Structural Safety 76 (2019) 149–161

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Optimal and acceptable reliabilities for structural design

Katharina Fischer[a,*], Celeste Viljoen[b], Jochen Köhler[c], Michael H. Faber[d]

[a] Matrisk GmbH, Alte Obfelderstrasse 50, 8910 Affoltern am Albis, Switzerland
[b] Department of Civil Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[c] Department of Structural Engineering, NTNU, Richard Birkelands vei 1a, Trondheim, Norway
[d] Department of Civil Engineering, Aalborg University, Thomas Manns Vej 23, 9220 Aalborg Ø, Denmark

A B S T R A C T

A common approach to define criteria to reliability performance of structures in the development of semi-probabilistic design codes and for probabilistic design of individual structures is to make use of the tentative target reliabilities provided in the JCSS Probabilistic Model Code. An acceptable level of life safety is, however, not guaranteed when applying the target reliabilities provided by the JCSS, as these have been derived based on monetary optimization. In the present paper, the underlying generic framework for structural design optimization is reviewed and extended for the derivation of life safety related target reliabilities based on the marginal lifesaving costs principle. The resulting minimum acceptable reliabilities may be used in combination with the JCSS target reliabilities to achieve designs that are both cost-efficient and consistent with societal preferences for lifesaving investments. The framework presented in this paper 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. An extended discussion of the general framework and its underlying assumptions includes considerations about the application of the target reliabilities at component or system level, accounting for structural robustness, as well as implications for the interpretation of the main variables entering the framework.

1. Introduction

The design of a structure is in principle a decision problem with the objective to identify a structural design with a performance that maximizes the expected utility for the corresponding decision maker. The objective can be directly sought by risk assessment where uncertainties, system boundaries, consequences, the decision maker's preferences, etc. are represented at a level of detail that is found to be appropriate to identify the optimal decision alternative. However, practical structural design is seldomly based on formal risk informed decision making, but applying simplified approaches like reliability based design and/or so-called semi-probabilistic design based on partial safety factors and characteristic values. In these simplified formats, the objective, i.e. the maximisation of the expected utility, is not directly assessed, but indirectly sought by aiming at requirements for the structural reliability or probability of failure. Compliance to a reliability requirement can be directly demonstrated in reliability based design. Semi-probabilistic design formats are calibrated such that design solutions that are identified with the help of these formats comply to the criteria – this is generally referred to as reliability based code calibration. It is important to note that the simplified methods, especially semi-probabilistic design, are compromising the overall objective, i.e. the expected utility might only be approximately maximised for a given design situation. However, the simplicity and crudeness of these methods make them obviously easier to apply, and more importantly, allow for a broad generalisation. Both attributes make simplified methods, and again especially semi-probabilistic design, well suited for design standards.

The Probabilistic Model Code [1] issued by the Joint Committee of Structural Safety (JCSS) provides tentative target reliabilities for structural design, see Table 1. Here, nine different values are given depending on two different attributes of the design decision problem: consequences of failure and relative cost of safety measure. This differentiation of target reliabilities does introduce a risk component into the simplified design methods, however, on a somewhat crude and generalized level of detail. In ISO 2394:2015 [2], these target reliabilities are complemented by tentative minimum acceptable reliabilities derived from a societal acceptance criterion for investments into life safety. In the present paper, the fundamental principles and the applied simplifications and generalisations underlying the derivation of the different reliability requirements are discussed and combined in a generic framework.

The JCSS target reliabilities in Table 1 have been derived based on monetary optimization, using a generic approach formulated by Rackwitz [3]. Consequences in terms of loss of lives due to structural failure are considered only qualitatively in the definition of the consequence classes provided in the Probabilistic Model Code [1]. The societal acceptability of structural design with respect to life safety risks is, thus, not explicitly taken into account when applying only the JCSS target

* Corresponding author.
E-mail addresses: fischer@matrisk.com (K. Fischer), cbarnardo@sun.ac.za (C. Viljoen), jochen.kohler@ntnu.no (J. Köhler), mfn@civil.aau.dk (M.H. Faber).

https://doi.org/10.1016/j.strusafe.2018.09.002
Received 18 July 2017; Received in revised form 7 July 2018; Accepted 8 September 2018

Table 1
Tentative target reliabilities and corresponding failure probabilities related to a one year reference period and ultimate limit states, based on monetary optimization, JCSS [1] (see also ISO 2394:2015 [2], Annex G).

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)	$\beta = 4.2$ ($P_f \approx 10^{-5}$)	$\beta = 4.4$ ($P_f \approx 5{\cdot}10^{-6}$)	$\beta = 4.7$ ($P_f \approx 10^{-6}$)

reliabilities. This can however be achieved by combining the approach underlying the JCSS target reliabilities with an acceptance criterion explicitly accounting for life safety, as proposed by Fischer et al. [4].

The goal of the present paper is first to provide a common framework for choosing an adequate reliability level for simplified structural design both in terms of monetary optimization and societal life safety risk acceptance. In a next step, this framework is applied to derive the reliability targets presented in the JCSS Probabilistic Model Code [1] and in ISO 2394:2015 [2] in a transparent and consistent way. The focus is on the formulation of reliability requirements that can be used for decision-making based on simplified methods, e.g. in the context of reliability-based code calibration and for reliability-based design of individual structures.

