COST Action TU0601
Robustness of Structures

THEORETICAL FRAMEWORK ON STRUCTURAL ROBUSTNESS

Editor

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EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Foreword

This report is a publication of the European research network COST[1] Action TU0601 "Robustness of Structures".

The COST Action TU0601 (website: http://www.cost-tu0601.ethz.ch/) entitled "Robustness of Structures" is a research network established under the aegis of COST (European Cooperation in Science and Technology). The main objective of this Action is to provide the basic framework, methods and strategies necessary to ensure that the level of robustness of structural systems is adequate and sufficient in relation to their function and exposure over their life time and in balance with societal preferences in regard to safety of personnel and safeguarding of environment and economy.

An important aspect of the Action concerns the development of a theoretically sound basis for the assessment of robustness and acceptance criteria for structural robustness which can facilitate the development of practice relevant methods for ensuring robust design as well as strategies for maintaining the robustness of existing structures throughout their service life. The present document is developed by Working Group 1 'Theoretical and methodological framework' within this scope of the Action.

John Dalsgaard Sørensen

Chair, Working Group 1, COST TU0601

[1] COST (European Cooperation in Science and Technology) is an intergovernmental European framework for international cooperation between nationally funded research activities. COST creates scientific networks and enables scientists to collaborate in a wide spectrum of activities in research and technology and is subdivided in several thematic domains. COST activities are administered by the COST Office (website: http://www.cost.eu/).

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1 Introduction

This document is prepared within the COST Action TU0601 "Robustness of structures", WG1 "Theoretical and methodological framework". The main objective of this working group is the development of a theoretically basis for the assessment of robustness and acceptance criteria for structural robustness which can be used as basis for development of practice relevant methods for ensuring robust design as well as strategies for maintaining the robustness of existing structures throughout their service life.

Robustness of structures has been recognized as a desirable property because of several high system failures, such as the Ronan Point Building in 1968, where the consequences were deemed unacceptable relative to the initiating damage. After the collapse of the World Trade Centre, robustness has obtained a renewed interest, primarily because of the serious consequences related to failure of advanced types of structures and further, that consequences due to structural collapse may exceed the mere rebuilding costs by orders of magnitudes. Furthermore, it was confirmed that robustness is strongly related to internal structural characteristics such as redundancy, ductility and joint behaviour characteristics, but also that the consequences of structural collapse strongly depend on the specific scenario of events starting with some triggering event over a complex series of intermediate events involving more localized damages which finally led to the collapse. In this scenario, the extent to which consequences are generated depends not only on internal structural characteristics but may even more pronounced depend on passive and active measures for damage reduction as well as possible non-conformities with design assumptions due to the quality of execution and or maintenance.

In order to minimize the likelihood of failures, as those mentioned above, many modern building codes consider the need for robustness in structures and provide strategies and methods to obtain robustness. In fact, in all modern building codes, one can find a statement (in this or a slightly different form): "total damage resulting from an action should not be disproportional to the initial damage caused by this action."

During the last decades, there have been significant efforts to quantify aspects of robustness. When modelling robustness, system effects are very important. However, the primary criteria in building codes are related to design and verification of sufficient reliability of components. It should also be noted that redundancy in systems is closely related to robustness. In principle, redundant system are believed to be more robust than non-redundant systems – but this is not always the case as illustrated by the failures of the Siemens Arena and the Bad Reichenhall Ice Arena, see (Frühwald, Serrano et al. 2007), (Hansson and Larsen 2005) and (Winter and Kreuzinger 2008). Robustness is related to scenarios where exposures, including unintentional and unforeseen loads and defects, result in local damage to the structural system, and where this damage may lead to further collapse of the structure. These aspects are treated in other working groups within this COST Action.

This publication describes an overall theoretical framework for assessing robustness of structures. Robustness can be defined in different ways and on different levels of complexity / applicability. On the most general level robustness is assessed taking basis in decision analysis theory by estimating both direct risk, which is associated with the direct consequences of potential damages to the structure, and indirect risk, which corresponds to the increased risk of a damaged structure. Indirect risk can be interpreted as risk from consequences disproportionate to the cause of the damage. Robustness of a structure can therefore be measured by the contribution of the indirect risks to the total risk. Such a risk based definition of robustness is proposed in (Baker et al. 2008) and the JCSS document 'Risk assessment in engineering' (JCSS 2008).

The document is partly based on fact sheets developed in the two COST Actions E55 "Modelling of the performance of timber structures' and TU0601 "Robustness of structures", see (Köhler et al. 2010). In Chapter 2, definition of robustness and related terms are presented. Chapter 3 describes basic risk-based principles for implementation of robustness. In Chapter 4 robustness measures are described and in Chapter 5 methods for assessing robustness measures are presented. Chapter 6 described acceptance criteria related to assessment of robustness of structures.

2 Glossary

Rizzuto, E.

In the following chapter, a few key definitions will be provided, with the aim of homogenizing the terminology of the present work

Structural system
Is an ensemble of structural components characterised by a specific function.

[Example: suspended bridge: function = let vehicles pass beyond a valley]

Component of a structural system
Is a structural unit with its own identity and behaviour, i.e. input, output, characteristics (for structural components: load, response, capacity) but without a definite function other than to cooperate with other components to the functionality of a system.

[Example: cable of a suspended bridge]

Environment (Surroundings, neighbourhood, universe) of a system
Everything interacts with the system, being external to it (i.e. not included in it).

Two classes of elements of particular relevance can be identified in the environment of a system:

- those which can affect the system (external threats for the system, *exposures*)
- those which can be affected by the (mal)functioning of the system. (external consequences) [Example: traffic on the road, persons/vehicles passing on the bridge, below the bridge….].

The concept of environment should be extended in space and in time to include all the possible interactions with the system.

NOTE*: According to the target of the analysis, the scale of the items under investigation can change dramatically and the same physical object can play different roles. [the single thread of the cable, the cable and the bridge can correspond respectively the three levels above defined i.e. component, system and environment; from another viewpoint, the bridge can be an component of a motorway and the motorway can 'see' the national road system as its environment].*

Scenario
A scenario corresponds to a specific state of the system and of the influencing environment or to a time sequence of states. Each scenario implies specific performances of the system: (=responses of the system and consequences on the environment).

The union of all possible scenarios provide the domain for the evaluation of the overall performances of the system. A continuous spectrum of ∞^n possible scenarios is in principle to be considered, together with their inherent probability distribution.

Performances
A number of performance indicators can be identified for the assessment of a system.

For structural systems very often the ultimate performance indicator is Risk (at least in a normative context).

In those cases, Performance Based Design coincides with Risk Based Design.

Assessment of a system
Comparison between the actual lifecycle performances of the system and minimum required performances (acceptance criteria). Usual acceptance criteria in Norms are based on risk limits.

Categories of scenarios
Scenarios that contribute much to the quantification of risk are, for structural systems, those which imply the failure of the system. Other categories are related for example to the loss of functionality of the systems or to overcoming other limit states.

Within the scenarios bringing to collapse, two types can be identified:
- progressive collapse scenarios (the collapse is reached passing through a sequence of states of progressively increasing damage)
- global collapse (the structure passes from the intact state to collapse without significant intermediate steps).

Design scenarios
In principle, the structure is to be checked in a ∞^n number of scenarios separately and the performances provided in each scenario should be weighted by the probability of occurrence of that scenario.

Among typical design scenarios:
- design scenarios for the intact structure
- accidental design scenarios in which the initial state of the structure corresponds to a damaged state. In those cases, the *damage tolerance* (see definition below) of a structure to that scenario is checked.

