Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

ASSESSMENT OF THE TARGET RELIABILITY DEPENDING ON STRUCTURAL PROPERTIES

LILITA OZOLA and DANA ZIRNOVA

Dept of Structural Engineering, Latvia University of Life Sciences and Technologies, Jelgava, Latvia

Although the establishment of the maximum acceptable failure probability for structures is not a mandatory requirement in design, it is important to develop a unified system for safety differentiation of bearing structures in public buildings so that people can feel equally safe in all the countries of the European Union. Differences from country to country in safety requirements declared by national codes may be permissible regarding the economic losses only. This study is aimed to clarify the understanding of how to examine a structure regarding the weakest link (element, fastener, system) in the limit state. In this study the authors propose a method for differentiation of structures regarding the variation of bearing capacity, which variates depending on a number of characteristics involved, and the failure mode anticipated when overloading takes place. Variation of bearing capacity is expressed in terms of reliability index variating correspondingly. Differentiation of the safety regarding failure modes anticipated has been developed using the toughness indices as a decisive criterion for the comparable assessment of structural compositions regarding the ability to sustain in the limit state for some period of time. Also, a criterion of possible redistribution of internal forces in the limit state is taken into account. The developed example of the assessment of the target reliability of structures is presented.

Keywords: Forensic engineering, Structures, Bearing capacity, Failure mode, Reliability index.

1 INTRODUCTION

An acceptable framework for the assessment of structural redundancy, moreover a set of criteria for sufficiently safe structures is a widely discussed issue in professional circles nowadays. The additional mandatory requirements for the redundancy of structures vary considerably from country to country. It is important to develop a unified system for safety differentiation of bearing structures in public buildings so that people can feel equally safe in every country of the European Union. Differences in safety requirements declared by national codes may be permissible regarding economic losses only, not the loss of human life.

Reliability, redundancy, toughness, robustness, and plastic failure mode of a structure- these are the properties in mutually interdependent complexity correlating closely with the safety level to be ensured. Highly sophisticated theoretical methods have been developed for the reliability analysis of structures (Zhao and Ono 2001, Ditlevsen and Madsen 2005, Nowak and Collins 2012, Schneider and Vrouwenvelder 2017) and the results sensitive to every influencing data group involved may be obtained quickly. The problem pertaining to reliability analysis has been constant due to the lack of input data samples for influencing factors. However, the uncertainty of the results of reliability analysis is mainly due to a complex interaction of factors both numerically measurable and logically quantified. A more comprehensive review on reliability-based performance criteria for structural systems has been completed by Ghosn *et al*. (2016).

In this study a proposal for the structural safety assessment incorporating essentially different indices of properties has been examined. The method proposed is based on the findings and examination of the behavior of the weakest link in structural system (element, fastener, whole system) when the limit state occurs.

2 BACKGROUND FOR THE SAFETY ASSESSMENT FRAMEWORK

Comprehensive structural design has been built upon three mutually interdependent categories:

- Code-based design
- Reliability and/or risk analysis
- Design for robustness, redundancy and plastic failure mode of a system

Most of the structural design codes are established in partial factor format. It is provided that load and resistance sets are located in a distance safe enough by means of partial factor values. Normally larger distance leads to a safer but more expensive structure. Also, some overlap zone is unavoidable in any case because of indeterminate factors peculiar to structural system in its complexity. Moreover, code conditions are developed to provide desirable safety margins for individual members and joints of a structure. The assessment of a safe behavior of an entire system remains in the competence of the professionals. Usually the approach to safety assessment is quite formal – basically done following some generalized safety provisions stated by national authorities. Normally these safety assessment procedures involve an uncertainty that should be taken into account.

Uncertainty is the main problem in structural design and construction. Variation of bearing capacity is generated by a large variety of input data (Keskküla and Ozola 2003). It has been proven by a large number of sample tests that material resistance variables may be assumed as normally distributed and mutually independent on load in terms of statistics. In such a situation the simplest linear limit state function has been applied for the definition of the reliability index as it is stated in Annex C of Eurocode EN 1990:2002/A1:2005/AC (2010). The reliability index in its often-used definition includes statistical properties of both data sets- those of resistance and load. However, it is doubtful that two variable reliability index reflects adequately a safety zone of the structure, since a large number of variables involved come from the load data set and thereby hide away some portion of resistance variation, which may occur more often. Let us consider the probabilities of negative performance function values in the case of combination of statistically distinctive load and resistance data set, illustrated by normally distributed probability diagrams in Figure 1. Case A is characterized by coefficient of variation (COV) for action (E) variables of 0.22 and COV=0.06 for resistance (R) variables. In Case B corresponding values of COV are 0.18 and 0.14. It is worthwhile to draw attention to big gap between the probabilities of the negative performance function (R-E) value in Case A, when P(R-E=-0.3)= 7.66E-18, and in Case B, when for the same (R-E) value the probability is P(R-E=-0.3)= 2.27E-06 due to different overlap zones.

