Target reliability of new and existing structures - A general framework for code making

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Target reliability levels, design and remaining working lifes and reference periods recommended in various national and international codes and guidelines are sometimes inconsistent. Design working lifes for new structures are typically 50 to 100 years for different types of structures. For existing structures the remaining working life is often smaller than 50 years. Recommended target reliability indexes are usually given for one or two reference periods (one year and 50 years), without an explicit link to the design working life. In this paper a general framework is given in order to make the reliability index independent of the design working life and to provide guidance for specification of the target reliability level for different situations. The study is based on probabilistic economic optimization. Using this methodology, annual targets – in terms of failure rates – can be set for new structures, and (deteriorating) existing structures, given the marginal cost for reliability, failure consequences and the uncertainty in loading and resistance.

Keywords: Target reliability, optimization, standardization, safety format, structural reliability, codes

1 Introduction

1.1 Motivation and problem statement

Target reliability levels for civil structures are always related to a certain reference period. In most cases this reference period is the design (or remaining) working life or a convenient time unit like the period of one year. The design working life is considered here as an assumed period of time over which a structure is to be used for its intended purpose without any major repair work being necessary. Note that the envisaged period of use may vary from maybe less than one year for temporary structures to design working lifes of 50 or 100 years for normal buildings and civil engineering works. If the reference period of one year is chosen, the corresponding failure probability for one year is also often understood as a failure rate.

From a theoretical point of view, lifetime targets seem to be the most appropriate if economic optimization is the driving force for design and the expected life is dominated by other factors than structural collapse. However, (Rackwitz, 2000) noted that annual failure rates are to be preferred over lifetime reliability indices and introduced the concept of "systematic reconstruction or repair after failure or due to obsolescence". In addition, he assumed that the time to reach obsolescence follows a Poisson distribution. Annual probability is also a more suitable measure for the reliability if acceptance criteria for risk to human life are involved.

In the present Eurocode EN 1990 (CEN, 2002) target reliabilities are presented for a period of 50 years as well as for a period of one year. The corresponding failure probabilities just differ by a factor of about 50. In practice, however, this turns out to be confusing. Should both requirements be considered simultaneously or is there freedom to make a choice? Is the annual target value an average over the lifetime or should every individual year have a lower probability of failure? In some countries, the 50-year values are interpreted as values for the design lifetime, which may be used for all new structures, regardless of the design working life is 50 years or more (e.g. 100 years) or less (e.g. 15 years).

In the JCSS Probabilistic model code [3] the recommended target reliability indices are given on an annual basis and are related to both the consequences of failure and to the relative costs of safety measures. The role of relative cost of safety measures is neglected in most codes. According to the background of the proposed safety levels (Rackwitz, 2000) the optimum annual targets also depend on the degree of variability in loads and resistances as well as on the anticipated working life due to temporary need or obsolesce.

Also for existing structures this issue is important and relevant. For the majority of existing buildings and infrastructures the design life has already been reached in the past or will be reached in the near future. These structures need to be reassessed in order to verify their reliability. The requirements for existing structures may (should) differ from those for newly designed structures since (1) increasing the safety level is usually more expensive for existing structures than for new ones; and (2) the remaining working life of existing structures is often shorter than the expected working life of new structures. Various interpretations of the target reliability index and corresponding reference period are given for the assessment of existing structures; however, codes and standards should in principle be suitable to assess the reliability of structures with various (remaining) lifetimes.

In the case of deteriorating (new as well as existing) structures, target reliability levels specified on an annual basis make more sense than target reliability levels on lifetime basis. In the case of fatigue for instance it does not make much sense to accept that the total failure normally accepted for say 50 years is concentrated in the last 3 or 4 years. In other words, in case of fatigue, if a 50-year target is chosen and ensured, the last few years will have much larger annual failure probability than the one year target given as the pair of the 50-year target in EN1990 (assuming mutually independent annual failure events with equal occurrence probability). Existing structures can also show sudden and substantial changes in their actual reliability level.

The purpose of this paper is to clarify the link between the design working life and the reliability requirements and to provide guidance for specification of the target reliability level for a given (remaining) working life. This is done on the basis of probabilistic, economic optimization supplemented by practical recommendations.

1.2 *Overview of previous work and current practice*

1.2.1 Research papers

The derivation of target reliabilities is the subject of multiple papers. In (Rackwitz, 2000) annual failure rates are preferred over lifetime reliability indices; based on earlier studies of Rosenblueth and Mendoza (1971) and the concepts developed by Hasofer (1974) and by Rosenblueth (1976). An important notion was introduced with respect to the reconstruction policy. There are just two extreme cases: no reconstruction after failure, and systematic reconstruction or repair after failure or obsolescence, respectively. For many civil engineering structures systematic rebuilding happens after failure, be it caused by extreme loading, poor construction, fatigue, other deterioration, loss of serviceability, or by demolition after obsolesce. This is a common practice since buildings and infrastructure serve the user and society. The generalization put forward by Rackwitz (2000) affects the philosophy for structures: obsolescence is accounted for; every structure is replaced after either failure or obsolesce (without failure); and for the time required to reach obsolesce the simple model of a Poisson distribution was used. Using this philosophy it is neither necessary to define arbitrary reference times of intended use, nor to provide a table of recommended reference times of usage of structures. The same targets, in terms of failure rates, can be set for temporary structures and monumental buildings, given the same marginal cost for reliability and failure consequences. One year is chosen as a reference time unit for civil engineering structures. Lifetime aspects are taken into account in case of fatigue and other deterioration processes. For each year of the lifetime the same target failure probability is used.

1.2.2 Current major standards

ISO 2394 (2014) states that target reliabilities should be derived by considering the "*consequence and the nature of failure, the economic losses, the social inconvenience, effects to the environment, sustainable use of natural resources and the amount of expense and effort required to reduce the probability of failure.*". In practice, typically those costs and consequences are considered which are easily convertible to monetary value, i.e. economic losses, expense and effort required to reduce the probability of failure. If risk of loss of human life is present then ISO 2394 recommends to use the marginal lifesaving costs principle, e.g. through the Life Quality Index, to account for these intangible consequences. ISO 2394 recommends target reliability indices using an annual basis; see Table 1.