NOTE: *In the latter scenarios the influencing environment may be characterised differently from the intact scenario. In general the probability of these scenarios is lower than those regarding the intact structure, but the probability for the structure of underperforming in this type of states/sequences is higher. For this reason, the contribution to the total risk may be not negligible and deserve special attention. In practise, a class of damage scenarios can be discretised into a single scenario, which should be calibrated to give the some expected performances of the whole class.*

In other words, usually the systems are checked in a finite number of design scenarios, chosen in order to be <u>realistic</u> and <u>representative</u> for the purpose of predicting the actual lifecycle performances of the system.

Exposure
Event during which the state of the component/system deviates significantly from the 'normal' state (average state in probabilistic terms) in a direction such that it gets closer to the failure surface. Usually the deviation occurs with respect to a single state variable (or a group of correlated state variables), but this does not apply always.

Magnitude of the exposure can be defined as the magnitude of the deviation.

An exposure can be represented, among other circumstances, by, see (Starossek and Haberland 2010):

- 'physical' exposures
  - accidental loads due to rare natural events (possibly included in the model, but with a low probability of occurrence)
  - extremely low capacity (extreme values in material characteristics, in geometrical defects or in degradation effects)
- 'logical' exposures = human errors
  - wrong construction procedures inducing fabrication defects
  - wrong maintenance, generating abnormal degradation
  - wrong operation inducing accidental loads and/or damage (reduced capacity) in the structure
  - wrong design

Damage
Total or partial loss of functionality, both for components and systems.

Failure
Total loss of functionality, both for components and systems.

Failure of a system is given by the collapse of one or more components, triggered by an initiating event (exposure).

Consequence
Any quantifiable loss due to the damage of components/ systems. It is a quantity to be measured in a unique unit (generally: money) for all types of scenarios.

It can be classified according to:

the item affected:

- Tangible assets:

Damage: partial loss of functionality	structural components /whole structural system
Failure: total loss of functionality of	other non struct. compon./systems (e.g. plants)
Physical Loss	third parties assets

- Intangibles:
  Deferred production
  Cost of investigation/lawyers
  Loss of opportunities /reputation
  Share prices/ market share

- Persons:
  Injuries
  Sickness affecting { crew/employees; clients/users/passengers; third parties }
  Fatalities
- Nature:
  Release of toxic pollutants
  Green House Gases emissions
  Loss/modification of bio-diversity

<u>according to the probability of occurrence:</u>

- systemic (P=1): example: construction cost, decommissioning cost, gas emissions (during construction, operation, dismantling)
- occasional (P<1): small and comparatively frequent accidents
- rare (P<<1): large (and rare) accidents

<u>according to the distance in space and time from the initiating event</u>

- Direct consequences: local consequences for the component(s) directly subjected to exposures
- Indirect consequences: consequences due to an escalation (propagation) of the damage to components not directly exposed, to the whole system and to its environment.

Vulnerability
Attitude of an element to be damaged by an exposure (probability of damage conditional to exposure (see figure 1).

Damage tolerance
Attitude of a system to survive to a damage (system probability of failure conditional to damage, see figure).

Robustness
Attitude of a system to survive to a damage (combination of Vulnerability + Damage Tolerance, see figure 1).

***NOTE**: Vulnerability, Damage Tolerance and Robustness are properties of the structure alone.*

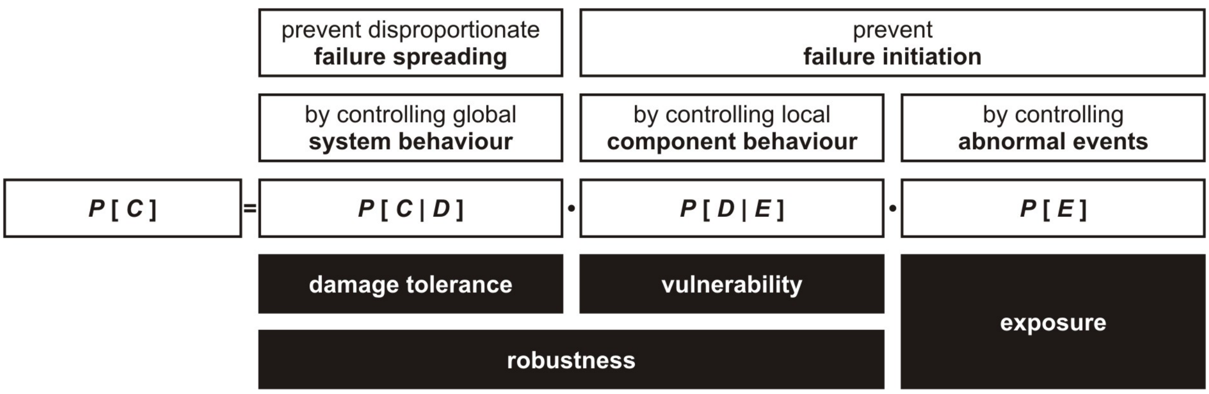

Figure 1. Definition of robustness (based on Starossek and Haberland 2010).

Robustness index
is an indicator of robustness.

With reference to the scheme in figure 1, it quantifies $P(C \mid E) = P(C \mid D) \cdot P(D \mid E)$.

3 Implementation of structural robustness

Sørensen, J.D.

This chapter is partly based on the fact sheet "J.D. Sørensen, E. Rizzuto and M. H. Faber: Robustness – theoretical framework" (Sørensen et al. 2010), see (Köhler et al. 2010) and (Vrouwenvelder and Sørensen 2009).

In Eurocode EN 1990:2002 (CEN 2002), the basic requirement to robustness is given in clause 2.1 4(P):
"A structure should be designed and executed in such a way that it will not be damaged by events such as:

- explosion,
- impact, and
- the consequences of human errors,

to an extent disproportionate to the original cause."

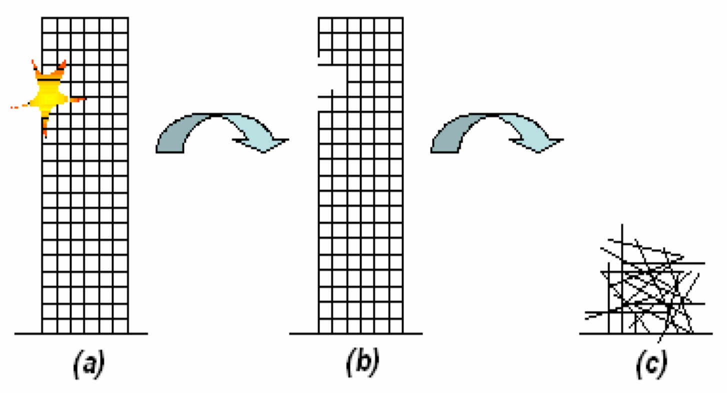

Figure 2. Illustration of the basic concepts in robustness (CEN 2006).

An illustration is presented in Figure 2 (CEN 2006). Due to an exposure (a) of any kind, local damage (b) may occur. This local damage is defined as the direct consequence of the exposure. Given this local damage, the structure may survive or (a substantial part) may collapse due to:

a) Exposures which could be unforeseen, unintended effects and defects (incl. design errors, execution errors and unforeseen degradation) such as:
   - unforeseen action effects, incl. unexpected accidental actions
   - unintended discrepancies between the structure's actual behaviour and the design models used
   - unintended discrepancies between the implemented project and the project material
   - unforeseen geometrical imperfections
   - unforeseen degeneration.
b) Local damage due to exposure (direct consequence of exposure).
c) Total (or extensive) collapse of the structure following the local damage (indirect consequence of exposure).

