Target reliability for bridges with consideration of ultimate limit state

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A B S T R A C T
The target reliability is a design constraint that assures the required safety level for structures. Derivation of
the target reliability is a complicated and challenging task. To determine the target reliability, two
main approaches can be considered. The first approach is based on engineering judgment with respect
to past observations of structural failure, while the second method is based on optimization theory. In
the past, structural design codes implicitly assumed the target reliability with regard to past experiences,
however, the objective of the optimization approach is to compute the target reliability using minimiza-
tion of the cost-failure function. This contribution attempts to establish an optimization procedure to
determine the target reliability for structures with consideration of the construction cost, failure cost,
maintenance cost, structural life-time, discount rate, time-dependency of the load and resistance, and
structural importance factor. Accordingly, the relationship between, target reliability, structural cost,
structural importance factor, and structural life-time are depicted using the contour concept. Eventually,
the target reliability for steel girder bridges is determined concerning the ultimate limit state.

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1. Introduction

The main objective of the design codes is to provide the safety level for the structures. Reliability index is a common safety metric in engineering cases. The first definition of the reliability index was initiated by Basler [7] and Cornell [8] for normal limit state func-
tions and the new generation of the reliability index has been developed by Ghasemi and Nowak [11] to measure the safety level for no normal limit state functions. Madsen et al. [24] defined four chronological categories for design codes. The first level is based on the deterministic design formulas using the deterministic safety factors. The second and current used level is established with regard to the closeness of the designed reliability index to the target. Level three is the development of the second level using fully reliability analysis of the system subjected to the different loadings scenarios. The most sophisticated code level is expected to develop the design formulas with consideration of the optimum target reli-
ability indices in which the total expected cost is minimized and the safety level is maximized. In this paper, it is tried to present an optimization procedure to calculate the target reliability for structures concerning the construction cost, failure cost, main-
tenance cost, structural life-time, discount rate, time-dependency of the load and resistance, and structural importance factor.

There have been extensive studies to determine the time depend-
ent reliability indices for structures. Mori and Ellingwood [25,26] combined a crack growth model in concrete with time-dependent reliability to evaluate the strength deterioration of the considered concrete structures. Using experimental data and the proposed approach, they developed a strategy to optimize the cost of inspection/maintenance. However, Mori and Ellingwood put a significant computational effort to solve the non-linear optimization problem for reorganization of the optimum inspection time and repair cost. American Bureau of Shipping [4] conducted a study to define a gen-
eral risk-based methodology in order to evaluate limit state func-
tions and target reliabilities for novel structures concerning the failure modes and their consequences. For this purpose a survey questionnaire was distributed among experts. Wen [39] considered the uncertainty involved in the loading process and structural response for buildings, in the design of new structures and evalua-
tion of existing ones. He tried to minimize the expected life-time cost as it corresponds to the target reliability. Katade and Katsuki [20] presented a new method to determine the target reliability for structures in which the target reliability has been achieved based on trade of between the probability of failure and the structural cost. Trbojevic [37] investigated the safety level of the struc-
tures with regard to the interaction between the societal risk...
criteria and target reliability. He [37] found that a significant incompatibility between the safety risk criteria and structural reliability criteria as the risk aversion point of the view. In an attempt to minimize the related cost of bridge foundation, Huaco et al. [17] defined the target reliability indices using the consideration of the socially and economical issue associated the total cost of the foundations. In doing so, Huaco et al. [17] took into account both socially acceptable risk and economic concerns. Frequency of failure and consequences of failure can determine the socially acceptable risk through FN curves (F = frequency of failure, N = number of lives lost). Economic concerns, on the other hand involve the life-time cost of a bridge depending on the reliability of the foundation and consequences of failure. They provided a procedure to minimize the bridge cost for a preselected reliability level. Furthermore, target reliability study can be considered using societal risk criteria. Arangio [5] conducted a study to assess civil engineering system based on the reliability analysis. She [5] attempted to provide the which can be used as a new safety assessment for the complex sys- tems. Holicky [16] attempted to find the influence of the characteristic parameters on the target reliability for structures. To do so, he considered construction cost, failure consequences, design life, and discount rate as characteristic parameters in his analysis. Yanaka et al. [40] analyzed the target reliability for prestressed girders, of bridges subjected to the corrosion conditions with consideration of the optimization of the initial, maintenance, and failure costs. Ghasemi et al. [14] conducted a probability-based analysis to derive the considered target reliability for serviceability limit states concerning the deflection criteria in AASHTO LRFD bridge design. In order to achieve this goal, Ghasemi and Nowak [12] utilized the obtained statistical parameters of moving loads on bridges which were collected by Ghasemi et al. [13]. Accordingly, they introduced a 3D probability plot to estimate the target reliability indices based on the engineering judgment. This paper establishes a new procedure to determine target reliability with consideration of the initial cost, failure cost, maintenance cost, structural life-time, discount rate, time-dependency of the load and resistance, and structural importance factor. To do so, first the interactions between the considered parameters are determined. For instance, as the state of the art, the relationship between the cost functions and reliability index is modified using a new formulation of the failure cost and maintenance cost in terms of the initial cost. Furthermore a new definition of the structural importance factor is presented based on the failure cost. Accordingly, the effects of the structural deteriorations on the target reliability indices are formulated. Then, the relationship between, target reliability, structural cost, structural importance factor, and structural life-time are depicted using the contour concept. Eventually, as the practical example, the target reliability for the steel girder bridges is determined for various life-time and span length with regard to the different corrosion conditions.