Table 1. Tentative target reliabilities related to one year reference period and ultimate limit states, based on monetary optimization (ISO 2394)

Relative cost of safety measure	Consequences of failure		
	Minor	Moderate	Large
Large (A)	$\beta = 3.1$ ($P_f \approx 10^{-3}$)	$\beta = 3.3$ ($P_f \approx 5 \cdot 10^{-4}$)	$\beta = 3.7$ ($P_f \approx 10^{-4}$)
Normal (B)	$\beta = 3.7$ ($P_f \approx 10^{-4}$)	$\beta = 4.2$ ($P_f \approx 10^{-5}$)	$\beta = 4.4$ ($P_f \approx 5 \cdot 10^{-6}$)
Small (C)	$\beta = 4.2$ ($P_f \approx 10^{-5}$)	$\beta = 4.4$ ($P_f \approx 5 \cdot 10^{-6}$)	$\beta = 4.7$ ($P_f \approx 10^{-6}$)

ASCE (2010) stipulates acceptable, annual reliabilities (maximum annual probability of failure) for load conditions that do and do not include seismic actions. In total 3 × 4 = 12 design situations and associated acceptable reliabilities are given. The design situations are distinguished based on the type (brittle–ductile) of failure, extent of the structural damage (localized–wide-spread), and the occupancy (number of lifes at risk). Although in ASCE (2010) the term acceptable reliability is used it is considered here as target reliability. Target reliabilities are given for one year and 50-year reference periods (see Table 2). Although their connection is not explicitly stated, inferring from the provided values they can be related by assuming independent annual failure events.

Table 2. Target reliabilities from ASCE (2010)

Basis		Occupancy Category			
		I	II	III	IV
Failure that is not sudden and does not lead to wide-spread progression of damage	$P_f\ [\frac{1}{\text{yr}}]$	$1.25\cdot10^{-4}$	$3.0\cdot10^{-5}$	$1.25\cdot10^{-5}$	$5.0\cdot10^{-6}$
	β	2.5	3.0	3.25	3.5
Failure that is either sudden or leads to wide-spread progression of damage	$P_f\ [\frac{1}{\text{yr}}]$	$3.0\cdot10^{-5}$	$5.0\cdot10^{-6}$	$2.0\cdot10^{-6}$	$7.0\cdot10^{-7}$
	β	3.0	3.5	3.75	4.0
Failure that is sudden and results in wide-spread progression of damage	$P_f\ [\frac{1}{\text{yr}}]$	$5.0\cdot10^{-6}$	$7.0\cdot10^{-7}$	$2.5\cdot10^{-7}$	$1.0\cdot10^{-7}$
	β	3.5	4.0	4.25	4.5

The reliability indices are provided for a 50-year service period, while the probabilities of failure have been annualized.

The occupancy categories in ASCE (2010) range from low hazard to human life in the event of a failure (cat. I) to very high hazard to human life (cat. IV).

The Canadian Highway code (CSA, 2014) has comparable regulations to ASCE. Besides the type of failure, and extent and consequence of structural failure they also differentiate targets based on inspection levels and loading type as well.

Eurocode EN 1990; 2002 recommends for new structures the target reliability index β for three consequence classes CC1, CC2 and CC3 as shown in Table 3. These target reliabilities are intended to be used primarily for the design of structural members. The β-values in the fourth column of Table 3 should be used in combination with a reference period of 50 years. EN 1990 provides the reliability indices also for a reference period of one year, assuming independence between annual failure events. This assumption is however in many cases not realistic since time invariant stochastic parameters may play an important role.

Table 3. Reliability index β_n for new structures (EN 1990)

Reliability classes	Consequences for loss of human life, economic, social and environmental consequences	Reliability index β		Examples of buildings and civil engineering works
		β_a for T_a =1 yr	β_d for T_d =50 yr	
RC3 high	High	5.2	4.3	Important bridges, public buildings
RC2 normal	Medium	4.7	3.8	Residential and office buildings
RC1 low	Low	4.2	3.3	Agricultural buildings, greenhouses

Currently, EN 1990 does not have the notion from ISO 2394 and the JCSS Probabilistic Model Code, that the target reliability level depends on the marginal safety costs. Especially for existing structures this is important as it takes more effort to increase the reliability level compared to a new structure. Consequently for an existing structure one should use lower reliability levels; see Steenbergen et al. (2015) and Steenbergen and Vrouwenvelder (2010). This is also in agreement with the recommendations of the new fib Model Code 2010.

In general ISO 2394 and JCSS Probabilistic Model Code, which are both based on the work of Rackwitz (2000) seem to provide a more appropriate reliability differentiation for existing structures than EN 1990 and ISO 13822 since costs of safety measures are taken into account.

*1.3 **Objective and contribution***

In this paper, based on the principles developed by Rackwitz (2000), the link between the design working life and the reliability index is clarified and guidance is provided for specification of the target reliability level for a given design working life. The probabilistic model proposed by Rackwitz (2000) is extended to adjust to recent advancements and improved knowledge. In addition, the effect of various load ratios between permanent and variable actions is considered; this allows for insight to the effect of having a structure which is dominated by a permanent action with small uncertainty or by variable action with often a larger uncertainty.

In Fischer et al (2019) the framework is presented that forms the basis for the target reliabilities defined in ISO 2394:2015 (where the target reliabilities proposed by the JCSS have been combined with minimum acceptable reliabilities to ensure societal acceptability in terms of life safety).

In the present paper the study of Fisher et al. (2019) is extended and special attention is given to comparing the lifetime reliability index of all cases to the annual reliability index. The intention is to motivate selection of the reference period. This can provide a basis for code making for new and existing structures.

2 Tools and methods

Economic optimization is performed to obtain optimal reliabilities which in turn can be considered as target reliabilities. The economic calculation requires probabilities of different events, e.g. failure of the structure. These probabilities are calculated by the methods of structural reliability.

*2.1 **Structural reliability calculations***

First order reliability method (FORM) is used to calculate the failure probabilities. The improved Hasofer-Lind-Rackwitz-Fiessler algorithm (Rackwitz & Fiessler, 1979; Zhang & Der Kiureghian, 1995) is applied to solve the constrained optimization problem in FORM. To study the effect of the linearization of the limit state involved in FORM, importance sampling analysis is also carried out.