As described in chapter 2, figure 1 robustness is related to the ability of the structure to survive damage (prevent/reduce the indirect consequences in step c) given an exposure (step a).

Robustness rules can also be seen as additional rules/requirements to the basic code-specific checking of individual components/failure modes in order to secure that the structure considered as a system has a satisfactory reliability. The system consists of the structure and the environment where it is situated.

Important aspects related to robustness, which will be described in the following, are:

- Key elements
- Progressive collapse
- Redundancy
- Ductility

During the last decades, there has been a significant effort to develop methods to assess robustness and to quantify aspects of robustness. The basic and most general approach is to use a risk analysis where both probabilities and consequences are taken into account. Approaches to define a robustness index can be divided into the following levels with decreasing complexity, see next chapter:

- A risk-based robustness index based on a complete risk analysis where the consequences are divided in direct and indirect risks.
- A probabilistic robustness index based on probabilities of failure of the structural system for an undamaged structure and a damaged structure.
- A deterministic robustness index based on structural measures, e.g. pushover load bearing capacity of an undamaged structure and a damaged structure.

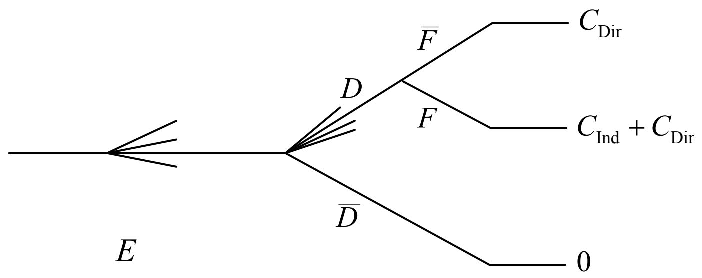

Figure 3. An event tree for robustness quantification (Baker et al. 2008).

Figure 3 presents the same idea as in Figure 2, but in a more general way in the form of an event tree, see (Baker et al. 2008). The assessment starts with the consideration and modelling of exposures (E) that can cause damage to the components of the structural system. The term “exposures” refers to extreme values of design loads, accidental loads and deterioration processes but also includes human errors in the design, execution and use of the structure. The term “damage” refers to reduced performance or failure of individual components of the structural system. After the exposure event occurs, the components of the structural system either remain in an undamaged state ($\overline{D}$) as before or change to a damage state (D). Each damage state can then either lead to the failure of the structure (F) or no failure ($\overline{F}$).

Consequences are associated with each of the possible damage and failure scenarios, and are classified as either direct (C_{dir}) or indirect (C_{ind}). Direct consequences are considered to result from damage states of individual component(s). Indirect consequences are incurred due to loss of system functionality or failure and can be attributed to lack of robustness (Baker et al. 2008) and (JCSS 2008).

The basic framework for risk analysis is based on the following equation in which risk contributions from local damages (direct consequences) and comprehensive damages (follow-up/indirect consequences), are added, see (Baker et al.2008) and (JCSS 2008):

$$R = \sum_i \sum_j C_{\mathrm{dir},ij} P(D_j|E_i)P(E_i) + \sum_k \sum_i \sum_j C_{\mathrm{ind},ijk} P(S_k|D_j \cap E_i)P(D_j|E_i)P(E_i) \tag{1}$$

where

$C_{dir,ij}$	consequence (cost) of damage (local failure) D_j due to exposure E_i
$C_{ind,ij}$	consequence (cost) of comprehensive damages (follow-up/indirect) S_k given local damage D_j due to exposure E_i
$P(E_i)$	probability of exposure E_i
$P(D_j\|E_i)$	probability of damage D_j given exposure E_i
$P(S_k\|...)$	probability of comprehensive damages S_k given local damage D_j due to exposure E_i

The optimal design (decision) is the one minimizing the sum of costs of mitigating measures and the total risk R. A detailed description of the theoretical basis for risk analysis can be found in (JCSS 2008).

It is noted that an important step in the risk analysis is to define the system and the system boundaries. This includes the definition/modelling of the structure itself, but also the effect of a possible collapse of the structure on the environment/surrounding society. It is noted that in some cases the failure of a structure can cause extensive indirect consequences for the society. These are important to include when defining the system to be considered in the risk analysis.

The total probability of comprehensive damages/collapse associated to (1) is:

$$P(\mathrm{collapse}) = \sum_i \sum_j P(\mathrm{collapse}|D_j \cap E_i)P(D_j|E_i)P(E_i) \tag{2}$$

where $P(\mathrm{collapse}|D_j \cap E_i)$ is the probability of collapse (comprehensive damage) given local damage D_j due to exposure E_i. Note that compared to (1) only one comprehensive damage (collapse) is included in (2).

The terms $P(\mathrm{collapse}|D)$ and $P(D|E)$ are related to the concepts damage tolerance and vulnerability, respectively. The product $P(\mathrm{collapse}|D)P(D|E)$ can be considered as a structure dependent measure of the robustness.

For damages related to key elements, the probability of collapse is $P(\mathrm{collapse}|D_j \cap E_i) \cong 1$.

From equation (2), it is obvious that the probability of collapse can be reduced by:

- Reducing one or more of the probabilities of exposures $P(E_i)$ – i.e. prevention of exposure or event control.
- Reducing one or more of the probabilities of damages $P(D_j|E_i)$ – i.e. related to element/component behaviour.
- Reducing one or more of the probabilities $P\left(\text{collapse}\middle|D_j \cap E_i\right)$.

If the consequences are included in a risk analysis, then reduction of direct (local) consequences, $C_{dir,ij}$ and comprehensive (indirect) consequences, $C_{ind,ij}$ are also important.

According to the description above and the robustness definition in (CEN 2002), robustness is mainly related to the reduction of the probabilities $P(D_j|E_i)$ and $P(\text{collapse}|D_j \cap E_j)$. Increasing the robustness at the design stage will in many cases only increase the cost of the structural system marginally – the key point is often to use a reasonable combination of a suitable structural system and materials with a ductile behaviour. In other cases, increased robustness will influence the cost of the structural system.

In the next chapter robustness measures are described.

4 Robustness measures

Sørensen, J.D.

This chapter is partly based on the fact sheet "J.D. Sørensen, E. Rizzuto and M. H. Faber: Robustness – theoretical framework", see (Köhler et al. 2010) and (Vrouwenvelder and Sørensen 2009). Three measures of robustness are described in the following: a risk-based, a reliability-based and a deterministic robustness index. Two of three general definitions of robustness heavily rely on stochastic modelling of the uncertainties (loads, strengths and models). Information on stochastic modelling can be found in the JCSS Probabilistic model code (JCSS 2002).

4.1 Risk-based robustness index

(Baker et al. 2008) proposed a definition of a robustness index based on risk measures. The approach divides consequences into direct consequences associated with local component damage (that might be considered proportional to the initiating damage) and indirect consequences associated with subsequent system failure (that might be considered disproportional to the initiating damage). An index is formulated by comparing the risk associated with direct and indirect consequences. The index of robustness (I_{rob}) is defined as:

$$I_{rob} = \frac{R_{Dir}}{R_{Dir} + R_{Ind}} \tag{3}$$

where R_{Dir} and R_{Ind} are the direct and indirect risks associated with the first and the second term in equation (1). The index takes values between zero and one, with larger values indicating larger robustness.

