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Applications of total expected cost concept to various decision making situations

Jun Kanda

The University of Tokyo, Japan

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ABSTRACT

The probabilistic safety measure has been common among structural engineers. Optimum Load factors based on the minimization of total expected cost were proposed in 1991. Applications of the total cost concept were developed for occasions of safety decision making. CO_2 emission can be used as an alternative scale to the monetary cost. Optimal seawall height against Tsunami was another example.

1. Introduction

The probabilistic safety measure has been common among structural engineers since the reliability-based limit state design was implemented as practical codes in US and Europe in 1980′s. Then the reliability index is regarded as a unique safety measure for structures as also stated in ISO documents. Nevertheless once the minimum design requirements specify the load factor based on the target reliability in regulations, engineers tend to simply follow the requirements and to forget to consider the appropriateness of target safety. The local condition of seismicity and the importance of structure depend on the site and building use respectively, and the engineer should provide sufficient information for the client to make a decision on the appropriate safety target. In particular when a building has the public nature, stakeholders including users should take part in the decision making on structural safety.

The minimization of total expected cost can provide a solution to such decision making procedures in a rational manner. This paper briefly reviews some previous studies on the applicability of total expected cost concept for 30 years. The role of engineers is also focused on the determination of target design safety for structure.

2. Basic concept

In periods when reliability-based limit state design was first introduced in practical codes, calibrations of reliability index to the existing codes were conducted in US and Europe, as the society basically needs the safety for buildings as has been accepted. Load factors based on the minimization of total expected cost for the appropriate safety were proposed by Kanda and Ellingwood in 1991 [1] as an alternative approach. Simple closed form solutions of the optimal reliability index are available for three probability models for loads; i.e. Gumbel distribution, Gauss distribution and the log-normal distribution. Major reason for the study progress of this approach is that probabilistic models for structural loads were practically established. And also the variability is generally greater for loads rather than for resistances and the design load determination is quite essential for the target safety of structure, although engineers do not pay much attention to the design load determination as they are specified in regulatory codes.

In 1970′s, the application of optimal safety to codified structural design was proposed by various researchers, such as Rosenblueth [2], Lind [3] and also Hanai in Japan [4] as a basis for establishing cost-effective requirements. Probabilistic models for structural loads have been developed significantly since then, as the reliability-based design has been popular in research as well as in practical codes. Wider aspects of the optimal reliability on codified procedure have been discussed in the Joint Committee of Structural Safety by considering a risk component and were summarized by Fischer et al [5].

Now the minimization of total expected cost has been widely accepted as ISO2394 for the general principle for the structural safety which introduces a procedure for optimization considering the risk information [6].

Basic formula for the total cost C_T is expressed as,

$$C_T = C_I + P_f C_f \tag{1}$$

where C_I is the initial cost, P_f is the probability of failure and C_f is the failure cost. C_T varies with the load factor and the minimization of the total cost C_T leads to the load factor with the optimum reliability.

In general, monetary optimization with the objective function may be defined as [5,7],

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$$\boldsymbol{p}^* = \underset{\boldsymbol{p}}{argmax}\{Z(\boldsymbol{p})\} \tag{2}$$

where $Z(\boldsymbol{p})$ is the objective function composed of the benefit minus the construction cost, the obsolescence costs, the ultimate failure costs, the serviceability failure costs, the degradation costs and the maintenance costs. $\boldsymbol{p}$ is a vector of decision variables for these costs and the optimal decision is attained with $\boldsymbol{p}^*$. Eq. (1) is a simplified case of Eq. (2) and still useful to reflect the basic idea of cost effectiveness.

Then three parameters in Eq. (1) play an important role on the determination of optimal safety. They are the cost-up gradient, the coefficient of variation for the load and the normalized failure cost, i.e. the estimated cost due to structural failure normalized by the reference construction cost. The cost-up gradient can be obtained by estimation of construction cost with varying the safety index or the load factor. Engineers can provide such information when they conduct the structural design with varying the design load intensity. The coefficient of variation of load is basic information for probability-based design and codified load factors are implemented based on such basic information. These two parameters are generally provided in objective manner with aids of engineering and/or scientific findings. However, the third parameter, normalized failure cost is dependent rather on the subjective value of failure damage. In other words, the social, cultural or psychological factors also influence on the normalized failure cost.

3. Risk communication tool

Monetary value is most convenient to compare values of various aspects. Although the normalized failure cost parameter could include various human factors, the owner of building can finally determine the monetary value for the failure of building. Kanda and Shah examined some possible evaluations of the normalized failure cost [8]. One of difficulties on the evaluation of failure cost lies on the cost of the human loss and casualties. Nevertheless, the property loss is comparatively much greater than the human loss in many cases.

