# Robustness – acceptance criteria

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## Summary

This factsheet describes the general framework on the bases of which acceptance criteria for requirements on the robustness of structures can be set. Such framework is based on the more general concept of risk-based assessment of engineering systems.

The present factsheet is to be seen in conjunction with the one on the theoretical framework for robustness (Sørensen et al. 2009). In the present factsheet, the focus is on normative implications.

## Keywords

Risk assessment, societal benefits, robustness of structures.

## Background / Introduction

The use of the term of robustness as applied to structures and the awareness of its meaning as opposed to attitude to progressive collapse was intensified following some well known cases, starting in 1968 from the partial collapse of the Ronan Point Building in the UK. During the last 10 years, the design criteria of major civil buildings has been even more focused towards the need for limiting the escalation of damage due to terrorist attacks.

As a consequence, a significant amount of research has been invested into the various aspects of robustness and has resulted in a number of useful recommendations on how to prevent progressive collapses and achieve robust structures. Despite many significant theoretical, methodical and technological advances over the recent years, structural robustness is however still an issue of controversy and poses difficulties in regard to interpretation as well as regulation. Typically, modern structural design codes require that the consequences of damages to structures should not be ‘disproportional to the causes of the damages’. However, despite the importance of such prescriptions, requirements to implement robustness in structural design are still not substantiated in details, nor has the engineering profession been able to agree on an interpretation of robustness which can facilitate its quantification and conversion into standards.

The present factsheet deals with the question on how an improvement in robustness can be quantified and how much effort can and must be put into achieving this target. The subject is part of the wider subject of risk acceptance criteria.

## Acceptance from a normative viewpoint

The development and management of societal infrastructures is a central task for the continued success of society. The decision processes involved in this task concern all aspects of managing and performing the planning, investigations, designing, manufacturing, execution, operations, maintenance and decommissioning of objects of societal infrastructure, such as traffic infra-structure, housing, power generation, power distribution systems and water distribution systems. From the perspective of individual stakeholders the objective may simply be to obtain a maximal positive economic return of investments. If we concentrate on the assessment from a normative point of view, the balance is to be considered from a societal perspective, weighting the positive and negative effects that the activity brings to the society at large. The main objective from a societal perspective for such activities is to improve the quality of life of the individuals of society both for the present and the future generations. This means a foreseen positive balance between societal gains and losses. In other words, the key acceptance criterion from a societal point of view can be formulated in general terms as a non negative difference between societal gains $G_s$ and losses $L_s$.

$$G_s - L_s \geq 0 \qquad (1)$$

## Probabilistic evaluation of the gain-loss balance

If all aspects of the decision problem were known with certainty, the identification of optimal decisions would be straightforward by means of traditional (deterministic) cost-benefit analysis. However, due to the fact that our understanding of the problems involved in the decision problems often is far less than perfect and that we are only able to model the involved processes of physical phenomena as well as human interactions in rather uncertain terms, the decision problems in engineering are subject to significant uncertainty (see e.g. JCSS 2001,2008). Due to this, it is not possible to assess the outcomes of decisions in certain terms. There is no way to assess with certainty all the consequences resulting from the decisions we take. However, what can be assessed are the risks associated with the different decision alternatives. Based on risk assessments, decision alternatives may thereby be consistently ranked and also accepted or rejected in absolute sense. If the concept of risk as the simple product between probability of occurrence of an event with consequences and the negative consequences of the event is widened to include also the aspects of the benefit achieved from the decisions, then risk may be related directly to the concept of utility from the economic decision theory and a whole methodical framework is made available for the consistent identification of optimal decisions. This framework is considered the theoretical basis for risk based decision making and the following chapters are concerned about the application of this for the purpose of risk management in engineering.