As mentioned above, the optimal decision is the one which minimizes the total risk obtained by equation (1). This could equally well be by reducing the first or the second term in equation (1). This implies that the definition of a robustness index by equation (3) is not always completely consistent with a full risk analysis, but can be considered as a helpful indicator based on risk analysis principles. It is noted that since the direct risks typically are related to code based limit states, they can generally be estimated with higher accuracy than the indirect risks.

A difficult step in the risk assessment is to model and quantify the probability of the exposures. Therefore, it can be very convenient and helpful to use a conditional index of robustness obtained using risks $R_{Dir|\text{exposure}}$ and $R_{Ind|\text{exposure}}$ conditioned of a given exposure:

$$I_{rob|\text{exposure}} = \frac{R_{Dir|\text{exposure}}}{R_{Dir|\text{exposure}} + R_{Ind|\text{exposure}}} \tag{4}$$

4.2 Reliability-based robustness index

(Frangopol and Curley 1987) and (Fu and Frangopol 1990) proposed some probabilistic measures related to structural redundancy – which also indicates the level of robustness. A redundancy index (*RI*) is defined by:

$$RI = \frac{P_{f(\text{damaged})} - P_{f(\text{intact})}}{P_{f(\text{intact})}} \tag{5}$$

where $P_{f(\text{damaged})}$ is the probability of failure for a damaged structural system and $P_{f(\text{intact})}$ is the probability of failure of an intact structural system. The redundancy index provides a measure on the robustness / redundancy of the structural system. The index takes values between zero and infinity, with smaller values indicating larger robustness.

They also considered the following related redundancy factor:

$$\beta_R = \frac{\beta_{\text{intact}}}{\beta_{\text{intact}} - \beta_{\text{damaged}}} \tag{6}$$

where β_{intact} is the reliability index of the intact structural system and β_{damaged} is the reliability index of the damaged structural system. The index takes values between zero and infinity, with larger values indicating larger robustness.

4.3 Deterministic robustness index

A simple and practical measure of structural redundancy (and robustness) used in the offshore industry is based on the so-called *RIF*-value (Residual Influence Factor), (ISO 2008).

A Reserve Strength Ratio (*RSR*) is defined as:

$$RSR = \frac{R_c}{S_c} \tag{7}$$

where R_c denotes characteristic values of the base shear capacity of an offshore platform (typically a steel jacket) and S_c is the design load corresponding to ultimate collapse.

In order to measure the effect of full damage (or loss of functionality) of structural member *i* on the structural capacity, the so-called *RIF*-value (sometimes referred to as the Damaged Strength Ratio) is defined by:

$$RIF_i = \frac{RSR_{\text{fail},i}}{RSR_{\text{intact}}} \tag{8}$$

where RSR_{intact} is the *RIF*-value of the intact structure and $RSR_{\text{fail},i}$ is the *RIF*-value of the structure where member *i* is failed/removed. The *RIF* takes values between zero and one, with larger values indicating larger robustness.

Other simple measures of robustness have been proposed based on e.g. the determinant of the stiffness matrix of structure with and without removal of elements.

5 Methods of assessing robustness of structures

Dean, C., Turk, G and J.D Sørensen

Quatification of the robustness measures in chapter 4 requires that the system reliability of a structure can be estimated both for the intact structure and for the structure damaged according to some scenario. This chapter describes aspects related to system reliability, and especially the importance of ductility, which is illustrated though illustrative examples. Further, aspects of implementation of robustness in codes of practice are briefly presented.

5.1 System models of structure

In general, when a structural system collapses, one or more structural elements have failed. In systems elements are often associated with failure modes. A system model of a structure can be assigned to one of the following three categories: series systems, parallel systems or combination of series and parallel system (also referred as hybrid systems). In series systems, failure of any element leads to the failure of the system. Parallel systems are those systems in which the combined failure of each and every element of the system results in the failure of the system.

Since a redistribution of the load effects takes place in a redundant structural system after failure of one or more of the structural elements it becomes very important for parallel or hybrid systems to describe the behavior of the failed structural elements after the failure has taken place, i.e. to take the degree of ductility into account.

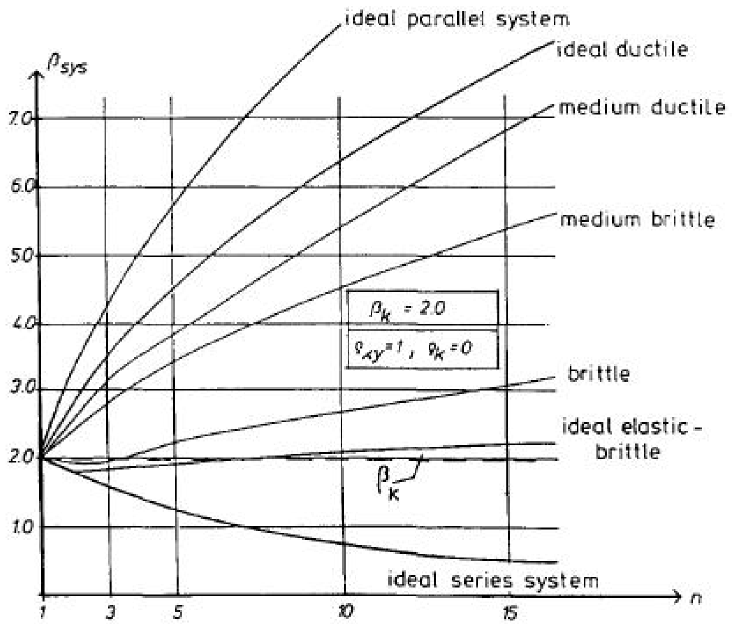

Figure 4. System reliability vs. numbers of elements, from (Gollwitzer and Rackwitz 1990).

In (Gollwitzer and Rackwitz 1990) numerical investigation concerning parallel/serial systems and ideal ductile/brittle elements is conducted. The components of the system were designed for a reliability index β_k = 2 as if no system effect exists. In Figure 4 the system reliability index versus number of elements is shown, demonstrating the influence of the mechanical behaviour of the elements (components) on system reliability. In this figure it can be seen that for a small number of elements the brittle system behaves much like the series system. As number of elements is increased the reliability of parallel system is increased significantly (and vice-versa for the series system). It is therefore important to take advantage of the plasticity of mechanical memebers and connections (e.g. for timber structures nails, dowels and bolts). One way to define a measure of ductility is to use

$$D_f = \frac{\delta_f}{\delta_y} \tag{9}$$

where δ_y is the yielding dicplacement and δ_f is the ultimate displacement.

E.g. for timber structures the level of ductility in joints have been measured in the range 10–23 (Stehn and Björnfot 2002), (Piazza et al. 2004), (Stehn and Borjes 2004) and (Leijten et al. 2006). From high grade timber material (C35 or C40) tests concerning deformation behaviour of a rectangular beam in bending a level of ductility in the range of 4-8 have been found (Brunner 2000) and (Piazza et al. 2004). Based on these observations levels of ductility D_f = 1, 2, 4, 8 have been investigated in (Kirkegaard et al. 2010). Figure 5 shows the system reliability for a parallel system with 1 to 10 elements, ductility values equal to1, 2, 4 and 8 and a ratio of variable to total permant and variables loads equal to 0.4.