*2.2 **Economic optimization***

The task of finding the target reliability for codification of structural design is formulated as an optimization problem where the total net benefit of having a structure with specific dimensions and properties is maximized. Mathematically the problem is:

$$\mathbf{p}_{\text{opt}} = \arg\max Z(\mathbf{p}) \qquad Z : \mathbb{R}^n \to \mathbb{R} \tag{1}$$

where:

$Z(.)$ total cost-benefit (objective) function

$\mathbf{p}$ vector of design parameters, e.g. characteristic dimensions

n number of design parameters

The economically optimal reliability, which is the target reliability for new design, results from the optimization. It is the reliability level at $\mathbf{p}_{opt}$. In this paper, for simplicity and brevity only a special case with a single design parameter is considered, $\mathbf{p} = p$, and $\mathbf{p}_{opt} = p_{opt}$. Given the focus of this study, this simplification is believed to have negligible influence on the outcomes and conclusions, those are generalizable to the multiple design parameters case. The calculation is performed as a nested, two-level optimization:

- Inner level: reliability analysis to calculate β; FORM analysis, importance sampling
- Outer level: maximize an univariate function: golden section search and parabolic interpolation

Rackwitz (2000) suggests a single level optimization for computational efficiency, but for the simple examples considered here the above two-level optimization suffices.

3 Economic optimization, typical cases

3.1 ***Overview***

The model proposed by Rackwitz (2000) is adopted in this paper, though some modifications are introduced to cover a wider range of design situations and to adjust to recent advancements and improved knowledge. It is considered to be a basic example that comprises all the essential components. For convenience the main assumptions of the model are recapitulated here:

- The following main costs are considered:
  - cost of safety measures
  - repair cost
  - demolition costs
- The uncertainty associated with loads and resistances are considered.
- (Extreme) loads are assumed to occur at discrete points in time, modelled with the aid of a homogeneous Poisson process.
- Interest rate for calculating the net present value
- Obsolescence is accounted for.
- Every structure is replaced by a similar one after either failure or obsolesce.
- The time required to reach obsolesce follows an exponential distribution.

3.2 *Objective function of the minimal economic example*

The total cost-benefit function is expressed as (Rackwitz, 2000):

$$Z(p) = B - C(p) - U(p) - A(p) - D(p) \tag{2}$$

where:

B	benefit from the existence of the structure
$C(.)$	construction cost
$U(.)$	repair cost (serviceability failures)
$A(.)$	demolition cost (obsolescence events)
$D(.)$	damage cost (ultimate failures)

The components of the total cost-benefit function are defined as:

$$B = \frac{b}{\gamma} \tag{3}$$

where:

b	benefit rate
γ	interest rate

$$C(p) = C_0 + C_1 p \tag{4}$$

where:

C_0	construction cost independent of p
C_1	construction cost coefficient dependent on p

$$U(p) = U \frac{\lambda}{\gamma} P_{f,SLS}(p) \tag{5}$$

where:

U	repair cost
λ	intensity rate of the Poisson process for the loading
$P_{f,SLS}(\cdot)$	probability of reaching the serviceability limit state

$$A(p) = (C_0 + C_1 p + A) \frac{\varpi}{\gamma} \tag{6}$$

where:

A demolition cost

ϖ rate of obsolescence; intensity (rate) of the Poisson corresponding process

$$D(p) = (C_0 + C_1 p + H)\frac{\lambda}{\gamma} P_{\mathrm{f,ULS}}(p) \tag{7}$$

where:

H direct failure cost (beyond the pure reconstruction cost)

$P_{\mathrm{f,ULS}}(.)$ probability of reaching the ultimate limit state

The failure probabilities are calculated by using the following limit state functions for ultimate limit state and serviceability limit state:

$$g_{\mathrm{ULS,1}} = R(p) - S \tag{8}$$

$$g_{\mathrm{SLS,1}} = \frac{1}{a} R(p) - S \tag{9}$$

Where R and S are the resistance and action random variables respectively. For simplicity the SLS resistance is obtained by dividing the ULS resistance by a number. The design parameter p is the ratio of the mean of R and S:

$$p_1 = \frac{E[R]}{E[S]} \tag{10}$$

This single design parameter represents the combined effect of multiple design parameters such as dimensions and reinforcement. For cases when the permanent actions G and variable actions S are distinguished the ULS and SLS considered, are respectively:

$$g_{\mathrm{ULS,2}} = R(p) - S - G \tag{11}$$

$$g_{\mathrm{SLS,2}} = \frac{1}{a} R(p) - S - G \tag{12}$$

The corresponding generalization of the design parameter:

$$p_2 = \frac{E[R]}{E[S] + E[G]} \tag{13}$$

Furthermore, to ease the parametrization a parameter to control the ratio of actions is introduced:

$$\chi = \frac{E[S]}{E[S]+E[G]} \tag{14}$$

All action random variables are normalised to $E[S]+E[G]$. Therefore, $E[S]+E[G]$ is set to be equal to 1.0. Thus, the mean values of the random variables are:

$$\begin{aligned} E[R] &= p_2 \\ E[G] &= 1-\chi \\ E[S] &= \chi \end{aligned} \tag{15}$$

Variable action random variable S corresponds to annual extremes. For the calculation of the lifetime failure probabilities, extrema models adjusted to the considered reference period are needed, e.g. 50-year maxima model. This adjustment can be accomplished by assuming that the annual maxima are independent, then the cumulative distribution function (cdf) of n-year maxima is:

$$F_n(x) = F_1(x)^n \tag{16}$$

The parametrization chosen above is used to define the cases in Table 4. Multiple cases are considered to cover a wide range of design situations and to explore the effect of selected modelling decisions.

3.3 *Case 1*

The parameters used for Case 1 are summarized in Table 5. In Figure 1-4 the optimal failure rate for Case 1 is presented for various assumptions for V_R and V_S. In Figure 1, the optimal failure rate is plotted against the construction cost coefficient C_1. In Figure 2, the optimal failure rate is plotted against the direct failure cost H. In Figure 3 the optimal failure rate is plotted against the rate of obsolesce ϖ. In Figure 4 the optimal failure rate is plotted against the resistance coefficient of variation V_R.