On the bases of what above, positive and negative terms are to be evaluated in terms of expected (or predicted mean) values, i.e. in terms of summation of probabilities times consequences, according to the classical risk assessment theory.

$$\sum_i p_i G_{si} - \sum_j p_j L_{sj} \geq 0 \qquad (2)$$

$p_i$ = probability of societal gain $G_{si}$ $p_j$ = probability of societal loss $L_{si}$

Accordingly, acceptance is to be tied to a positive average value of the above balance. This also implies that for single realizations the balance may result to be negative (i.e. a single infrastructure may cause negative effects in excess of benefits: f.i. if a major collapse takes place), but, for a large number of realizations, a positive average value implies that the societal benefits will prevail 'on the long run'.

## Boundaries of the analysis

A key point in the risk assessment procedure is represented by the need for a truly holistic analysis, with inclusion of all possible consequences (and inherent probabilities). It is evident that omissions of any term can alter results and conclusions.

It is worth noting that the awareness about the existence of classes of risks has changed in the recent past. This was due in some cases to the lack of knowledge about initiating events and/or of specific escalation sequences that did not occur previously and were not foreseen: when a new case occurs, the existence of a corresponding risk contribution becomes evident. For example, it is believed that the damage sequences connected to terrorist attacks were under considered until the recent escalation of major damage cases related to this type of threats.

Another situation that has changed the picture in the last years is the recognition of the importance of whole classes of consequences that, even though known and foreseen, resulted to be under-evaluated in their implications. This is the case of global consequences of known events affecting the environment, like pollution and gas (in particular greenhouse gases) emissions.

Generally speaking, it can be said that the 'universe' of a given infrastructural system (meaning by this term the boundary encompassing the whole set of known interactions the infrastructure may have) has continuously enlarged following an increasingly holistic perspective. This enlargement is to be intended both in spatial sense (stretching the boundaries up to include in some cases planetary effects) and in temporal terms, including a time span well longer than the operational life of the infrastructure (and, possibly, even inter-generational considerations: see nuclear power plants).

## Categories of losses

Traditionally, three main categories of consequences are considered in risk analysis applications: those involving assets (belonging to the infrastructure or external), human beings (workers, users or third parties) and the environment. Many sub-categories can be defined.

A category transversal to the previous ones is represented by those consequences that can be quantified in monetary terms and those which cannot. It is generally relatively simple to establish a cost for construction, reconstruction or repairing of a physical element, for a medical treatment or for a pollution recovery action. It may be more difficult to quote intangible assets like the loss in terms of reputation or goodwill for a company, but when it comes to the quantification in monetary terms of casualties (loss of life, of health, of physical integrity) of psychological status like pain, grief or disturbance (e.g. due to noise) or of loss of environmental attributes like scenic beauty, biodiversity or similar, a single consequence indicator is not at hand. In principle, however, it would be important the all quantified risks were presented in a single scalar unit (possibly monetary units) by means of a ‘utility’ function tying together and weighting, according to the ‘preferences’ of the (societal) decision maker, the various types of consequences. Only through an explicit formulation of preferences a transparent assessment of decision alternatives can be sought. For a more formal treatment of the relevant elements of Utility Theory and of the terms of ‘utility function’ and ‘preference’, see JCSS (2008), the inherent background document #1 and Keeney & Raiffa (1993).

Another way of classifying risks is according to the frequency of occurrence. The various risk terms to be evaluated during the whole lifecycle can span from those connected with systemic phenomena (occurring with probability 1 and, in general, with comparatively low intensity) and those related to accidental phenomena (with comparatively low probability of occurrence, but high negative consequences). Table 1, slightly modified from ISSC(2009), provides a picture for the case of a ship-based transport system. As shown, in that field the concern for the various types of losses is somehow shared by different actors

| **Entity** | **P=1 (systemic)** | **P<1 (random)** |
|---|---|---|
| Economical | First & operating costs<br>(Design concern) | Loss, damage of vessel<br>(Owner’s concern hedged via insurance) |
| Human | Quality of Life / quality of the workplace(Regulatory concern) | Loss of Life<br>(Regulatory concern) |
| Environmental | Exhaust Gas emissions, “Sustainability”<br>(New Regulatory concern) | Accidental Pollution<br>(Regulatory concern) |

