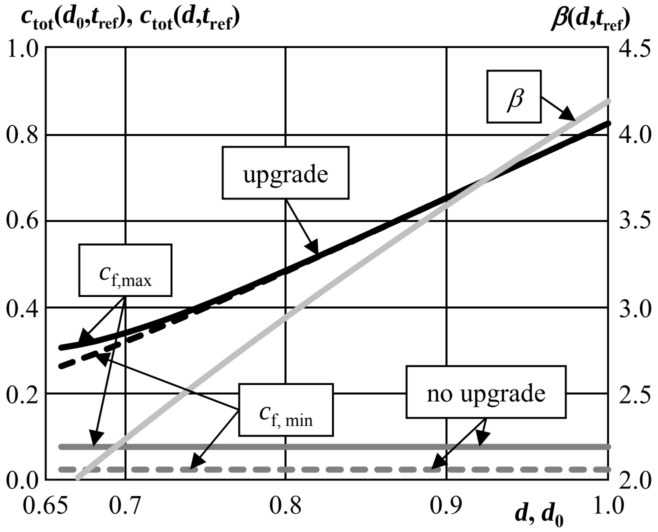

Figure 2. Variation of the total costs and reliability index with the decision parameter for CC1 ($1 < c_f < 3$).

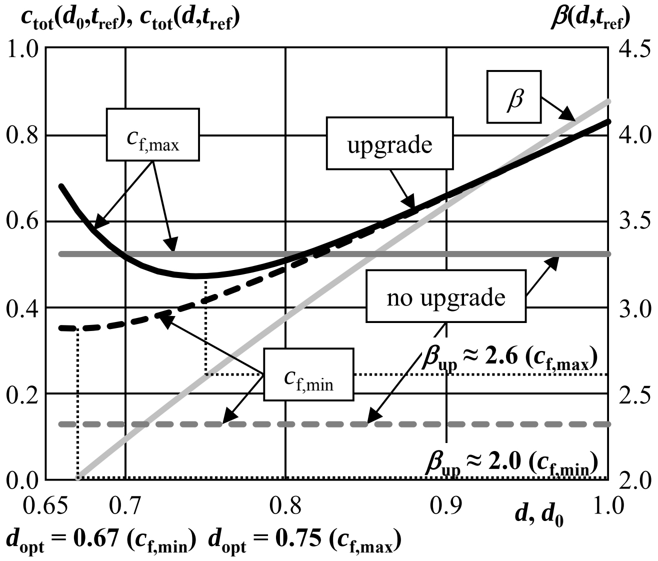

Figure 3. Variation of the total costs and reliability index with the decision parameter for CC2 ($5 < c_f < 20$).

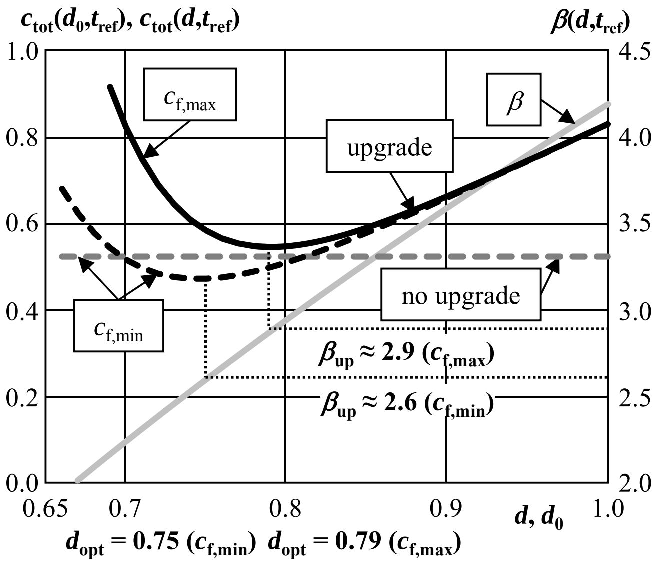

Figure 4. Variation of the total costs and reliability index with the decision parameter for CC3 ($20 < c_f < 50$).

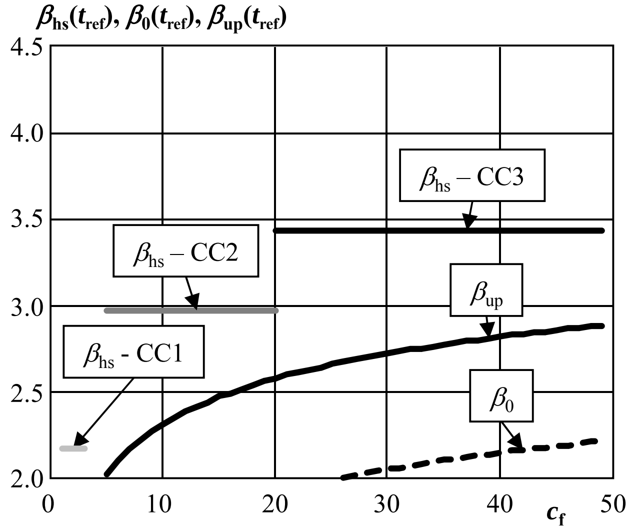

Figure 5. Variation of the target reliability indices with the failure consequences c_f (t_{ref} = 15 years).