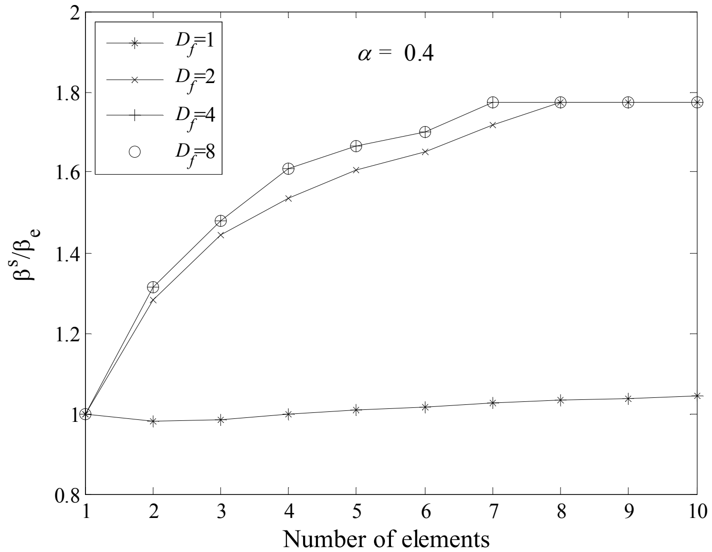

Figure 5. β^s/β_e versus number of elements for different levels of ductility D_f. and α = 0.4.

From figure 5 it is seen that the system reliability increases with the number of elements. As ductility increases the reliability of the system increases much steeper, so a relatively little ductility can account for a considerable extra reliability. On the other hand, for a brittle system (D_f =1) a decrease in system reliability with number of elements is shown first, followed by an increase if the number of elements is large enough, i.e. there is a relatively little effect of the system (especially for the small systems). This is not surprising since load redistribution is very unlikely to occur in small brittle systems.

5.2 Robustness in codes

In many codes of practice as e.g. the Eurocodes, the primary design requirements are related to checking that each component/ element/connection has sufficient reliability. A sufficient reliability level is secured by using characteristic values and partial safety factors calibrated to a reliability level which typically correspond to an annual probability of failure of the order 10^{-6}. However, additional requirements/measures are needed to secure that the structure also as a system has sufficient reliability. Further, provisions are needed to reduce/eliminate the effect of design errors, execution errors, unexpected deterioration of components, etc. Robustness requirements in codes of practice should cover these aspects together with quality control systems and application of best practices in design, execution and operation & maintenance as illustrated in Figure 6, see (Sørensen 2011).

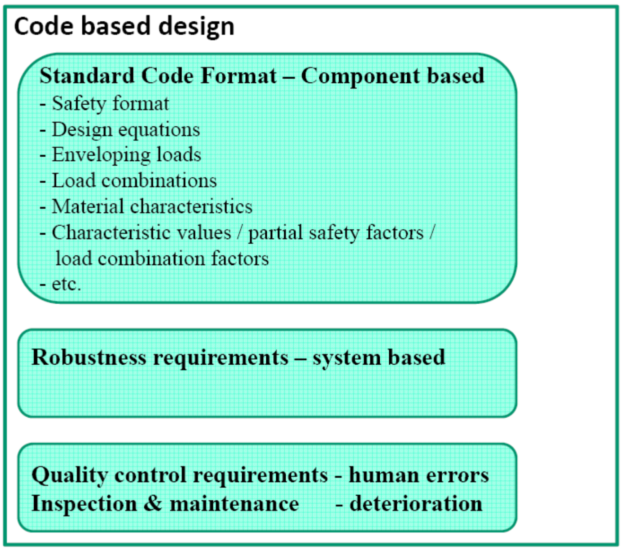

Figure 6. Code based design.

It is noted that many codes of practice contain some robustness rules, e.g. requirements to tie together concrete elements, but the rules/provisions are not formulated in a consistent way on a rational basis. In countries where structures are designed for seismic loads, the requirements to obtain earthquake resistant structures include many of the same aspects as those considered good for robustness, e.g. redundancy and ductility.

For the assessment of robustness, the structural behaviour models of structures need to be considered with emphasis on modelling of damage scenarios resulting from various foreseen or unforeseen exposures. The risk and reliability based robustness measures require estimation of the probability of total collapse, given some exposure event like a human error in design or execution or an accidental as fire or explosion has occurred. Typical for this type of analysis is that local damage is not considered as the ultimate failure, like in standard design for permanent and variable actions. The focus is on the consequences for the structural system after occurrence of a local damage. Therefore, models to be considered are: partly damaged structures; large cracks and/or plastic deformations; large deflections and membrane actions; high temperatures in case of fire; dynamic effects on various scales.

Because of several potential means by which a local collapse in a specific structure may propagate from its initial extent to its final state, there is no universal approach for evaluating the potential for progressive collapse (Ellingwood et al. 2007).

For reduction of the risk of progressive collapse in the event of loss of structural element(s), the following general structural traits should be incorporated in the design, according to (Ellingwood et al. 2007):

Redundancy: Incorporation of redundant load paths in the vertical load carrying system.

Ties: Using an integrated system of ties in three directions along the principal lines of structural framing.

Ductility: Structural members and member connections have to maintain their strength through large deformations (deflections and rotations) so the load redistribution(s) may take place.

Adequate shear strength: As shear is considered a brittle failure, structural elements in vulnerable locations should be designed to withstand shear load in excess of that associated with the ultimate bending moment in the event of loss of an element.

Capacity for resisting load reversals: the primary structural elements (columns, girders, roof beams, and lateral load resisting system) and secondary structural elements (floor beams and slabs) should be designed to resist reversals in load direction at vulnerable locations.

Connections (connection strength): connections should be designed in such a way that it will allow uniform and smooth load redistribution during local collapse.

Key elements: exterior columns and walls should be capable of spanning two or more stories without bucking, columns should be designed to withstand blast pressure etc.

Alternate load path(s): after the basic design of a structure is done, a review of the strength and ductility of key structural elements is required to determine whether the structure is able to “bridge” over the initial damage (Ellingwood et al. 2007).

In Eurocode 0 (CEN 2002), the following measures to increase structural robustness are mentioned: “Potential damage should be avoided or limited by appropriate choice of one or more of the following:

- avoiding, eliminating or reducing the hazards to which the structure can be subjected.
- selecting a structural form which has low sensitivity to the hazards considered.
- selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localised damage.
- avoiding as far as possible structural systems that can collapse without warning.
- tying the structural members together.

The basic requirements should be met:

- by the choice of suitable materials.
- by appropriate design and detailing.
- by specifying control procedures for design, production, execution, and use relevant to the particular project."

Next, probabilistic models are needed for modelling and estimation of the risks and probabilities in the risk and reliability based robustness measures. The probabilistic modelling can be based on available information, e.g. in the JCSS Probabilistic Model Code for actions and materials, especially timber, see (JCSS 2002). The JCSS PMC mainly deals with the models for normal design situations and it is noted that for model uncertainties in extreme situations, no data is presently available. Therefore, subjective assessment of the uncertainties is needed. Further, probabilistic models for human errors are difficult to formulate and are under consideration in WG 2 in this COST Action TU0601.

Estimation of the probabilities themselves requires system models of the failure modes. This aspect is considered in more detail in the next chapter. It requires a system model of the collapse events using series and parallel systems, and careful modelling of the correlation/dependency between the stochastic variables and the exposure events. Design and execution errors and unforeseen degradation could in many cases be expected to be present in all similar connections/elements, especially for a new and unconventional structural system. If an accidental action is the main exposure then this action typically results in an extreme load on one or a few structural elements and then (local) failure of this element.

6 Acceptance criteria

Cichocki, K. and Rizzuto, E.