In order to put focus on the variation of resistance effect being studied, it is assumed that the action effect is a certain fixed value (e_o), which may be adopted as the fractile of the resistance (R), and probability of failure (P_f) is expressed by Eq. (1). But one variable reliability index (β) is defined by Eq. (2), where μ_R is the average value of bearing capacity data set and σ_R is the standard deviation.

$$P_f = P(R < e_o) = \Phi_R(e_o) \tag{1}$$

$$\beta = (\mu_R - e_o)/\sigma_R \tag{2}$$

Redundancy, robustness and the anticipated failure mode of a structure, when overloading takes place, are essentially important properties in safety analysis not measurable by unambiguously defined characteristics. During recent years, the topic of the complex interaction of the above-mentioned important phenomenon in limit state has been discussed by Fang and Fan (2011) and many others.

As a result of the current study and previous research (Ozola 2013) a logically built-up bridge has been created between the reviewed properties of a structure in the final stage of decision making. Both the measurable and logic estimates proposed are presented in Table 1.

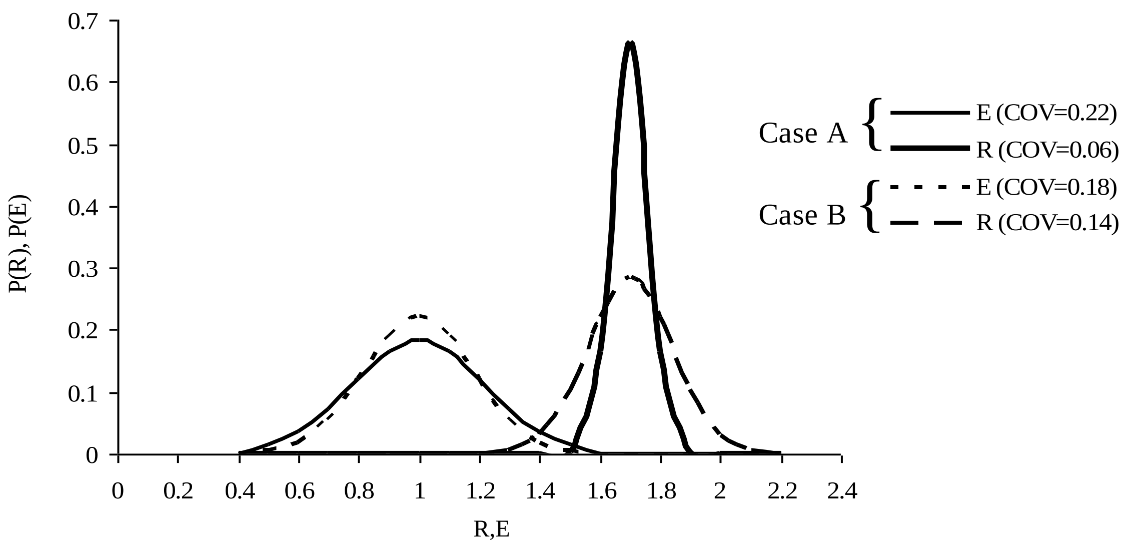

Figure 1. Randomness of action effect E and resistance R variables.

Table 1. Criteria proposed for the assessment of target reliability.

Description	**Criteria corresponding to buildings' failure severity**			**Assessment mode**
	high consequence for loss of human life (RC3)	**medium consequence (RC2)**	**low consequence for loss of human life (RC1)**	
Minimum value of reliability index recommended by EN 1990	4.3	3.8	3.3	Calculation
One variable reliability index	3.7	3.2	2.8	According test
Characteristic value of bearing capacity by design conditions	X	X	X	Code based design
Characteristic value of bearing capacity by tests	X	X	X	Experimental test
Coefficient of variation (COV)	COV≤0.15	COV≤0.20	COV≤0.25	Experimental test
Redundancy/ failure mode/ robustness	Robust/ redundant/ plastic failure	Robust/ plastic failure	Brittle failure	Professional judgement

3 ASSESSMENT OF TARGET RELIABILITY ACCORDING TO TEST DATA

The floor structure named by manufacturers as "Easi-Joist" has been tested and analyzed with the purpose to assess the target reliability. The experimental and design model inspected are shown in Figure 2. The span of simply supported model is 1.64 m, the span to depth ratio – 9.6. Section sizes of solid timber (C24) elements are 70 x 45 mm. Structural steel profiles of class S275 (U-profile of thickness 1.2 mm, depth 30 mm, width 12 mm). Ten "Easi-Joist" models were tested up to failure using the universal testing machine "Instron" under static load of a rate of 50 N/s. Buckling of compressed steel elements were observed over thin section around upper chord as predominant failure mode during the static tests of ten models (see Figure 3).