Table 1: Holistic risk matrix (modified from ISSC 2009)

Robustness provisions are specifically aimed at tackling accidental phenomena and at controlling the consequences of an escalation of damage due to (comparatively) rare events. The characteristics of the relevant contributions to the total expected losses (low probability of occurrence and large and far-reaching consequences) make particularly delicate the evaluation of these terms. As mentioned, the longer the escalation sequence, the farer (in space and time) the consequences stretch out from the originating event and the larger is the difficulty in quantifying the risk.

## Practical instruments for risk acceptance

As above stated, the lack of a unique quantification of the various types of risk prevents in practice the establishment of an holistic risk acceptance criterion. However, from a practical point of view, the problem has been tackled by separating selected portions from the total risk (and the total benefits) and establishing criteria on each of them. From a conceptual point of view, this corresponds to a limitation in the model, because it prevents trade-offs between the different types of risk that (in principle) could correspond to further degrees of freedom available in fulfilling the global societal objective.

Given this restricted perspective, the gain-loss balance is often formulated in terms of reduction in the specific type of risk and of increase in the construction cost of the infrastructure that is necessary to achieve the reduction. These two quantities have a much more limited meaning than the correspondent holistic gains and losses regarding the societal balance. It is noted that, on the contrary, the construction cost may represent a very significant part in a ‘private’ balance established from the viewpoint of a specific stakeholder.

The ratio between the expected values of the latter and former quantities can be generically defined as ‘Cost to Avert a Risk Unit’ (CARU in the following) A typical example is represented by the Cost for Averting a Fatality per year (CAF). The criterion for acceptance is then set as a check that the CARU is less than an empirically defined Societal Willingness To Pay (SWTP) to avoid the same risk unit.

$$\text{CARUi} < \text{SWTP (RUi)} \qquad (3)$$

This formulation of the problem is often used in a normative context, because it allows to choose between different formulations of a Norm (usually between an existing one and an updated formulation). This process for example has been codified by the IMO (International Maritime Organisation) into the so called FSA (Formal Safety Approach) for Norm development (see IMO 1997).

It is worthwhile noting that this practical approach corresponds to a criterion for a judgment in differential sense, i.e. what is evaluated is whether a given modification in a Norm is ‘acceptable’ or not. It does not tell anything about the ‘acceptability’ in absolute sense of either solutions. The underlying idea of this approach in the normative field is that what is already existing has already been accepted and is therefore ‘acceptable’ by definition. The question is then moved to improve the Norm in an efficient way.

Another note regards the identification of the SWTP. This quantity has an empirical nature: it is a value derived by (best) practice, which is implicitly considered as acceptable. On the other hand, it has already been pointed out that what is commonly accepted is not necessarily acceptable in objective (explicit) sense. This applies not only to the acceptance of a given situation, but also to the effort that is to be devoted to improve the situation (which gives the definition of 'efficient' improvement).

In other words, if we f.i. consider the SWTP to balance a ton of $CO_2$ delivered to the atmosphere, we may recognize, without entering into details about the intense debate on the subject carried out in the last decade by major governmental and NG environmental agencies, that this was until recent very low, and has started to climb up when more objective evaluations of the implications of GHG emissions on a planetary scale have started to circulate. The example is meant to point out that, when evaluating key factors of the utility formulations, implicit methods can be considerably less accurate (even if of much easier application) than explicit procedures.