6.1 Introduction

The following considerations are essentially based on the documents published in the framework of COST Action TU0601 and Joint Committee on Structural Safety. Parts of the factsheet “Robustness – acceptance criteria” by (Rizzuto et al. 2009) and the JCSS document “Risk Assessment in Engineering - Principles, System Representation & Risk Criteria” by M.H. Faber (JCSS 2008) were directly implemented in this chapter.

The concept of structural robustness is based on intuitive understanding of structural resilience against propagation of damage caused by local loss of structural resistance. This can lead to total collapse of the structure, with final effects disproportional to the direct cause. The problem is very often illustrated with the example of partial collapse of the Ronan Point Building.

It is difficult to establish the overall procedure to evaluate such defined structural robustness for large variety of existing and designed structures, due to their different configurations, foreseen and not foreseen possible exposures, environmental factors, economic conditions and social expectations concerning the structures under consideration. Nevertheless, many efforts have been focused recently to avoid such devastating effects of local structural damages. As the result of these studies, many useful recommendations have been formulated concerning various aspects of structural configuration and methods of structural robustness assessment at the design stage. However, these recommendations and requirements formulated in order to achieve the adequate level of robustness for the considered structure are still fragmentary and do not cover all possible solutions to obtain the adequately robust structure. This is not only because we cannot foresee all possible scenarios of progressive collapse, but also there are difficulties to define the acceptable level of risk of such collapse. It is not possible to totally exclude by technical means the probability of progressive collapse of the structure.

The necessity to establish an unequivocal robustness acceptance criteria is very important for the purposes of structural designing and analysis of possible damage scenarios. This problem may be defined as the *question on how an improvement in robustness can be quantified and how much effort can and must be put into achieving this target* (Rizzuto et al. 2009).

Evidently, this problem is a part of overall issue of risk acceptance criteria, limited to structural robustness analysis.

The main aim of this study is to define and describe the possible acceptance criteria, from a normative viewpoint, assign them the adequate probabilistic evaluation, define the boundaries of the whole procedure, establish categories of losses and procedures for risk acceptance analysis. The study is based on considerations presented by (Rizzuto et al. 2009), (Sørensen et al. 2009), (JCSS 2008).

6.2 Methods for risk acceptance

Generally, the methods of risk acceptance can be divided into two major groups: implicit and explicit methods. Implicit methods make use of available quantitative risk criteria from similar scenarios for other industrial sectors. This method, although simple in application, is characterized by serious limitations concerning the doubtful accuracy of the method, due to its comparative character. Explicit methods used recently are based on direct evaluation of risk acceptance, providing the quantitative decision tool or a comparable requirement for the industrial applications. The criteria for explicit formulation can be defined as follows (Diamantidis, 2008).

6.2.1 Human Safety criterion

This approach is based on statistics about human fatality risk, which is the base to define the risk of death for the various activities scenarios. For this criterion two types of risk are considered:

a) Individual risk: no individual involved in certain activity can be exposed to an unacceptable risk. In a case an individual (or group of individuals) is exposed to the risk exceeding the acceptable level, it is necessary to take up the adequate safety measures, regardless to the cost-benefit effectiveness.

b) Societal risk: this criterion assumes that a certain activity scenario cannot result in high frequency occurrences of large-scale accidents, understood as the accidents with particularly severe consequences. In this case, the unacceptable level of risk varies for assumed different accident sizes. This criterion although less restrictive than the former one, captures the global tendency to avoid large accidents with severe social, economical and political consequences.

6.2.2 Safety Cost-Benefit criterion

This criterion is based on evaluation of possible safety measures, in order to choose the solutions which produce benefits greater than costs. For this set of solutions, the one with greatest net value (i.e. the difference between benefits and costs) is selected for realization.

This approach, essentially linked to economical measures, is particularly suited for situations when it is possible to evaluate costs and benefits in terms of economical conditions. The typical applications are the analyses of the results of serviceability failure. In certain conditions also the societal inconveniences can be quantified.

6.3 Acceptance from a normative viewpoint (Rizzuto, 2009)

The success of the society in terms of its prosperity is strongly connected with development and management of societal infrastructures. This includes all activities concerning managing and performing the planning, investigations, designing, manufacturing, execution, operations, maintenance and decommissioning of objects of societal infrastructure (traffic infra-structure, housing, power generation, power distribution systems, water distribution systems, etc.).

Concentrating on the assessment from a normative point of view, the balance between positive and negative effects of certain activity should be considered from a societal perspective. This means that the activity should improve the quality of life (defined later) of individuals or groups of individuals of the society, in the present time and for the future. In other words, we foresee the positive balance between societal gains and losses (in economical terms).

The key acceptance criterion from a societal point of view can be formulated as follows:

$$G_s - L_s \geq 0 \tag{10}$$

where G_s are the societal gains, and L_s are the societal losses. There is still an open problem of quantitative evaluation of these values, which are relatively easy to calculate in case of serviceability failure, energy supply breakdown, collapse of transportation system, etc., but extremely difficult to evaluate for subjective items as discomfort, level of disturbance, quality of health, and many other problems concerning the non-economical aspects of life quality.

Notwithstanding these obstacles, for many practical situations where the economical measures of quantitative evaluation are possible to define and apply, the described approach is efficient and unequivocal.

Another important problem is the probabilistic evaluation of the balance between benefits and losses. Only for limited number of cases it is possible to define all factors with certainty and directly perform the identification of optimal decision by means of deterministic cost-benefit analysis. More often our knowledge of the nature of the phenomena involved in our decision problem is more or less uncertain and restricted more to the qualitative than quantitative description. This is because the decision problems in engineering are subjected to significant uncertainty (JCSS 2002, 2008), due to the very complex field of possible factors influencing directly or reciprocally the problem. Also the consequences resulting from the undertaken decisions are difficult to assess with certainty.

It is possible to evaluate the risks for the different decision alternatives. Based on risk assessment, the results for various decision alternatives may thereby be ranked and then accepted or rejected.

In order to relate the risk directly to concept of utility from the economic decision theory it is necessary to widen the concept of the risk as the simple product between probability of occurrence of an event with consequences and the negative consequences of the event to include also the aspects of the benefit obtained from the decisions. These are the theoretical basis for risk based decision making.

Positive and negative terms (benefits and losses) have 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:

$$\sum_i p_i G_{si} - \sum_j p_j L_{sj} \geq 0 \tag{11}$$

where

p_i probability of societal gain G_{si};

p_j probability of societal loss L_{sj}

Following the above formulation, the acceptance is tied to a positive average value of the left-hand side of the inequality above. This means that for single realizations the balance may result to be negative (i.e. in a single case losses may exceed benefits), but for a large number of realizations, an average value should result to be positive – i.e. the social benefits prevail on the long range.

The main problem of the risk assessment analysis is the need for a entirely holistic analysis, taking into account all possible factors, their consequences and inherent probabilities. Although the knowledge about the nature of cases under consideration is growing recently very rapidly, it is still an open question to decide about the scenarios taken into account, or omitted. This decision based on experiences, bonding regulations and rules, leads to the results and conclusions depending from assumed boundary conditions of the entire analysis.

Although the creation of databases concerning the possible factors (exposures, example cases, structural response, etc.) influencing risk assessment procedure is the task of growing importance, and recently are the subject of interest of many scientific and practical studies devoted to their creation and critical analysis, it is still difficult to define the closed set of boundary conditions for the analysis. Foreseen possible terms of the analysis may turned out to be of secondary meaning, whereas important terms may be omitted due to wrong recognition of the entire problem.