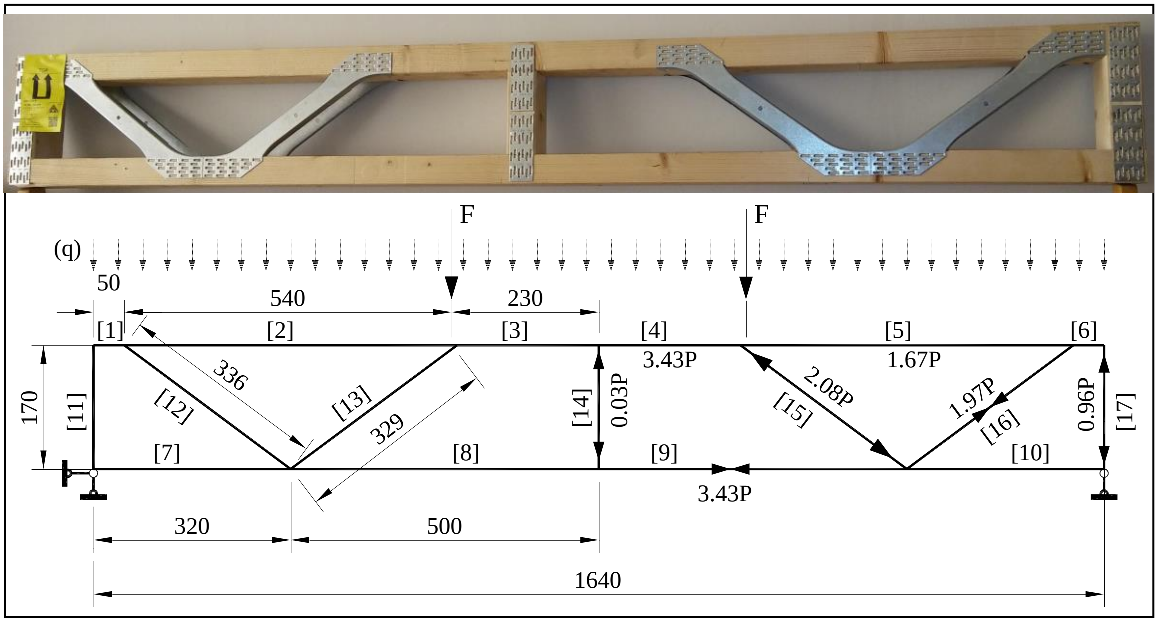

Figure 2. "Easi-Joist" model, geometric shape and axial force multipliers.

Figure 3. Characteristic failure mode of "Easi-Joist" model.

The safety assessment procedure of "Easi Joist" was completed with the results listed as follows:

- Characteristic value of shortterm point load is F_k= 6 kN according to Eurocode-based design methodology determined as a minimal value from nine limit state conditions of EN 1995-1-1 (2004) and EN 1993-1-1 (2005) referable to the timber-steel composition inspected.
- Processing of experimentally determined bearing capacities data set using the EN 14358 (2006) method "Acceptance criteria for a sample" results to value very close $F_{k,t}$= 6.04 kN. Capacities data set exhibited good fitness with lognormal distribution, see Figure 4, and the proper value of the coefficient of variation estimated is COV= 0.078.
- Experimental tests are useful to reveal the weakest link in the system. For system inspected it is a section of buckled steel element near upper chord where flanges of U-profiles are cut off, and the whole compression force remains to be transferred by a thin (1.2 mm) web section only. Normally this weakest section may be overlooked by designer in routine design procedure.
- Regarding the anticipated failure mode, the "Easi Joist" structure may be characterized as one capability, which depends on the behavior of the elements in the longitudinal buckling. That means an inherent trend of the structures toward a plastic failure mode in the ultimate limit state.
- The part of the area under force – displacement diagrams reproduced by the INSTRON software is indicative for the limit state toughness of a structure. It was estimated as a positive feature in terms of safety of the structure as an onset of the limit state is expected to be accompanied by progressive growth of plastic deformations.
- Assuming design capacity F_d= 5.4 kN (F_d= F_k/γ_f) equal to fixed maximal value in load side of performance diagram (see Figure 1), a value of one variable reliability index is β= $(\mu_R - e_o)/\sigma_R$ = (7.14-5.45)/0.56 =3.0.
- Redundancy of the "Easi Joist" structure was assessed by gradually excluding elements assumed to be broken. Large deformations are expected but not a brittle failure.