From Figures 1-4 it can be concluded that the relative cost to achieve reliability C_1 / C_0; the expected failure consequences H / C_0 and the degree of uncertainty in S or R have a large effect on the optimal failure rate. Large uncertainty in either loading or resistance increases the relative cost of safety measures. The influence of the rate of obsolescence, although present, is relatively small for usual working lifes.

Table 4. Summary of the considered cases and their main characteristics

Case	Variable	Distribution	Mean	Coefficient of variation
Case 1 (Rackwitz, 2000)	R	Lognormal	p	{0.2,…, 0.6}
	S	Lognormal	1	{0.2,…, 0.6}
Case 2 (reference)	R	Lognormal	p	0.3
(alternative parameters)	S	Lognormal	1	{0.3, 0.5}
Case 3	R	Lognormal	p	0.3
(Case 2 + adjusted distr. types)	S	Gumbel 1	1	0.4
Case 4	R	Lognormal	p	0.3
(Case 3 + adjusted limit state	G	Normal	$1 - \chi$	0.1
function)	S	Gumbel	χ	0.4

See Section 3.2 for the explanation of variables and Sections 3.3 - 3.5 for the adjustments.

Table 5. Summary of the main parameters used for Case 1

Variable/parameter		Value
p	Design parameter	to be optimised
V_R	Coeff. of var. of resistance, R	Range 0.2-0.4
V_S	Coeff. of var. of action, S	Range 0.3-0.6
λ	Intensity (rate) of Poisson process	1/a
γ	Interest rate	0.035/year
b	Benefit	$= 2\gamma$
ϖ	Rate of obsolescence	0.02/year
	Intensity (rate) of Poisson process	
a	Ratio of ULS and SLS resistance means	$= E[R_U]/E[R_S] = 1.5$
C_0	Constr. cost independent of p	1 [unit cost]
C_1	Constr. cost coeff. dependent on p	$= 0.03\,C_0$ (varied*)
U	Repair cost	$= 0.3\,C_0$
A	Demolition cost	$= 0.2\,C_0$
H	Direct failure cost	$= 3\,C_0$ (varied*)

* This parameters has been given several values.

3.3.1 Optimal annual versus lifetime failure probability

The reciprocate of the obsolescence rate can be seen as the mean reconstruction interval of a structure, and in turns the mean reconstruction interval as the expected lifetime of a structure. ("Note that $\varpi = 0.01$ implies a mean reconstruction interval of 100 years." (Rackwitz, 2000)) Then the expected lifetime of the structure can be expressed as:

$$E(t_L) = \frac{1}{\varpi} \tag{17}$$

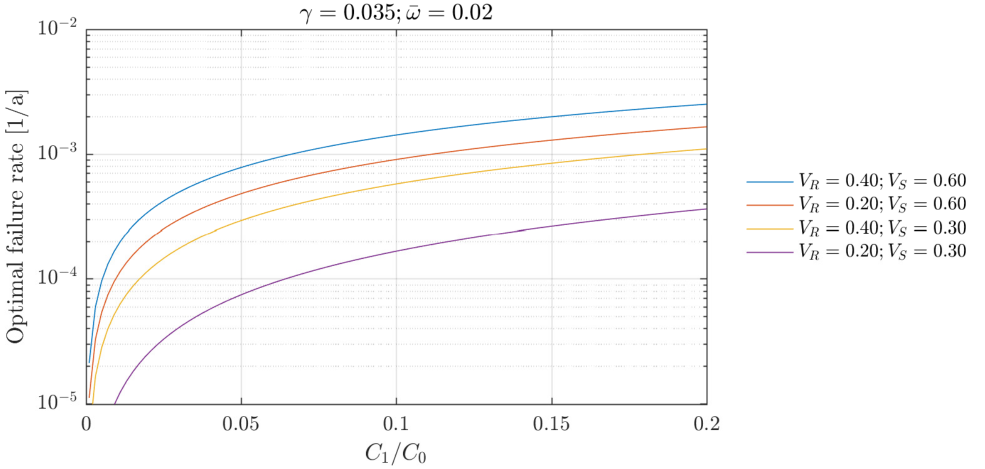


Figure 1. Optimal failure rate plotted against construction cost coefficient C_1 / C_0

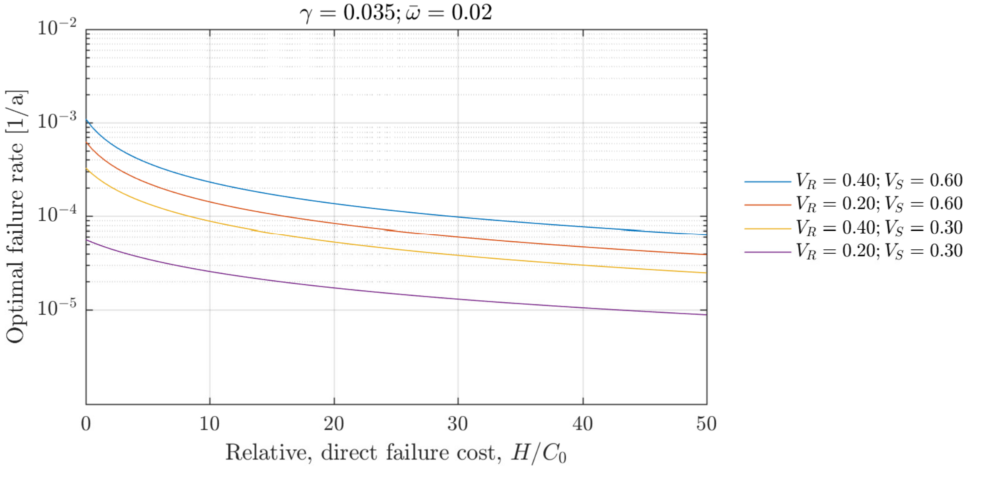


Figure 2. Optimal failure rate plotted against direct failure cost H / C_0

(Rackwitz, 2000) assumes a Poisson process for the event of obsolesce. This is, however, a simple mathematical representation with exponential failure times for the time required to reach obsolesce. In reality the lifetime distribution is more like indicated in Figure 5. Therefore, the Poisson model can only be used to obtain insight in the order of magnitude of the influence of the lifetime on the optimal annual failure probability and on the optimal lifetime failure probability.