## Explicit methods for the formulation of societal preferences

As regards human-related risks, an efficient life saving activity may be understood as a measure which in the most cost effective manner reduces the mortality or equivalently increases the statistical life expectancy. Life expectancy, in turn, can be related to the Gross National Product (GNP) pro capite of a nation by observing that a certain percentage of the life of any single citizen is devoted to generate the average GNP value. On the other hand, a part of the GNP may be devoted to lower the risk for life (or enlarge the life expectancy). These demographical indicators are the main bases of the definition of the Life Quality index (LQI), as first proposed by Nathwani et al. (1997), which can be used to model the societal preferences quantitatively as a scalar valued indicator. Every action relevant for society (e.g. the introduction of a risk reduction measure or the construction of a large infrastructure) will affect the value of the LQI (in general both in terms of GNP and of life expectancy). It is straightforward to establish an acceptance criterion in terms of an increase of the LQI, i.e. the decision should be positive only if the value of the index increases.

$$\Delta(LQI) \geq 0 \tag{4}$$

The subject is covered in JCSS 2008 and in the inherent background documents, in particular JCSS (2008d,e). In JCSS(2008d) detailed analyses of the philosophy behind the LQI and its evolutions since the original formulation are presented. Without going into more details on the subject, it is here remarked that acceptance criteria based on LQI are in principle different from those derived by empirical values of SWTP, because the former ones originate from objective societal macro-indicators and have the potential to represent the 'actual' preference of society in respect to life saving. Some differences in the empirically determined SWTP can even be explained, on the basis of the LQI theory, by differences in the macroeconomical indicators of different nations.

Among the various upgraded versions of the LQI, Ditlevsen & Friis-Hansen (2009) proposed an interesting extension of the concept to account, in a single indicator, for the reduction not only of mortality but also of damages to the environment.

## Robustness requirements presently formulated in codes

So far, requirements in codes aimed at limiting the probability of occurrence of progressive collapse can be grouped, following the analysis presented for building design in Ellingwood & Dusenberry(2005) into two general categories: (1) those providing specific local resistance for abnormal loads, and (2) those aiming at developing alternative load paths. The latter category is further differentiated into provisions for general continuity in the structure through (i) minimum connection/tie forces or (ii) identification of an area or volume of damage and requirement for the structural system to be designed in order to bridge over the damage. In the same paper, a discussion is presented about the practical implications of the various approaches.

Provisions of category (1) are devoted to enhance the local behaviour of components (i.e. to lower the probability/extension of the initial damage), while those in (2) are actually more related to the prevention of damage propagation, following the common understanding of the term ‘robustness’. In any case, it is noted that a proper calibration of these deterministic or semi-probabilistic prescriptions should be performed in principle on the basis of a risk assessment and cost-benefit analysis that should identify on one hand the most risky scenarios and on the other one the most efficient provisions to be adopted. This does not appear to be the state-of-the-art of the present normative situation, which seems to be based on notional prescriptions based at most on experts judgement.

This is partially due to the not yet clear formulation of performance expectations for robustness (i.e. of objectives for design). On this subject, reference is made to Sørensen et al. (2009) and in particular to the discussion there reported about the relationship between robustness and redundancy, with reference to the collapse cases of the Ballerup Super Arena and the Bad Reichenhall Icehall. The typology of structures there involved is different from the class of buildings mentioned earlier in this paragraph, but these example may indicate that the definition of performances in the design for robustness may still require refinements, at least in the definition of the scopes for the criteria.

A second motivation of the empirical basis of the present formulation of norms regarding robustness is represented by the objective difficulties in performing complete risk assessments and cost-benefit analyses of complex structures. This type of investigations for representative cases, however, seems to be an unavoidable step towards an improvement in the normative situation.

## Conclusions

Acceptance criteria for robustness in a normative framework are seen as a particular aspect of risk acceptance criteria. In this respect, all the features of risk assessment procedures are recalled in the context of robustness evaluations. These features include the need for a complete and truly holistic assessment of all the societal risks and benefits connected with the activity or the infrastructure under consideration. A second and equally important aspect is represented by the combination of the above terms related to societal preferences into a unique scalar utility function. Even in the simplifying hypothesis of a linear dependence of the utility function on the single risk units, the process may result to be delicate when conversion criteria are to be identified to define the linear coefficients. A powerful means to relate economical aspects and live-saving design criteria is represented by the formulation of the Life Quality Index, based on objective macroeconomic indicators at national level. The index has also the potentiality of including different types of risks. The final acceptance criteria can finally be expressed in terms of a positive variation of the index itself.