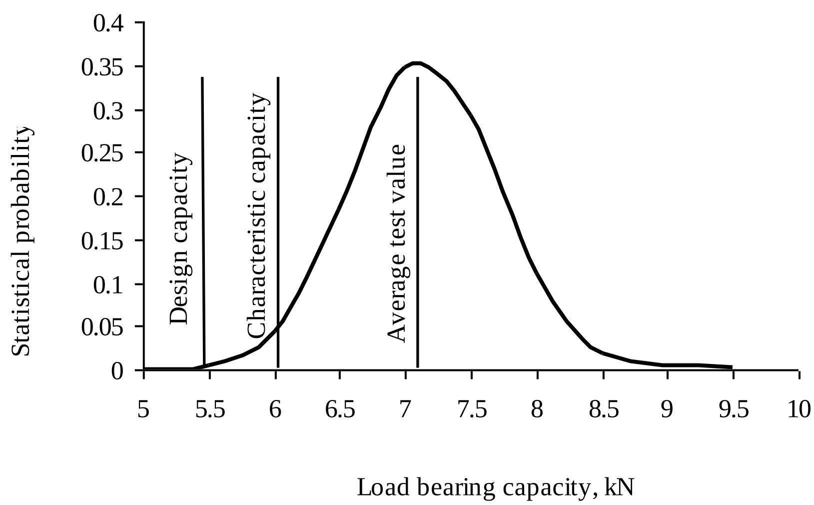

Figure 4. Lognormal distribution curve superimposed on static test data of bearing capacity and its codified values.

4 CONCLUSIONS

- Both measurable and logically examined variables shall be considered in the structural safety assessment.
- It is necessary to establish a codified system for the requirements of experimental tests for newly implemented structures with the purpose to obtain: (1) statistical characteristics of bearing capacity, (2) predominant failure mode including some indices for toughness, and (3) professional assessment of robustness and redundancy of structure desirable with a trend to the plastic failure mode of higher toughness indices.
- It is recognized that one variable reliability index computed according to the experimental test data sets is more adequate for the characterization of structural safety.
- The initial framework for the safety assessment of newly designed structures has been created, but further development is needed for the implementation in practice.

Acknowledgments

The authors sincerely appreciate the material support from the manager Mr M.Karlsons of Ltd “JMR-Frame” with the test models.

References

Ditlevsen, O., and Madsen, H.O., *Structural Reliability Methods*, Technical University of Denmark, 2005.

EN 14358, *Timber Structures - Calculation of Characteristic 5-Percentile Values and Acceptance Criteria for A Sample*, European Committee for Standardization, 2006.

EN 1990:2002/A1:2005/AC, *Eurocode - Basis of Structural Design*, European Committee for Standardization, 2010.

EN 1993-1-1, *Eurocode 3: Design of Steel Structures - Part 1-1: General Rules and Rules for Buildings*, European Committee for Standardization, 2005.

EN 1995-1-1, *Eurocode 5: Design of timber structures - Part 1-1: General - Common Rules and Rules for Buildings*, European Committee for Standardization, 2004.

Fang, Z.X., and Fan, H.T., Redundancy of Structural Systems in the Context of Structural Safety, *Procedia Engineering*, 14, 2172-2178, 2011.

Ghosn, M., Frangopol, D.M., McAllister, T.P., Shah, M., Diniz, S.M.C., Ellingwood, B.R., Manuel, L., Biondini, F., Catbas, N., Strauss, A., and Zhao, X.L., Reliability-Based Performance Indicators for Structural Members, *Journal of Structural Engineering*, 142(9), F4016002, F4016002-1: F4016002-13, September, 2016.

Keskküla, T., and Ozola, L., Codified Design and Reliability Aspects of Structural Timber Elements, *System-Based Vision for Strategic and Creative Design*, Bontempi, F. (ed.), 25-30, Balkema, Netherlands, 2003.

Nowak, A. S., and Collins, K. R., *Reliability of Structures*, CRC Press, New York, 2012.

Ozola, L., Some Considerations for Safety and Robustness of Structures, *New Developments in Structural Engineering and Construction*, Yazdani, S. and Singh, A. (eds.), 1505-1510, Research Publishing, Singapore, 2013.

Schneider, J., and Vrouwenvelder T., *Introduction to Safety and Reliability of Structures*, International Association for Bridge and Structural Engineering - IABSE, Zurich, 2017.

Zhao, Y-G., and Ono, T., Moment Methods for Structural Reliability, *Structural Safety*, 23, 47-75, 2001.