In Figure 6, the optimal annual failure probability is shown for various combinations of V_R and V_S . In Figure 7, the optimal lifetime failure probability is shown for these

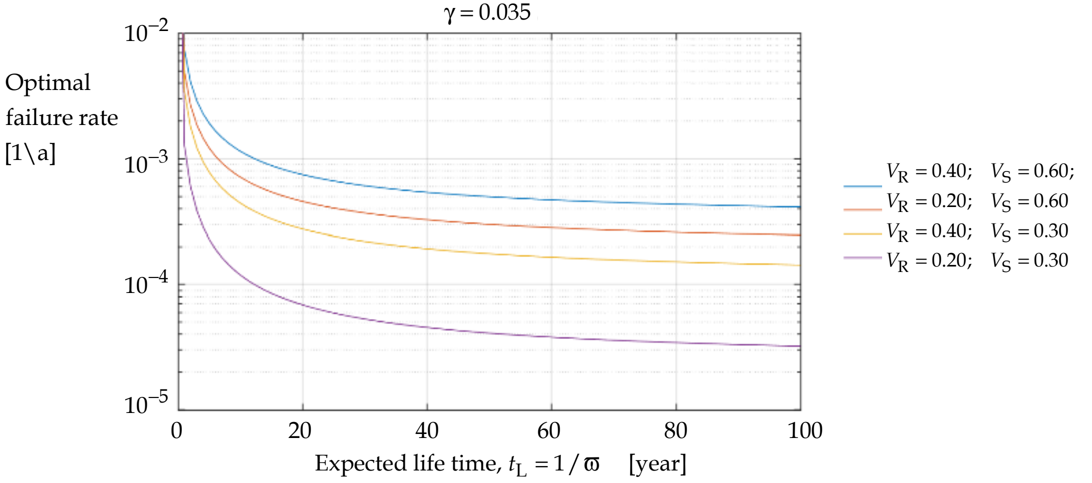


Figure 3. Optimal failure rate plotted against the rate of obsolesce ϖ

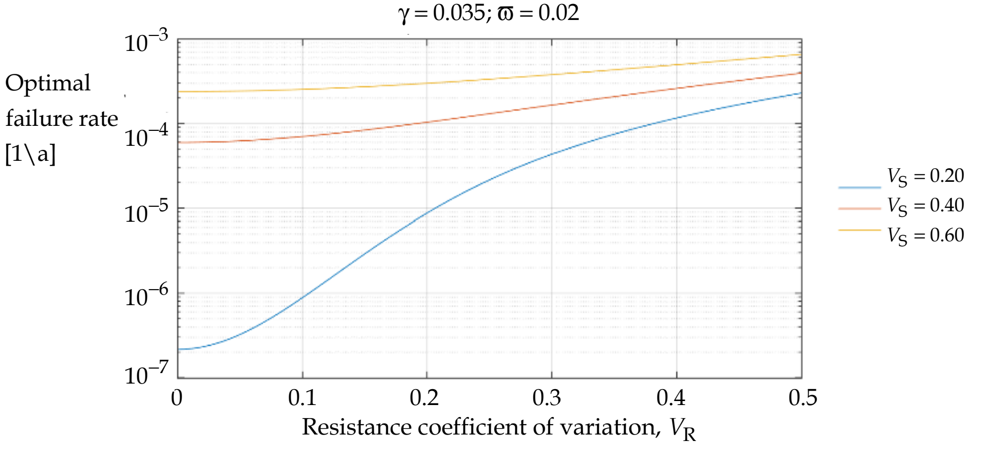


Figure 4. Optimal failure rate plotted against the resistance coefficient of variation V_R

combinations of V_R and V_S . The computation of lifetime failure probabilities includes dependence between annual failure events.

We see in the figures 6 and 7 that with increasing anticipated lifetime the annual β increases and the lifetime β decreases slightly. However, the lifetime β is slightly more *constant* for different rates of obsolescence or design lifetimes. From an economic optimization point of view for longer lifetimes the annual β goes down while the lifetime β is more or less constant or slightly going up. This property of β is especially true for short design or remaining working lifes, however the influence is limited for normal design lifes (> 20 years).

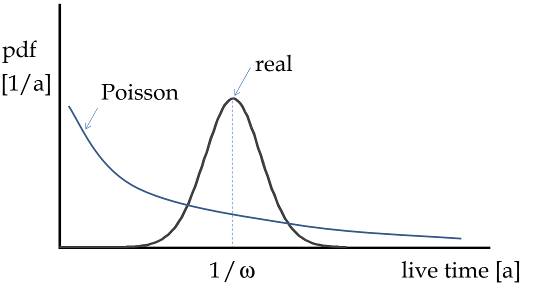


Figure 5. Distribution function of the lifetime; Poisson assumption and real distribution function

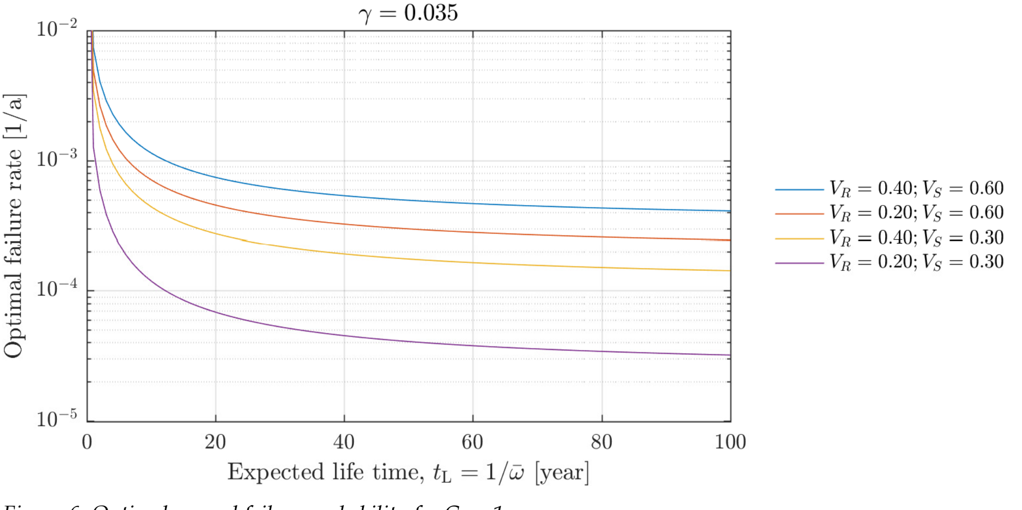


Figure 6. Optimal annual failure probability for Case 1

On the basis of these calculations one may conclude that in case of a given design working life, the lifetime target reliability does depend on the duration of the design working life. However, this effect is small and negligible with respect to the dependence of the target reliability on the relative cost to achieve reliability, the expected failure consequences and the degree of uncertainty in load or resistance.