As a typical case further simplified relation between the normalized failure cost parameter, g and the optimal safety index, β is indicated as,

$$\log g = \beta - 1.7 \tag{3}$$

The normalized failure cost can be an alternative measure for the appropriate safety index for a decision maker, although at the same time the professional engineer must provide sufficient information and meanings of the normalized failure cost, which play an important role in Eq. (1). Some studies on design decisions of Nuclear Power Plant indicate similar cost coefficients supporting Eq. (3) [9].

Further consideration was made for a case study on the appropriate seismic safety of school gymnasium [10]. An enquiry was attempted in a workshop to obtain information regarding the monetary value of human life. Most school gymnasium buildings in Japan are to be used as shelter facilities when natural disaster occurs. If the building is damaged, it may not be used any more as a shelter facility. Residents near the school are likely to be occupants during the disaster and they can think how much would be the failure cost as their own matter of interests. Information for the relationship between the monetary value of human life and the cost of construction with minimum total expected cost was provided before the enquiry. Such a study and discussion could provide an alternative for the optimal structural safety from the aspect of users.

The probabilistic safety measure itself may not be easy to be discussed among stakeholders. Nevertheless, it is important for the society where structures have the optimum safety degree. The design seismic load for school gymnasium building is specified to be 1.25 times of ordinary building according to the order by the Ministry of education, culture, sports, science and technology in Japan. It is a good example to discuss the appropriateness of the seismic safety by applying the total expected cost concept. After the workshop people can accept the idea that the structural safety should be determined by the social consensus rather than simply by the regulatory minimum requirements. It may be time consuming to make a decision on each building but when a building has public nature it would be nice for the people who are involved to take part in the decision making.

The willingness to pay (WTP) approach is sometimes useful for the monetary evaluation of human life [11]. An alternative approach is available and quoted in ISO 2394 in terms of Life Quality Index (LQI) [12]. These indexes are based on rational assessment considering different situations of people and provide reasonable monetary values. Consideration of human loss and injury is essential for the design decision and contributions from ordinary people involved in the structural safety are necessary. Engineers should play a role more for the risk communication.

4. CO_2 emission could be an alternative measure for the cost from the environmental aspect.

It is convenient to use the monetary value to persuade stakeholders on the appropriateness based on the minimization of total expected cost. However, CO_2 emission can be an alternative measure to the monetary value from the global environmental aspect. Some statistics provide the CO_2 emission for the construction of buildings and also the failure of buildings. As far as the ratio of structure to the whole building, the CO_2 emission is more than the cost, as the CO_2 emission is approximately proportional to the weight, while the structural cost is relatively less expensive in comparison with non-structural components and equipment. Then the optimal reliability is less for the CO_2 emission [13]. Such observation does not simply lead to the unique optimal reliability in the society, but provide useful information for the environmental conscious people.

5. Influences of probabilistic load models on the optimal safety

The log-normal distribution can be used for the load effect probability model as a typical model as studied in the reference [1]. It is interesting to find out the influences of tail behavior of the probability model of load effect on the optimal safety. A systematic examination was conducted by applying three extreme value distributions, i.e. Gumbel, Frechet and Weibul distributions [14]. The optimum reliability varies with the probability model with the same c.o.v., but differences in the load factor are rather insignificant. This result encourages use of the minimum total cost approach for practical decision making on the target safety.

6. Consideration of minor and major damages in addition to the collapse

The Eq. (1) is a simple formula for the total expected cost. In reality, minor damages are more likely to occur and major damages have higher probability than the collapse probability. Then the normalized failure cost parameter becomes a function of damage degree. When damage levels for the failure are introduced, Eq.(1) becomes,

$$C_T = C_I + \sum_i P_{f_i} C_{f_i} \tag{4}$$

The subscript i indicates a damage level. Obviously inclusion of damage levels prior to the collapse increases the optimum safety degree [15,16]. Nevertheless, the contribution of damage levels to the total expected cost makes more clear views to the meanings of the minimum total cost [17]. The current design criteria for the seismic safety in Japan and U.S. with $\beta = 1.5 \sim 2$ for 50 years roughly correspond to the optimum target [1], but when expected cost for minor and major damages, the optimum target safety becomes much higher. Regulatory requirements are always the minimum requirements for the structural safety, but engineers can encourage the client to increase the safety by consideration of damage stages before the ultimate limit state.

Environmental loads depend on regions and the code cannot provide full information on locality especially for the seismicity. The failure cost depends on individual buildings. Therefore the optimum safety has to be determined for each building on a specific site, if the situation allows. On the other hand, recent studies attempted a framework for the optimum safety for a building class [18]. Since similar type buildings in a class behave similarly, results are useful to even other occupancy type or risk category.

7. Risk management with insurance

Risk of structural failure can be transferred to the insurance premium and then the total expected cost formula of Eq. (4) is expanded to,

$$C_T = C_I + \sum_i P_{f_i} C_{f_i} + C_{ins} - \sum_j P_{f_j} C_{f_j} \tag{5}$$

where $C_{ins}$is the insurance premium and the new subscript j in the last term indicates the damage level to be covered by the insurance. The insurance premium is generally much greater than the expected failure cost since the insurance company charges administrative cost, however, the client has advantages to avoid huge losses due to the earthquake disaster. Insurance policy for the coverage of minimum damage or the upper limit can be considered based on Eq. (5) in order to determine the appropriate design safety level.