The above mentioned problem is difficult to overpower by means of simple intuitive procedures. In the authors' opinion there is an urgent need to elaborate and develop adequate databases concerning case studies, possible exposures, typical structural behavior in extreme load (and exposure) conditions, etc. This should lead to reduce the possibility to exclude unintentionally factors and terms of crucial meaning for overall gain and losses analysis.

There is also the danger of under-evaluation of importance for certain classes of consequences, especially developing in long time period (for example environmental pollution, etc.). Their results, although severe, develop in long time and cannot be evaluated immediately as the simple consequence of certain event.

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 structure 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.

6.4 Categories of losses

In order to compare the gains vs losses, it is necessary to define properly the expected losses, dividing them into certain categories. Traditionally, three main categories of consequences are considered in risk analysis applications:

- losses involving assets. The assets would be the part of infrastructure or belong to the external system.
- losses concerning human beings. This means the death, injuries or harm for the health of the staff, users or other persons.
- losses concerning environment.

It is also possible to define the categories based on different criteria, for example quantified in monetary terms, and intangible ones. Although it is generally relatively simple to calculate and consider the cost for construction, reconstruction and repair for the structure, cost of measures necessary to maintain the infrastructural functionality, and other expenses connected with so defined losses, there are many other categories impossible to quantify in monetary terms: casualties (loss of life, health), psychological effects on the individuals or the whole society (pain, grief, disturbances), losses in environmental attributes (pollution, scenic beauty, biodiversity).

For the scope of gain-loss evaluation it would be important if all quantified risks were presented in a single scalar unit (for example – monetary units) by means of a 'utility' function tying together and weighting, according to the defined preferences, the various types of consequences.

For such formulation of the entire problem the explicit definition of preferences gives a transparent and unequivocal assessment of decision alternatives. This problem was discussed in details in (Kroon et al. 2008) and (Keeney & Raiffa 1993).

Another important criterion to classify the risks is their frequency of occurrence. Typically, one can define for risk terms developed during the whole lifecycle those which are the systematic phenomena (i.e. occurring with probability 1 and, in general, with relatively low intensity) and those related to accidental phenomena (with relatively low probability of occurrence, but high negative consequences). Also in this case we can distinguish the risks with well-known frequency of occurrence, and others which are difficult to define in terms of their probability of occurrence. Available databases concerning occurrence of risks of various types cover only a limited number and type of risks, and can not be considered as the decisive tool for overall analysis.

Nevertheless, the main goal is to take into account the majority of possible accidental phenomena, and to control the consequences of an escalation and propagation of damages caused by events of various probability of occurrence. Although in many cases the scenarios for risk occurrence are known and defined in details (in terms of cause – course – direct consequences), in many cases it is difficult to define the consequences which are extended in time (long term consequences). Very often these consequences are of different type than their original cause. For example the breakdown of societal infrastructure can produce short time consequences (damages, repairs) and long time consequences (environmental effects arising after certain time, diminished comfort of life, reduced real estate prices, etc.). The last one are difficult to define due to their dependence to other factors, developing also with time.

6.5 Instruments for risk acceptance

Due to the lack of a unique quantification for various types of risks it is practically impossible to establish an acceptance criterion for the entire risk. In order to find a practical solution of this question, the overall problem is divided by rating out the parts from the total risk and total benefits and define criteria for each part. Although this approach simplifies the problem but also leads to the limitation in the entire model. The exchange between the different types of risk is disabled. This impedes an increase of the degrees of freedom available for fulfilling the assumed goals – the global societal objectives. Due to this restrictions, the balance between losses and benefits is often formulated in a way assuming the reduction of the specific type of risk (often selected as most probable to occur or characterized with severe consequences for the society) and the subsequent increase of the construction (improvement, modernization) cost of the infrastructure which is necessary to achieve the assumed reduction of the risk. This limited consideration of gain-loss balance has a much more limited meaning than the corresponding global gains and losses concerning the overall societal balance. This last criterion is much more general, taking also into account other criteria exceeding simple dependence between risks and cost of means assumed to achieve their reduction. Nevertheless, this criterion is used very often, because the cost of necessary construction, modernization or improvement of infrastructure necessary to reduce the risk is very important form the individual point of view, which may be different from the global societal objectives.

From the practical point of view it is important to define the ratio between the expected values of the above mentioned quantities, which can be defined as the “Cost to Avert a Risk Unit” (CARU). Following this formulation, the criterion for acceptance is than set as a check of inequality between CARU and empirically defined Societal Willingness To Pay (SWTP) to avoid the same risk unit:

$$CARU < SWTP \tag{12}$$

This approach is often used to compare the different formulations of the normative, usually between existing one and its updated version. Because of its clear and unequivocal character it is particularly useful in decision-making procedure.

This practical approach corresponds to a criterion for a judgment in a differential sense. It means that what is evaluated is whether a given modification in a normative 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 normative in an efficient way.

The Societal Willingness To Pay (SWTP) has a pure empirical nature, with value defined on the basis of the best practice and experience. It is necessary to outline 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 (in any meaning) that is to be devoted to improve the situation. SWTP depends on current societal accepted level of efforts necessary to avoid certain risk unit. This level may be expressed in various units: monetary or others, depending on the nature of the considered risk. It is worth noticing, that SWTP for the same type of risk may vary qualitatively being expressed in different entities. For example, the society may accept high costs of constructional improvements and modifications, and may not accept increase of number of accidents with resulting casualties (or vice versa).

An established practice for the assessment of the SWTP for reducing life and injury risks does exist. As regards other intangible values such as loss of landscape beauty, environmental pollution there is at present no established scientific basis to define the SWTP for specified cases.

The diagram of dependence of benefit in function of continuous parameter *p* is shown in figure 7 (JCSS 2008):

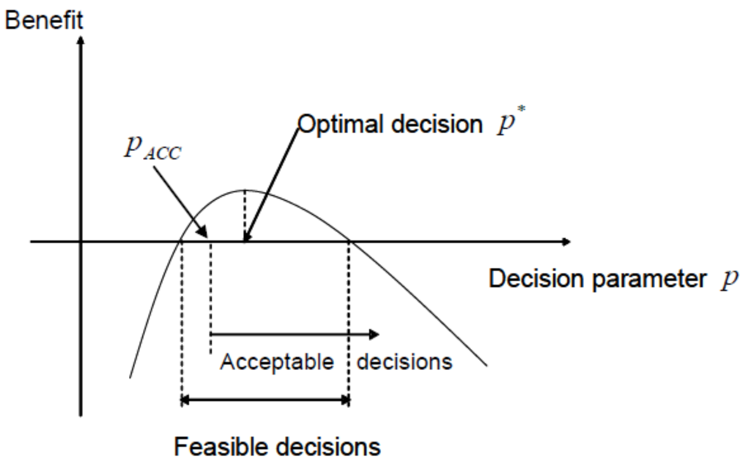

Figure 7. Illustration of identification of acceptable decisions, (JCSS 2008).

In this figure the benefit function is expressed in economic, tangible terms. Only a certain range of a decision parameter *p* will result in positive benefit. This range corresponds to feasible decisions.

After the definition of the parameter p^* corresponding to optimal decision, it is necessary to check whether this decision is acceptable from the perspective of society. The value of the decision parameters which corresponds to the societal preferences should be assessed; thus value of *p* is denoted p_{ACC}. The acceptability level does not only depend on the risk level but also the efficiency of risk reduction. Focus is thereby directed not only on the highest sources of risks but moreover on the risk reduction activities with the highest efficiency.