3.4 *Cases 2 and 3*

For Case 2 some values in the probabilistic model are adjusted to reflect better our current state of knowledge, i.e. the interest rate is reduced to 0.02. Moreover, for simplicity only a single coefficient of variation for the resistance (V_R = 0.3) is considered. The results are shown in Figures 8 and 9.

We see in the Figures 8 and 9 an even stronger effect than in Figures 6 and 7: with increasing anticipated lifetime the annual β goes down and the lifetime β is almost constant. More figures have been produced but are not included in this paper. Also here we can conclude that the effect of the expected working life is small and negligible.

The target reliability is strongly influenced by the relative cost to achieve reliability C_1 / C_0 ; the expected failure consequences H / C_0 and the degree of uncertainty in

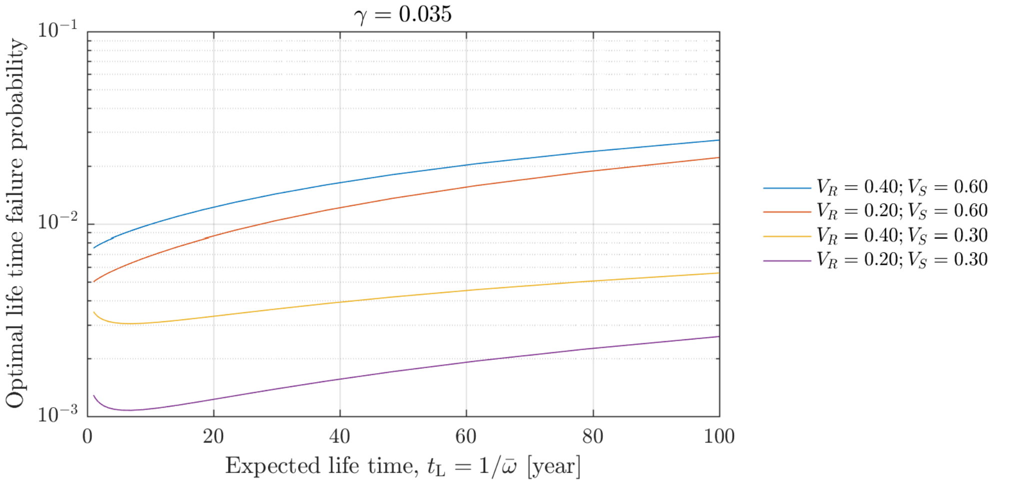


Figure 7. Optimal lifetime failure probability for Case 1 accounting for the dependence between annual failure events

load V_S and resistance V_R . Using a Gumbel distribution for S has therefore a very small influence, and does not change the figures above.

3.5 Case 4

In this example we work with various load ratios χ; this allows for insight to the effect of having a structure which is dominated by a permanent action with small uncertainty or by variable action with often a larger uncertainty. In Figure 10 the optimal failure rate [1/a] is