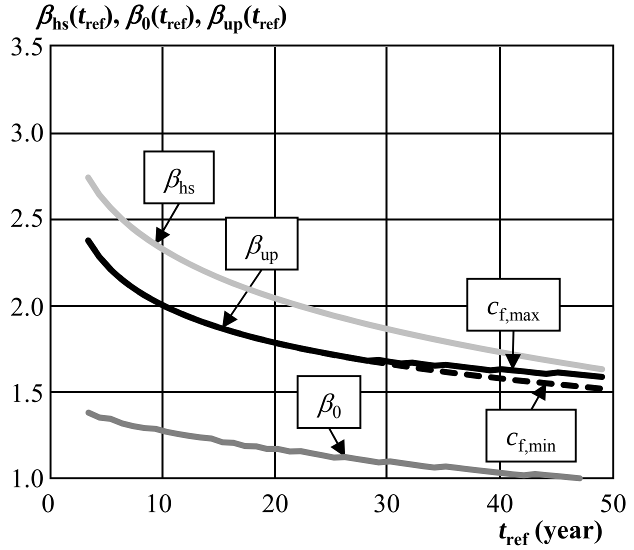

Figure 6. Variation of the target reliabilities with t_{ref} for CC1.

6.4 *Human safety criteria*

The target reliabilities obtained in Section 6.3 are clearly rather low when compared to the human safety criteria. Using results provided in Section 5 for small to medium collapsed areas, minimum human safety levels β_{hs} are compared with the target reliabilities β_0 and β_{up} in this sub-section.

Figure 5 shows variation of the target reliability indices with the failure consequences c_f (t_{ref} = 15 years). It is clearly indicated that the human safety levels are governing the target reliabilities for any of the considered failure consequences. It can also be observed that the human safety levels (considered here to be the same for existing and new structures) are lower than the target reliabilities for the design of new structures according to (EN 1990 2002).

These observations can be explained as follows:

– For existing structures, upgrades are expensive and economic criteria yield lower optimum reliabilities than those required to assure acceptable human safety,

Table 5. Overview of target reliabilities for the considered member (t_{ref} = 15 years).

Code, method	Consequence class			
	CC1*	CC1**	CC2	CC3
EN 1990	3.6	3.6	4.1	4.6
ISO 13822	2.3/3.1***	2.3/3.1***	3.8	4.3
ISO 2394****	1.3/2.3***	1.3/2.3***	3.1	3.8
NEN 8700	1.8	1.8	2.5	3.3
Human safety β_{hs}				
small-medium A_{col}	-	2.2	3.0	3.4
large A_{col}	-	2.2	3.5	4.2
Optimisation β_0	0.7-1.2	0.7-1.2	1.4-1.9	1.9-2.2
Optimisation β_{up}	no upgrade		2.6*****	2.6-2.9

*Human safety not endangered, **human safety endangered, ***small or some failure consequences, ****moderate relative costs of safety measures, *****for c_f = 20.

– For new structures, costs of safety measures are relatively low and it is affordable (economically optimal) to design for higher reliabilities than those required for the human safety.

Figure 6 indicates variation of the target reliabilities with t_{ref} for CC1. It appears that the human safety level is higher than both β_0 and β_{up} levels. For structures where human safety is not endangered, the following target reliabilities might be accepted considering $t_{ref} \in$ (15 y., 50 y.):

– $\beta_0 \approx$ 1.2 to 1.0,
– $\beta_{up} \approx$ 1.8 to 1.5.

Similar trends of the target reliabilities as shown in Figure 6 are observed for the CC2 and CC3 classes for which variation of β_0 and β_{up} with t_{ref} becomes less significant.

Complementary studies indicate that the optimum reliabilities β_0 and β_{up} are insignificantly influenced by the discount rate.

7 COMPARISON OF THE TARGET RELIABILITIES

Table 5 provides a comparison of the target reliabilities estimated for the considered member using different procedures in structural codes, or based on the total cost optimisation and the requirements on human safety (t_{ref} = 15 y.). A great scatter is observed, for instance the reliability index varies within the range from 2.5 to 4.1 for the CC2 member (disregarding β_0).

It should be noted that (EN 1990 2002) recommends considerably greater values that seem to be applicable primarily for new structures. Also (ISO 13822 2010) provides rather high reliability levels. (ISO 2394 1998) and the human safety criteria yield similar values that might be acceptable for existing structures. (NEN 8700 2009) and particularly the cost optimization (β_0 and β_{up}) lead to somewhat low reliability levels.

8 CONCLUSIONS AND RECOMMENDATIONS FOR STANDARDISATION

The following general conclusions are drawn from the present study:

– It is uneconomical to require that all existing structures comply with the target reliability levels for new structures. Lower target reliability levels can be used if justified on the basis of social, cultural, economical, and sustainable considerations,
– Decisions in the assessment can result in the acceptance of an actual state or in the upgrade of a structure; in principle two target reliability levels are thus needed - the minimum level below which the structure is unreliable and should be upgraded (β_0), and the level indicating an optimum upgrade strategy (β_{up}),
– Minimum levels for human safety based on individual and societal risk concepts should not be exceeded.

Case study based on general estimates of upgrade costs and failure consequences reveals that:

– The target reliability levels are primarily dependent on the failure consequences and on the marginal cost per unit of a decision parameter; upgrade costs independent of the decision parameter, remaining working life and discount ratio are less significant.
– Economic criteria yield lower optimum reliabilities than criteria for human safety,
– The following annual target reliability indices might be accepted (Figure 1):
  -- for CC1 $\beta \approx$ 3.1,
  -- for CC2 $\beta \approx$ 3.7 ($\beta \approx$ 4.2 for exceptionally large collapsed areas),
  -- for CC3 $\beta \approx$ 4.1 ($\beta \approx$ 4.8 for exceptionally large collapsed areas).

Further research should be aimed at improvements of the background information needed to establish the human safety criteria.

The results of this study may be implemented in design using the partial factor method as follows:

- The characteristic values of the basic variables including time-variant loads remain independent of the remaining working life (in accordance with (EN 1990 2002));
- The design values are specified on the basis of an appropriate reliability index,
- The partial factors are determined considering specified design values and unchanged characteristic values.

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