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RISK-BASED ASSESSMENT OF STRUCTURAL ROBUSTNESS

BY

OANA-MIHAELA IONIŢĂ, N. ŢĂRANU, *SILVIA ROMÎNU
and CĂTĂLIN BANU

Abstract. Providing safety of structures is one of the main aims of design. In traditional design it is achieved by designing structural components against specified limit states. However, as showed the Ronan Point collapse in UK in 1968, when a gas explosion in one of flats on the 18-th floor of the residential building caused the failure of an entire section of the building, this approach is not sufficient. The approach does not exclude the risk of local damage to a structure due to accidental events that can occur during service life of the structure. While probability of occurrence of such events for ordinary structures is low, and, therefore, they are not considered explicitly in design, their effect on structural safety becomes significant if the structure is not robust, that is when some local damage can trigger a chain reaction of failures causing collapse of the whole structure or of a major part of it, the so called *progressive collapse*.

The purpose of this paper is to outline the basic premises for the utilization of risk assessment in evaluating the robustness of structures. In the following the robustness assessment is understood as a process of decision making based on risks.

Key words: robustness of structures; risk assessment; decision making; consequences evaluation; index of robustness.

1. Introduction

During the last decades a growing concern regarding the durable development focused on the environment preserving, the individual wealth and safety and also on the optimal allocation of societal, natural and economical resources. This led Brundtland to the conclusion that a sustainable development is defined as a development "*that meets the needs of the present without compromising the ability of the future generations to meet their own needs*" [1]. This complex of problems can be easily assessed as a decisional problem complex strongly influenced by the potential consequences of human activities and by the possibility that these consequences could manifest, their result being known as risk.

The continuous societal development supposes an intelligent, consequent and rational managing of the predominant natural and human hazards. According to the fundamental principles of the decision theory this is the mandatory premise for the continued success of the society. The most important aspects of the decision theory are the assessment of consequences and probabilities and in a very simplified manner it can be stated that risk and reliability analysis in civil engineering is concerned with the problem of decision making subjected to uncertainty [2].

2. Risk Assessment and Decision Making in Civil Engineering

The risk management implies the analysis, evaluation and decision making related to the risks involved by a given activity or associated to a given hazard. The risk management process comprises the overall consideration of all predominant uncertainties and all potential consequences.

The new civil engineering projects should be planned, designed and executed in such a manner to imply minimum costs taking into consideration the projects' profits as well as the potential adverse consequences as the human fatalities, the negative impact on the environment and of course the direct costs.

The risk assessment should consider all phases of a technical system from the early concept stage to the end of the service life including decommissioning. The decision process involved in this task concern all aspects

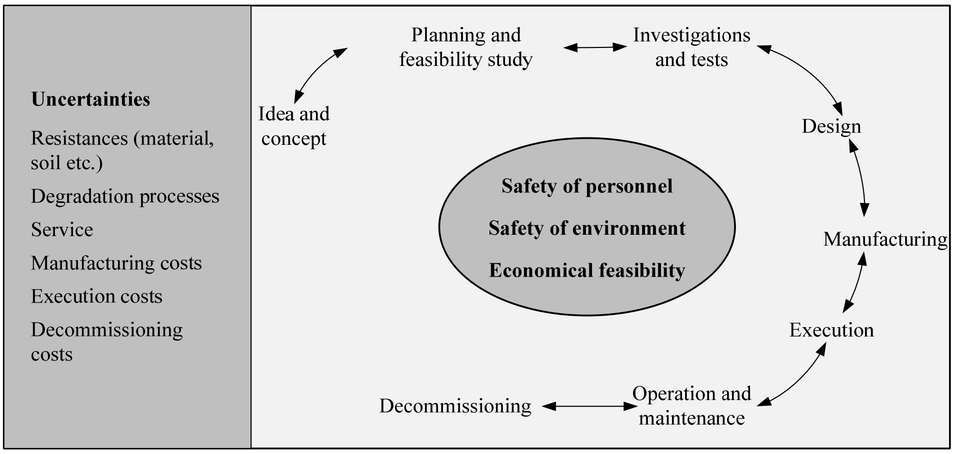

Fig. 1 – Risk contributors from different service life phases [2].

of managing and performing the planning, investigations, designing, manufacturing, execution, operations, maintenance and decommissioning of objects of societal infrastructure, such as traffic infrastructure, housing, power generation, power distribution systems and water distribution systems. The main objective from a societal perspective by such activities is to improve the quality of life of the individuals of society both for the present and the future generations. From the perspective of individual projects, the object may simply be to obtain a maximal positive economic return of investments (Fig. 1) [3].