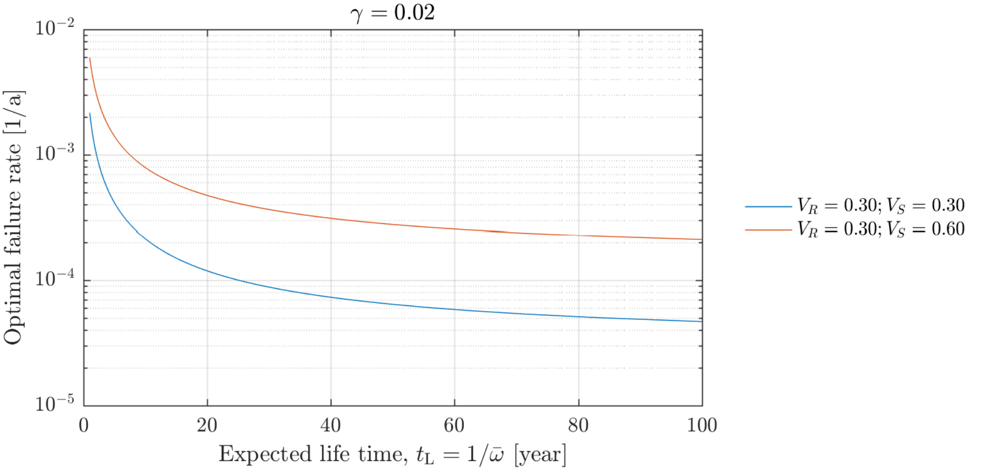


Figure 8. Optimal annual failure probability for Case 2

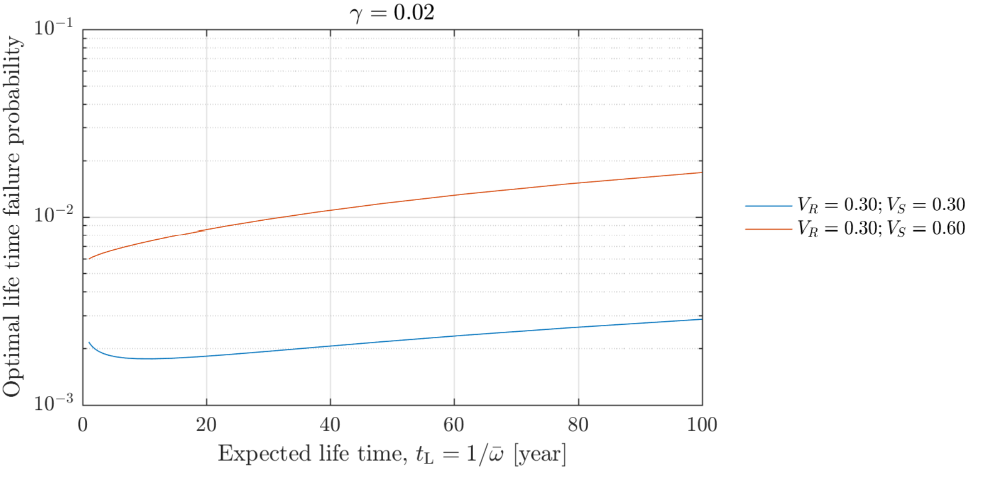
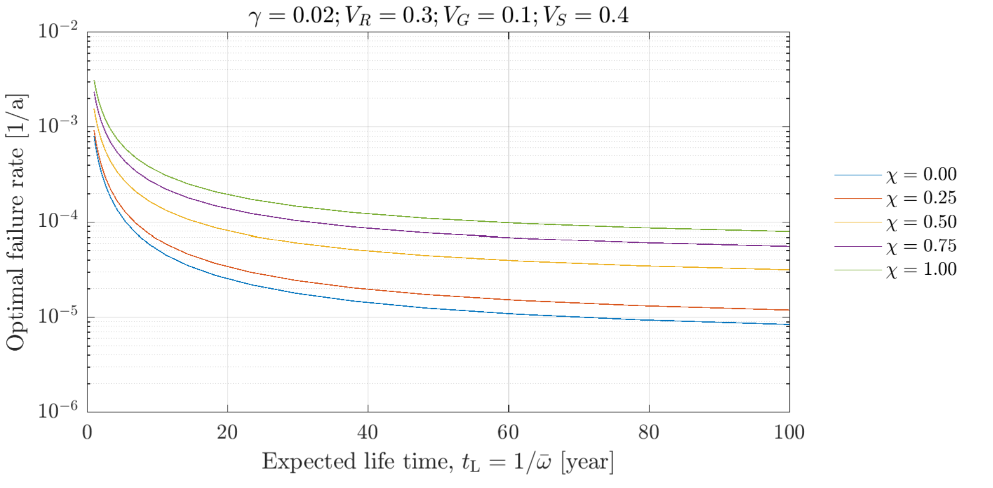


Figure 9. Optimal lifetime failure probability for Case 2 accounting for the dependence between annual failure events

plotted against the load ratio for different design lifetimes t_L or obsolescence rates. We observe that for t_L >20 year the influence of the obsolescence rate (or the design lifetime) is very small. For normal design or remaining lifetimes, the influence of the obsolescence rate (or the design lifetime) can therefore be neglected with respect to the influence of other parameters. In Figure 10 the influence of the degree of uncertainty in the load is clearly visible; on the left hand side the optimal failure rate for a structure dominated by permanent action, on the right hand side the optimal failure rate for a structure dominated



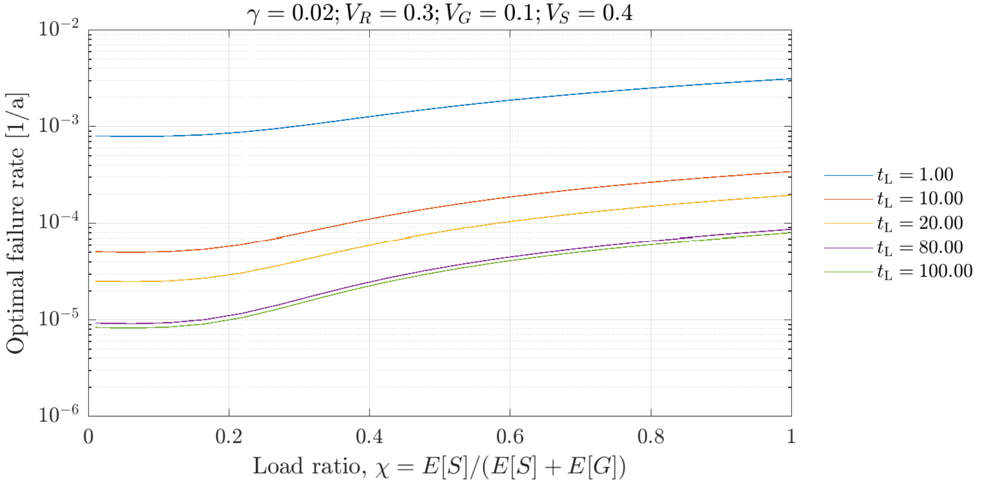


Figure 10. Optimal annual failure probability for Case 4 as a function of expected lifetime (top) and load ratio (bottom)

more by the uncertain variable action: the difference in optimal failure rate is about a factor of 10.

3.6 *Optimal annual failure rates*

From an economic optimization point of view three main parameters govern the optimal β-value: the failure consequences; the relative cost to achieve reliability, and the scatter of action or resistance parameters. The dependence on the obsolescence rate or the design working life is present but its influence is very limited. Therefore, consequence classes are defined in which the dependence on the three parameters is shown.

The JCSS (Probabilistic Model Code, 2001) defines consequence classes based on the consequence ratio:

$$\rho = \frac{\text{construction cost + direct failure cost}}{\text{construction cost}} \tag{18}$$

Using the components of the basic example it can be expressed as:

$$\rho = \frac{C_0 + C_1 + H}{C_0 + C_1} = 1 + \frac{H}{C_0 + C_1} \approx 1 + \frac{H}{C_0} \tag{19}$$

This leads to the values in Table 6 for the ranges of failure consequences. In Table 7, the Consequence Classes are derived and proposed according to ISO 2394 (2015) and the JCSS probabilistic model code (2001).

Table 6. JCSS [3] consequence classes in terms of ρ *and their connection to the quantities used here*

Measure of failure consequence	Ranges of failure consequence		
	Minor (Insignificant)	Moderate (Normal)	Large (Large)
ρ	< 2	2 ≤ < 5	5 ≤ < 10
H / C_0	< 1	1 ≤ < 4	4 ≤ < 9

In Figure 11, the optimal failure rate is plotted for different failure costs and the relative cost to achieve reliability. The colour regions are corresponding to the limits given in Table 7. A target failure probability in a particular class is considered as upper limit for that class and coloured in accordingly, e.g. the Small-Insignificant class is considered on the [10^{-5} , 0] interval.