In Japanese building regulation, the design seismic intensity are not based on the probabilistic hazard study but insurance premium are based on the probabilistic failure estimation. Some examples of relation between the current premium and the expected loss indicate the inconsistency of the premium due to the insufficient reflection of the local hazard and the individual strength of house [19].

8. Total expected cost was also examined to tsunami attack and seawall height.

As a last example of application of total expected cost, discussions on the appropriate seawall height against tsunami attack were introduced [20]. Number of significant tsunami attacks is rather limited, but an empirical extreme value distribution with both upper and lower bounds [21] was successfully applied to model the annual maximum of tsunami wave heights. The discussion concluded rather negative aspects for the seawall construction in particular in small villages with relatively less population as the failure costs are much less than the construction cost. Nevertheless, the huge construction cost was promised by the government at early stages after the Great East Japan Earthquake disaster, 2011 and was not rejected by the locals, although some villages prefer the natural coast to the high wall construction. Unfortunately many seawalls have already been constructed and beautiful ocean views were lost. People tend to overact to prevent the failure immediately after the disaster psychologically. Engineers can provide rational discussions for the safety in future.

9. Concluding remarks with acknowledgement

The total expected cost concept is quite essential and powerful for decision making on the appropriate structural safety. The concept of idea has been proposed before the limit state design procedure is codified. Significant contribution of the load model to the optimum safety was discussed. A simple model will be welcome to ordinary people who are responsible to the safety of building. Models can be sophisticated by considering details whenever necessary. The author gratefully acknowledges Professor Bruce Ellingwood with whom this study began almost 30 years ago. As the regulation provides only the minimum requirements for structure, the appropriateness should be more widely discussed in the environmentally conscious society. Further development of the total expected cost concept and the practical applications for various occasions will be expected in future. The role of engineer is not only to use correctly the codified design procedure but also to provide full information and to make use of it in order to find the optimum safety for the individual client as well as the society.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Kanda J, Ellingwood B. Formulation of load factors based on optimum reliability. Struct Saf 1991;9:197–210.
[2] Rosenblueth E. Towards optimum design through building codes. J. Struct. Div. 1976;102:591–607.
[3] Lind NC. Approximate analysis and economics of structures. J. Struct. Div. 1976; 102:1177–96.
[4] Hanai M. Assessment of load factors by means of structural reliability theory. Trans. Archit. Inst. Japan. 1975;231:13–7.
[5] Fischer K, Viljoen C, Kohler J, Faber MH. Optimal and acceptable reliabilities for structural design. Struct Saf 2019;76:149–61.
[6] I.S.O. ISO2394:2015 General principles on reliability for structures. 2015.
[7] Rackwitz R. Optimization – the basis of code-making and reliability verification. Struct Saf 2000;60:22–7.
[8] Kanda J, Shah H. Engineering role in failure cost evaluation for buildings. Struct Saf 1997;19:79–90.
[9] McGuire RK. Seismic hazard uncertainty and its effects on design decisions, Trans. SMiRT 9, K. 3-12, 1987.
[10] Kanda J. Target safety criteria for school gymnasium structure. Seoul: Proc. IABSE Congress; 2012.
[11] Soby BA, Ball DJ, Ives DP. Safety investment and the value of life and injury. Risk Anal 1993;13:365–70.
[12] Nathwani JS, Lind N, Pandey M. Affordable safety by choice: the life quality method. University of Waterloo; 1997.
[13] Kanda J, Takada T, Choi H. Target structural reliability in life cycle consideration. Intern. J. Risk Assess Manage 2007;7:846–61.
[14] Kanda J, Adachi T. Influence of probability distribution of loads on optimum reliability. Reliab Eng Syst Saf 2001;73:197–204.
[15] Kanda J, Hirakawa T. Failure cost estimation equivalent to multi-level limit state failure. Kyoto: Proc. ICOSSAR; 1997.
[16] Kanda J, Satoh I. Optimum seismic load considering multi-damage criteria, Case studies in optimal design and maintenance planning of civil infra-structure systems, ASCE, 152-163, 1999.
[17] Kanda J. Optimal design safety as a risk communication tool. Aust J. Struct Eng 2009;9:27–34.
[18] Gudipati VK, Cha EJ. A framework for optimization of target reliability index for a building class based on aggregated cost. Struct Saf 2019;81.
[19] Kanda J. Aspects of insurance premium for residential houses against seismic risk in Japan. Aust J. Civ Eng 2007;4:27–33.
[20] Kanda J. Consideration for effective height of seawalls against tsunami. Struct Infrastruct Eng 2016;12:484–9.
[21] Kanda J. Application of an empirical extreme value distribution to load models. J. Res NIST 1994;99:413–20.