During the hazard event the concern is to limit consequences by containing damages and by means of rescue, evacuation and aid actions. After the producing of the hazard, the main concern is to decide on the rehabilitation of the losses and functionalities and to reconsider strategies for prevention measures. In Fig. 2 is illustrated as an example all these decision situations with the focus on the earthquake risk management [3].

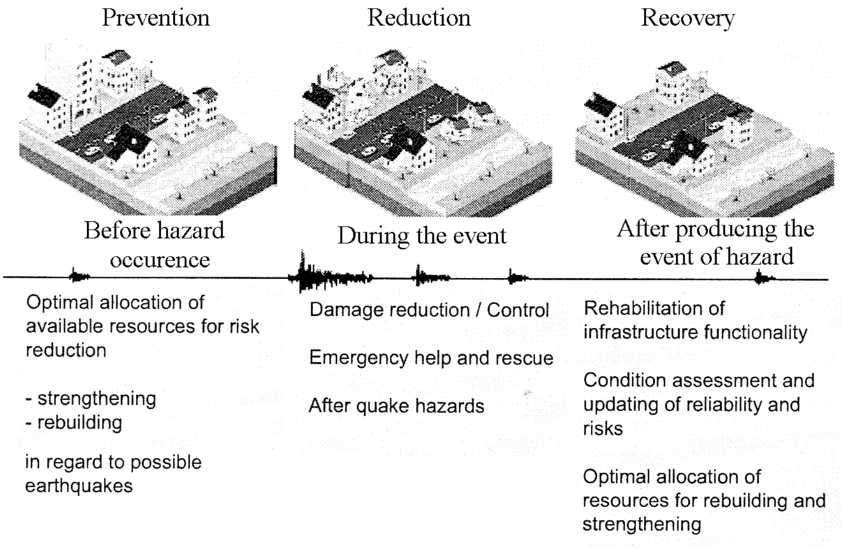

Fig. 2 – Decision situations for management of earthquake risks [3].

3. Robustness of Structures

3.1. General Aspects

Robustness is a property, the description of which varies so much with context that it is difficult to put order into its manifold aspects, relationships and ramifications.

Robustness is the property of systems that enables them to survive unforeseen or unusual circumstances without undue damage or loss of function. It has become a requirement expressed in modern building codes, mostly without much advice as to how it can be achieved. Engineering has developed some approaches based on traditional practice as well as recent insight. However, knowledge about robustness remains scattered and ambiguous, making it difficult to apply to many specific cases. Robustness provides a measure of structural safety beyond traditional codified design rules.

The design of a system, being it a natural or an artificial one, is typically oriented towards normal use, more precisely towards circumstances which must or can be anticipated to exist during the intended working life of the system. Limiting the design to this may however leave it vulnerable to the effects of events that were not included in the set of anticipated circumstances. These effects can be of very diverse character and may be related to the features that were anticipated in the design but for an unanticipated intensity, or that may not be of a description altogether foreign to the design circumstances [4].

Related to the life span of a building, robustness can represent the preserving of the integrity of the component elements properties, starting with the framing system, closings, finishes and ending with the installations.

Robustness must not be understood as an overdimensioning of the elements but as the capacity of the system of adapting without damages to current actions and with minimum shortcomings to the extraordinary ones.