The present formulation in structural Norms of acceptance criteria on robustness issues as deterministic checks is seen as a practical solution for an easier implementation of the requirements in standard designs (particularly when such checks are expressed in terms of tie and connection forces). However, the bases of such deterministic formulations are still empirical and a proper calibration based on risk assessment and evaluation of the cost-benefit balance is considered as a necessary step forward.

## References

Sørensen, J.D., Rizzuto, E. and Faber, M.H. (2009). Robustness – Theoretical Framework. In J. Köhler, H. Narasimhan and M.H. Faber (Eds.), *Proceedings of the Joint Workshop of COST Actions TU0601 and E55*. Zurich: ETH Zurich

DEFRA(2008) Climate change policy cost-effectiveness indicator March 2008. www.defra.gov.uk

Ditlevsen,O. & Friis-Hansen, P. (2009) Cost and benefit including value of life, health and environmental damage measured in time units, Structural Safety 31 (2009) 136–142

Ellingwood, B.R. & Dusenberry, D.O. (2005), Building Design for Abnormal Loads and Progressive Collapse, Computer–Aided Civil and Infrastructure Engineering 20 (2005) 194-205

IMO(1997) Circular on Interim Guidelines on the Application of FSA to the IMO Rule-making Process (MSC Circ. 829/MEPC Circ. 335)

ISSC (2009) Design Principles and Criteria Report of Committee iv.1 of the 17th International Ship and Offshore Structures Congress Aug.2009 Seoul, Republic of Korea (Vol.1)

JCSS (2001) Probabilistic Model Code (PART I) the Joint Committee of Structural Safety, ISBN 978-3-909386-79-6

*[available from: http://www.jcss.ethz.ch/publications/publications.html]*

JCSS (2008) Risk Assessment in Engineering Principles, System Representation & Risk Criteria, the Joint Committee of Structural Safety, M. H. Faber Ed., June 2008, ISBN 978-3-909386-78-9

*[available from: http://www.jcss.ethz.ch/publications/publications.html]*

*See also from the same source the background documents:*

JCSS (2008a) Theoretical Framework for Risk Assessment and Evaluation (Bgd. Doc. #1) by Kroon, I.B. & Maes, M.A., Nov. 2008.

JCSS (2008b) Interpretation of Uncertainties and Probabilities in Civil Engineering Decision Analysis (Bgd. Doc. #2) by Faber, M.H. and Vrouwenvelder, A.C.W.M., Nov. 2008

JCSS (2008c) Risk Acceptance Criteria (Bgd. Doc. #3) by Diamantidis, D., Nov. 2008

JCSS (2008d) The philosophy behind the Life Quality Index and Empirical Verifications (Bgd. Doc. #4) by Rackwitz,R., Nov. 2008

JCSS (2008e) Optimisation with a Life Quality Index Acceptance criterion (Bgd. Doc. #5) by Rackwitz,R., Nov. 2008

JCSS (2008f) Utility, Preferences and Risk Perception in Engineering Decision Making (Bgd. Doc. #6) by Maes, M.A. & Faber, M.H., Nov. 2008

JCSS (2008g) Terminology (Bgd. Doc. #7) by Holický, M., Nov. 2008

Keeney, R. L. & Raiffa, H. (1993), Decisions with Multiple Objectives: Preferences and Value Tradeoffs, Cambridge University Press, 1993. First published in 1976.

Nathwani J.S., Lind N.C. and Pandley, M.D., 1997, Affordable Safety by Choice: The Life Quality Method, Institute for Risk Research, University of Waterloo, Canada.