6.6 Formulation of societal preferences for risk acceptance purposes

One of most important societal preferences concerning human-related risks is to reduce the mortality or to equivalently increase the statistical life expectancy. Following this preference any efficient life saving activity may be understood as a measure which in the most cost effective manner reduces the first factor or increase the second one. The mortality is expressed directly as the incidence of death in a population. It is measured in various ways, often by the probability that a randomly selected individual in a population at some date and location would die in some period of time. Life expectancy is defined as the probable number of years a person will live after a given age, as determined by the mortality rate in a specific geographic area. This number may be individually qualified by the person's condition, race, sex, age, and other demographic factors.

The last term 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 citizen is devoted to generate the average GNP value. On the other hand, a part of the GNP may be devoted to reduce the risk for life, or to enlarge the life expectancy.

Both indicators are used to define the Life Quality Index (LQI), used to characterize quantitatively the societal preferences as a scalar indicator. The main idea of the LQI is to model quantitatively the preferences of a society as a scalar valued social indicator, comprised by relationship between, GNP pro capite *g*, the expected life at birth *l* and the proportion of life spend for earning at living *w*. LQI can be expressed in the following principal form:

$$L = g^r \left[(1-w) l \right]^{1-r} \tag{13}$$

where the parameter *r* is a measure of the trade-off between the resources available for consumption and the value of the time of healthy life.

In equation above only the part of GNP available for risk reduction investments is considered. This value *g* is estimated as 70% of the total GNP. Following the approach proposed by Cobb Douglas, *g* is assumed to be proportional to a work related factor to the power β and a capital related factor to the power (1-β). This means that *g* can be written in the following form:

$$g = p w^{\beta} \tag{14}$$

To estimate the value of *r* it is necessary to consider the part of life concerning the economic activity. The value of *w* for which *L* reached the maximum may be derived from the equation below, formulated for the condition of extreme value of the function:

$$\frac{\partial L}{\partial w} = \beta r \frac{L}{w} - (1-r)\frac{L}{(1-w)} = 0 \tag{15}$$

This gives the following equations:

$$\begin{aligned} q &= \frac{r}{1-r} = \frac{1}{\beta}\frac{w}{(1-w)} \\ r &= \frac{w}{\beta - w\beta + w} \end{aligned} \tag{16}$$

If β would be equal to 1.0 the value of *r* would be equal to *w*. Parameter *q* is applied in an alternative expression for LQI:

$$L = g^q l (1-w) / q \tag{17}$$

The value of *w* (proportion of life spend for earning at living) in modern economies of developed countries is equal approximately 0.10. If we assume that these countries are in their stationary optimum, and assuming β = 0.7 it may be found that the preference parameter *r* should be equal about 0.13.

It is obvious that any risk reduction measure will influence the LQI. Each investment into life risk reduction should lead to an increase of the LQI. This results in the following risk acceptance criteria:

$$\Delta L = \frac{\partial L}{\partial g}\Delta g + \frac{\partial L}{\partial l}\Delta l \geq 0 \tag{18}$$

or, alternatively:

$$\frac{\Delta g}{g}+\frac{(1-r)}{r}\frac{\Delta l}{l}\geq 0 \tag{19}$$

The relationship between Δg and Δl which increases the LQI may be determined, and used for assessing the corresponding probability of different types of failures of relevance for a considered system. So the derived probability may be applied as a target value for structural design or assessment purposes.

Taking into consideration the structural reliability, the relative change in life expectancy expressed by the term $\frac{\Delta l}{l}$ may be exchanged by a change in mortality $d\mu$ as follows:

$$\frac{\Delta l}{l}=C_x\Delta\mu=C_x P_{D|F}\Delta\nu \tag{20}$$

where ν is the failure rate, C_x is a demographical constant corresponding to a given scheme *x* for mortality reduction and $P_{D|F}$ is the conditional probability of dying given a failure. Finally:

$$dC_y=g\frac{r}{1-r}C_x N_{PE}P_{D|F}d\nu \tag{21}$$

In equation above dC_y are the annual investments into life safety and N_{PE} is the number of persons exposed to the failure.

Of course, there are also possibilities to enlarge the formulation for LQI in order to include various specific phenomena influencing this index. This is still an open question, depending on the problem characteristics, assumed boundary conditions, its formulation, etc. The problem was studied in detail by Rackwitz (2005).

6.7 Conclusions

The problem of definition of acceptance criteria for robustness is always related to the well known question of risk acceptance criteria, and may be considered as a particular aspect of it. Methodology and procedures applied in order to assess the risk are also applicable to evaluate the robustness. Due to this, there is a direct interrelation between these two problems, in their methodology and field of application. This leads to the need of complete evaluation on possible societal losses and benefits associated with the considered activity or infrastructure. Due to the fact this evaluation is a crucial factor for risk acceptance purposes and consequently for robustness assessment, in practical applications the entire process should be performed taking into account all possible elements of the analysis (i.e. losses and benefits).

Although the entire problem is very complex, in order to retain a simple and unequivocal measure of societal preferences a scalar utility function defined as Life Quality Index has been adopted. This allows for relating the various economic aspects and life-saving design criteria on the basis of objective macroeconomic indicators at national level.

The Life Quality Index includes various types of risks in a unified manner. This allows for expressing the broad variety of possible factors as a single scalar value. The final acceptance criteria can finally be expressed in terms of a positive variation of the index itself.

The acceptance criteria applied for robustness problems in existing structural regulations are defined as deterministic checks performed on the structural level. This is to facilitate the implementation of the adequate requirements in standard designs. 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.

7 Summary

A risk-based approach for implementation for robustness is described and different measures of robustness are described and discussed – a risk-based, a reliability-based and a deterministic measure. These measures require probabilistic models to be formulated for the important failure modes and the uncertain parameters related to loads, strengths and models. Further, for quantification of the risk-based measure of robustness, modelling of the consequences of failures is needed. These probabilistic and consequence models are in general difficult to establish and not directly applicable for recommendations for practical applications. But the risk and reliability based robustness measures can be used as a rational basis for formulating recommendations for practice.

Estimation of the probability of extensive failure and collapse requires system models of the failure modes to be formulated. Especially the importance of ductility is investigated and shows that the level of ductility should be at least 1.5 - 2.0 before a significant increase in system reliability is observed for redundant structural systems.

The system model of collapse events using series and parallel systems requires careful modelling of the correlation/dependency between the stochastic variables and the exposure events. Design and execution errors and unforeseen degradation could in many cases be expected to be present in all similar connections/elements, especially for new and unconventional structural systems. If an accidental action is the main exposure then this action typically results in an extreme load on one or a few structural elements and then (local) failure of this element. If exposures on different structural elements can be considered statistically independent then a parallel system model should be preferred from a reliability point of view. This can be obtained by increasing the redundancy of the structural system. On the other hand, if the exposures on different structural elements can be considered statistically dependent, then a parallel system model should be avoided from a reliability point of view. This can e.g. be obtained by using compartmentalization of structural systems.

The problem of definition of acceptance criteria for robustness is discussed and is related to the question of risk acceptance criteria. Methodology and procedures applied in order to assess the risk are also applicable to evaluate the robustness. Although the entire problem is very complex, in order to retain a simple and unequivocal measure of societal preferences a scalar utility function defined as Life Quality Index has been adopted. This allows for relating the various economic aspects and life-saving design criteria on the basis of objective macroeconomic indicators at national level.

The acceptance criteria applied for robustness problems in existing structural regulations are defined as deterministic checks performed on the structural level. This is to facilitate the implementation of the adequate requirements in standard designs. 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.

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