If we refer to the framing system of a building, the robustness has to provide it with the capacity of keeping its integrity to current actions and to not reach collapse in the case of extraordinary actions. When the extraordinary action is the seismic load, robustness must also include the dissipating capacity of the induced energy by ductility, through the capacity of the structural system to form plastic hinges in sensed zones even from the design phase. This means the capacity of the structure of accommodating to an unfavourable situation.

3.2. Typical Aspects of a Robustness Assessment

The currently used methods for designing robust structural systems consider of a great importance the study of the actions effects upon the entire structural system. Normally, the design codes primarily focus on a design philosophy where the individual components or subsystems and also sometimes, but less frequently, the structural systems are assessed and designed considering their load carrying capacity subjected to different relevant load scenarios. In the definition of the different load scenarios the different relevant types of loads are in turn considered as being the leading load and its extreme effect is combined with the corresponding effects of other relevant loads. Structural design in this way explicitly takes into account the relevant load scenarios including environmental extreme loads, accidental loads, earthquake loads and the effect of degradation. This design philosophy has generally been successful, excepting those instances where systems have suffered cascading systems failures due to lack of robustness. These potential failure mechanisms are the reason why robustness criteria require system-level analysis [5].

When the ability of structures to sustain damages is considered, the codes and existing design practices are much less specific. Typically, this issue is treated in the design codes by stating that structures must be robust in regard to damages such that *the consequences associated with damages shall not be disproportional to the effect causing the damages*. Even though, the information contained in such a statement may be substantial, it is highly ambiguous. In deed, the engineers and the owners of structures have little help on the quantification of robustness and no clear definition on acceptability of robustness [6]. This situation is clearly not desirable and more research must be invested on this subject to provide more clear and practicable directives for ensuring the robust performance of structures. In this perspective the present paper sets out with a risk based definition of robustness. The suggested approach assesses robustness in the context of decision making such that not only the performance of damaged structures are considered in regard to various relevant loading conditions, but also the effect of human interventions, monitoring schemes and inspection and maintenance strategies are taken into account.

A robustness assessment involves the following aspects:

Step 1 – *a system* must be identified and clearly defined.

Step 2 – *the specific system objectives* must be identified; the structural robustness relates to certain desirable system objectives (features, characteristics or properties).

Step 3 – *the specific disturbances* such as hazards, internal or external influences, abnormal, deliberate or unexpected circumstances, or any other trigger events must be identified.

Step 4 – *the robustness analysis:* this one focuses on the overall effect (consequences) of the specific disturbances (Step 3) as they affect the system objectives (Step 2).

Step 5 – *the robustness ranking*: any measures or indicators of robustness used to rank system robustness must be such that they assign high “marks” to the persistence of the system objectives subjected to the specific disturbances, or to a low and acceptable effect on the system objectives as a result of the disturbances.

The above process is illustrated in Fig. 3 and it can be applied to any system (and its identified features) and to specific disturbances when none of these are subject to uncertainty. In many technical and scientific domains the robustness analyses are in fact entirely deterministic.

However, in structural applications, the system, the system response, the cause–effect relationships, the hazards and the consequences are usually subjected to considerable uncertainty. Therefore it is necessary to consider an additional element [7] in the process of robustness assessment.

Additional step – the risk assessment: the assessment of robustness must account for all uncertainties associated with system assumptions (Step 1), system objectives (Step 2), the occurrence of disturbances or hazards (Step 3), and model uncertainties involved in the system consequence analysis (Step 4).