The following terms are introduced to clearly distinguish between the two aspects of the decision problem:

– *Optimal reliabilities* are derived based on monetary optimization
– *Acceptable reliabilities* are derived based on societal preferences for investments into life safety

The JCSS table contains optimal reliabilities. Adding acceptable reliabilities to this format, as in ISO 2394:2015 [2], ensures that designs that comply to both requirements are both optimal and acceptable in terms of investments into life safety.

The content of the paper is outlined as follows: In Section 2, the concept of monetary optimization with a life safety acceptance criterion is introduced. The application of these concepts to the development of requirements for simplified structural design is presented in Section 3 for the derivation of optimal reliabilities in consistency with the JCSS target reliability format, and in Section 4 for the extension based on the marginal lifesaving costs principle, leading to the derivation of acceptable reliabilities. Section 5 contains an extended discussion of the underlying assumptions as well as the interpretation and practical implementation of the reliability targets, followed by a summary and the conclusions in Section 6.

2. Monetary optimization and societal risk acceptance

Increasing the safety of structures is generally associated with costs, e.g. as more material is used to construct structural components. The optimal level of safety is achieved by minimizing the total costs, which are defined as the sum of the safety costs (invested or committed for the purpose of risk reduction) and the expected value of failure costs, see the upper part of Fig. 1 for illustration.

To identify and ensure appropriate levels of structural safety, monetary optimization needs to be constrained by a societal acceptance criterion for decisions affecting life safety. To maximize the number of lives that can be saved given technical and financial constraints, societal resources for life safety must be directed to the most efficient risk reduction measures available, in accordance with best practice applied technology. This can be achieved by applying the marginal lifesaving costs principle, as shown in the lower part of Fig. 1. The efficiency of lifesaving measures is assessed by evaluating the marginal lifesaving

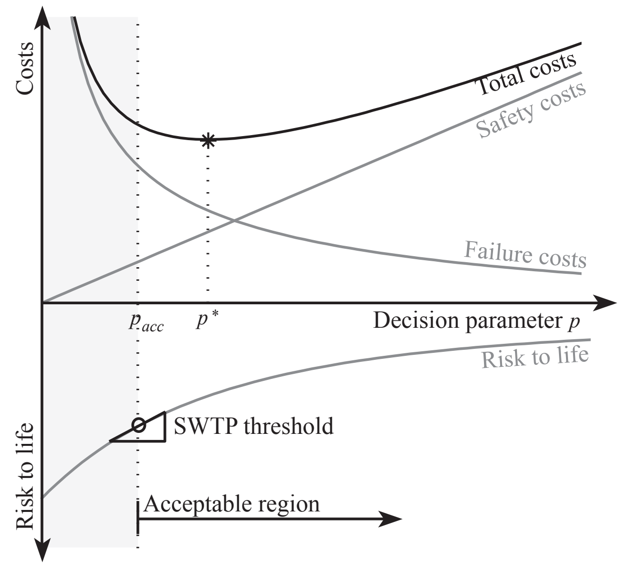

Fig. 1. Monetary optimization with societal acceptance criterion for investments into life safety (see also ISO 2394:2015 [2] and Faber and Maes [5], among others).

costs, i.e. the investments necessary for a small increase in life safety. A risk reduction measure is deemed efficient from a societal point of view if the marginal lifesaving costs are smaller than the Societal Willingness To Pay (SWTP), which represents the amount of money that society is willing – and can afford – to spend for saving an additional anonymous life. A discussion of the underlying economic principles can be found e.g. in Schelling [17].

In practice, the marginal lifesaving costs will typically increase with the level of safety, as illustrated by the decreasing slope of the "risk to life" curve in Fig. 1. This is equivalent to a decrease in efficiency of (additional) risk reduction measures. The application of the marginal lifesaving costs principle as a societal acceptance criterion necessitates that all efficient investments (with marginal lifesaving costs smaller than the SWTP) have to be implemented, which is why the acceptable region starts at the SWTP threshold.

Fortunately it turns out that in practice, the ranking of decision alternatives for life safety risk reduction is not sensitive to moderate variations in the SWTP, provided that all decisions affecting life safety are consistently based on the marginal lifesaving costs principle; thus promoting the most efficient risk reduction measures and avoiding the most inefficient ones. To illustrate this point, one may consider e.g. the seminal work by Tengs et al. [6], showing a very large variation of costs per life year saved in different lifesaving interventions that have been implemented in the past. Applying the marginal lifesaving costs principle would clearly have improved decision-making, independent of the exact SWTP value assumed.

A possible way to estimate the SWTP using socio-economic indicators was introduced by Nathwani et al. [7] based on the Life Quality Index (LQI). In a paper presented at the first LQI Symposium in Denmark (Fischer et al. [4]), we used this approach for the derivation of minimum acceptable reliabilities for structural design. In the present paper we utilize the same framework, but in a more general formulation that does not refer to a specific approach for estimating the SWTP.

The principle interaction between monetary optimization and societal risk acceptance is illustrated by combining the two parts of Fig. 1. Optimization is admissible only within the acceptable region, which is derived from the marginal lifesaving costs principle. As highlighted in Faber and Maes [5], this is fully consistent with the As Low As Reasonable Practicable (ALARP) approach. All efficient risk reduction measures (with marginal lifesaving costs smaller than the SWTP) have to be implemented to achieve societal risk acceptance, but higher safety