The default case that applies for usual structures and normal relative cost of safety measure gives annual target reliability of β = 4.2.

Normal relative cost of safety measure is associated with medium variabilities of the yearly extreme of the total loads and resistances ($0.1 < V < 0.4$). Deviation from normal relative

Table 7. Proposal for quantitative limits for target failure probability classes

Relative cost to achieve reliability, C_1 / C_0		Expected failure consequences Proposal for quantitative limits, H / C_0		
		< 1 Insignificant	$1 \leq < 4$ Normal	$4 \leq < 9$ Large
$5 \cdot 10^{-4} \geq$	Small	10^{-5}	$5 \cdot 10^{-6}$	10^{-6}
$5 \cdot 10^{-4} > \geq 5 \cdot 10^{-3}$	Normal	10^{-4}	10^{-5}	$5 \cdot 10^{-6}$
$> 5 \cdot 10^{-3}$	Large	10^{-3}	$5 \cdot 10^{-4}$	10^{-4}

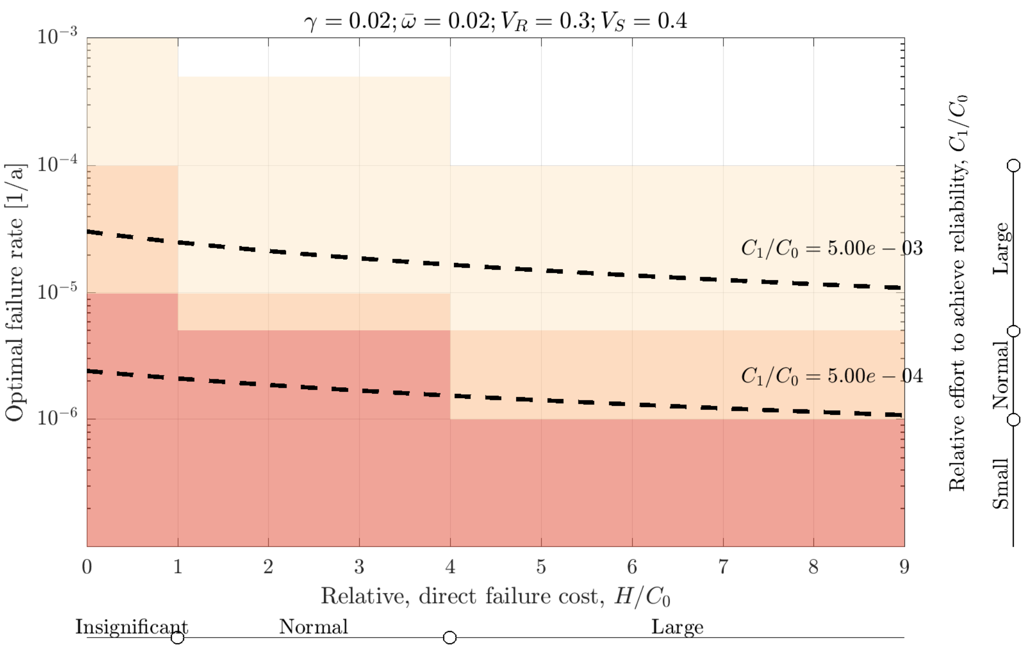


Figure 11: Illustration of the proposed target failure rates, the associated quantitative limits, and optimal failure rates to the proposed C_1 / C_0 bounds (dashed lines)

cost of safety measure can be considered based on the following characteristics:

1. Degree of uncertainty; large uncertainty in either loading or resistance ($V > 0.4$) may increase the relative cost of safety measure to Large, small uncertainty ($V < 0.1$) may decrease the relative cost of safety measure to Small.
2. Existing structures; as the cost for increasing reliability are in general higher as compared to structures under design the relative cost of safety measure may be classified as Large.
3. Service life and/or obsolescence; for structures with a short expected service life or otherwise rapid obsolesce in the order of less than 10 years the relative cost of safety measure may be classified as Large.

4 Discussion and conclusion

It is an ongoing matter of debate what changes should be used for the target reliability index in the case of a design working life other than 50 years. Design codes like the Eurocodes are not very explicit about it, partly because the problem was given insufficient attention, partly because of opposing opinions. Many people share the opinion that the structural dimensions should not depend on the value of the design working life. On the other hand it seems economically justified to spend more money on structural reliability if one can profit from that for a longer time. Often, the design lifetime is unknown in advance; it depends on various random events and also depends on decisions to be made in the future. The calculations in this papers shed light on this problem from a decision making point of view.

From an economic optimization point of view three main parameters are governing the optimal β-value: the failure consequences; the relative cost to achieve reliability, and the scatter of action or resistance parameters. The dependence on the obsolescence rate or the design working life is very limited. The recommendation is therefore to implement a format for specifying target reliabilities taking basis in annual values.

The format for specifying target reliabilities on an annual basis should be interpreted as a target limit for every individual year during the design or remaining working life of the structure:

- If the annual failure probability is a decreasing function of time (like in the case when time independent random variables like resistance and self-weight are dominating) the first year is decisive.

- If the annual failure probability is an increasing function of time (like in the case when aging processes like fatigue, corrosion or climate change and future (uncertain) trend are relevant the last year of the design service life may be decisive.

The target reliabilities given in Table 1 should be seen as indicative for the support of economic optimization; in that optimization also loss of human lifes can be included, making reference to the marginal life saving costs principle. Acceptance criteria for risk to life - that are based on "absolute risk" levels deemed to be acceptable - may have to be checked independently of the optimization results. In that case a reference period that is short compared to the average human life makes sense. Longer periods than one year, like 5 or 10 years, could also be chosen but are less practical in codification.

However on an individual basis life safety risks should also be assessed. Within society some people might be exposed to significantly larger risks than other; this should always be checked individually as explained in the foregoing. The target value chosen may depend on considerations like, individual risk, see (Faber et al. 2015). Since both economic and human safety target reliability levels are proposed to be on an annual basis the values become comparable and can be used in a format for writing building standards.

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