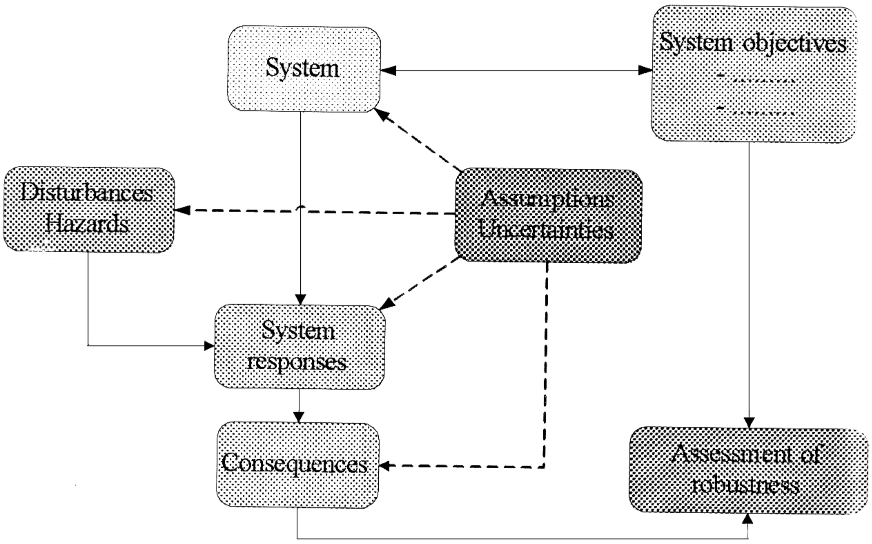

Fig. 3 – Schematic process of assessing robustness [7].

3.3 A Probabilistic Framework for Robustness Assessment

Risks are normally associated with various scenarios of events. That's why it is important to be able to quantify either the probability or the rate of occurrence of these scenarios and this in general implies a probabilistic modeling involving conditional probabilities or rates respectively. In this respect, the logical trees can be used for the quantification of risks and also for the evaluation of each individual component contribution to the total risk. The event trees are among the most common logical trees with a wide application in the qualitative and quantitative risks assessment [2].

In Fig. 4 events that may damage a system and also their consequences are modeled.

First, an exposure which may have the potential of damaging components in the system occurs. This is termed *the exposure before damage*, or EX_{BD}. If no damage occurs ($\overline{D}$), then the analysis is finished. If damage occurs, a variety of damage states (D) can result. For each of these states, there is a probability that system failure (F) results. Consequences are associated with each of the possible damage and failure scenarios, and are classified as either direct (C_{dir}) or indirect (C_{ind}). The event tree representation in Fig. 4 is a graphical tool for evaluating event scenarios that could occur to the system, and it also incorporates the associated probabilities of occurrence. This formulation is based on risk assessment methodologies from the Joint Committee on Structural Safety, with particular attention paid here to aspects of robustness [3].

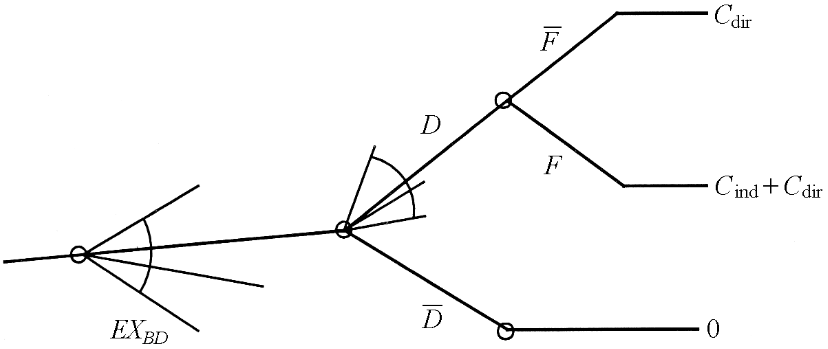

Fig. 4 – An event tree for robustness quantification [8].

An exposure is considered to be any event with the potential to cause damage to the system. Damage could come from extreme values of design loads such as snow loads, extraordinary loads such as explosions, or deterioration of the system through environmental processes such as corrosion. *Damage* refers to reduced performance of system components, and *system failure* refers to loss of functionality of the entire system. In the case that a design allows for some degree of reduced function, then damage should refer to reduced function beyond the design level. *Direct consequences* are those associated with the initial damage, while *indirect consequences* are associated with the subsequent system failure. Thus, the damage branch of Fig. 4 is associated with direct consequences, while the failure branch is associated with the direct consequences plus additional indirect consequences.