2. Objective function to determine the target reliability

Target reliability can be determined by:

1. Minimization of the total expected cost
2. Maximization of utilities
3. Minimization of human casualties and environmental damage

In all optimization problems, it is necessary to establish an objective function. The objective function in this study is a cost function. According to the conducted study by Lind and Nowak [22], the cost function can be defined in terms of the initial cost and failure cost, which is related to the probability of failure. Lind and Nowak proposed the following model to consider the total structural cost:

\[ C_t = C_i + C_f(P_f) \]  (1)

where

- \( C_t \) = total cost,
- \( C_i \) = initial cost,
- \( C_f \) = failure cost, and
- \( P_f \) = probability of failure.

Basically, the failure cost can be categorized into the cost at the failure moment (General Cost) and the cost of the consequences of failure (Operational Cost). Also both mentioned costs can be divided into economic, social and environmental cost [23].

In this research, the maintenance cost \( (C_{M}) \) is added to the total cost. Maintenance is required when the structure is exposed to expected or unexpected severe conditions that reduce the structural capacity or functionality. Expected causes are related to material deterioration or reduction of capacity due to severe conditions such as corrosion, fatigue or vibrations. In other words, the main reason for maintenance is to return the structural performance capacity to its original condition. Therefore, this research proposes the following object function to calculate the target reliability.

\[ C_t = C_i + \sum_{j=1}^{k} (C_M) j (\{ P_d \}) j + C_f(P_f) \]  (2)

where \( (C_M) j \) = maintenance cost and \( \{ P_d \} j \) is the probability of the structural deterioration at the jth sequence out of the n required maintenance periods during the structural life-time. Although Val and Stewart [38] proposed a formula for the life-cycle cost, the maintenance cost has not been clearly defined as an expected cost value. Since the cost of the maintenance is inherently considered as an expected cost value of the maintenance, herein, the proposed equation (Eq. (2)) for the total cost is written in terms of both expected cost of the failure and the expected cost of the maintenance at the maintenance time.

2.1. Proposed objective function for target reliability calculation

The target reliability is a limit for the safety margin of the structure that indicates the minimum structural cost. The objective function consists of several parameters, such as an initial cost, failure cost, and maintenance cost. The initial cost can be directly determined based on the construction cost. The maintenance and failure cost, however, depend on probabilities of maintenance and failure, respectively, and those cost can be deliberated as expected cost values. Moreover, during the life-time of the structure, failure cost and maintenance cost can be changed by the discount rate influence. Therefore, the objective function is a time-dependent function. Hence, the following equation is proposed as the objective function to compute the target reliability:

\[ \min_{\beta} \left\{ C_i(\beta) + \sum_{i=1}^{n} (C_M(\beta, t)) i \{ P_d(\beta, t) \} i + C_f(\beta, t) [P_f(\beta, t)] \right\} \]  (3)

where \( \beta \) represents the reliability index and \( t \) indicates the intended life-time of the structure. As the state of the art, all costs are written as the functions of the reliability index. Therefore, the target reliability can be easily derived from the optimization of Eq. (3). According to Basler [7] and Cornel [8], if the probability of failure and maintenance behave as normal distributions, the relationship between the probability of failure and the reliability index can be expressed as follows:

\[ \text{failure: } \beta = -\Phi^{-1}(P_f) - P_f = \Phi(-\beta) \]  (4)
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