Consequences typically come in several forms: inconvenience to system users, injuries, fatalities, and/or financial costs. To allow for comparison, these effects can be combined into a scalar measure of consequences, often termed *utility*. Although combining financial costs with other consequences can be difficult and controversial, it is implicitly done whenever one makes decisions about system design, and so combining consequences explicitly makes the decision process more transparent and objective.

Current codes already require damage scenarios and consequences to be identified, so that it can be determined whether the two are proportional. The event tree of Fig. 4 requires the additional step of assigning probabilities to the exposures. This may be straightforward for typical design loads, but more difficult for other exposures such as sabotage. Despite this challenge, occurrence probabilities are needed if one wishes to efficiently allocate resources for risk reduction. For example, progressive collapse may be found to occur for some unusual damage scenario, but that one might be extremely unlikely and thus no possibly a time-dependent aspect, it is appropriate to assess probabilities in terms of probabilities *per annum* over the expected lifetime of the system. Many design exposures are characterized in this manner already [8].

With the event tree defined in Fig. 4, it is possible to compute the system risk due to each possible event scenario. This is done by multiplying the consequence of each scenario by its probability of occurrence, and then integrating over all of the random variables in the event tree. The risk corresponding to each branch is

$$R_{\text{dir}} = \int_x \int_y C_{\text{dir}} f_{D|EX_{BD}}\left(y|x\right) f_{EX_{BD}}\left(x\right) \mathrm{d}y \mathrm{d}x, \tag{1}$$

$$R_{\text{ind}} = \int_x \int_y C_{\text{ind}} P\left(F|D=y\right) f_{D|EX_{BD}}\left(y|x\right) f_{EX_{BD}}\left(x\right) \mathrm{d}y \mathrm{d}x, \tag{2}$$

where: $f_z(z)$ is used to denote the probability density function of a random variable, Z. These integrals may be evaluated either through numerical integration or Monte Carlo simulation. For computing damage and failure probabilities, techniques from systems reliability can be used [8].

To quantify robustness it is necessary to compute the direct risk associated to the direct consequences of the potential damages to the system and the indirect risk which corresponds to the increased risk of failure of the damaged system.

A robust system is considered to be one where indirect risks do not contribute significantly to the total system risk. With this in mind, the following *index of robustness* (denoted I_{rob}) is proposed, which measures the fraction of total system risk resulting from direct consequences:

$$I_{\text{rob}} = \frac{R_{\text{dir1}}}{R_{\text{dir1}} + R_{\text{ind1}}}. \tag{3}$$

The index takes values between zero and one depending upon the source of risk. If the system is completely robust and there is no risk due to indirect consequences, then $I_{\text{rob}} = 1$. At the other extreme, if all risk is due to indirect consequences, then $I_{\text{rob}} = 0$.

By examining Fig. 4 and the above equations, several links between system properties and the robustness index can be identified.

Firstly, this index measures only the relative risk due to indirect consequences. The acceptability of the direct risk should be determined through other criteria *prior* to robustness being considered. A system might be deemed robust if its direct risk is extremely large and thus large relative to its indirect risk, but that system should be rejected on the basis of reliability criteria rather than robustness criteria.

Secondly, the index will depend not just upon failure probabilities of damaged systems, but also upon the relative probabilities of the various damage states occurring. Thus, a building could be designed to have a low failure probability after an individual column is removed, but if it is deemed likely that an exposure would cause the loss of two columns and if the building was vulnerable to that damage, then it could still be deemed non-robust.

Thirdly, the index accounts for both the probability of failure of the damaged system and the consequences of that failure. For instance, if sensing systems were able to detect damage and signal an evacuation before failure could occur, then robustness could be increased without changing the probabilities of damage or failure. Thus, the possibility of detection and the time between damage and failure can be accounted for in an appropriate manner. The property of robustness depends upon system properties such as redundancy, ductility, load redistribution and damage detection, but it also depends upon failure consequences. This ability to incorporate consequences as well as probabilities is an important new development.

Finally, this index can be easily extended to account for multiple exposures, or more complicated event trees than the one represented in Fig. 4. The robustness index will still be equal to the sum of direct risk divided by the sum of total risk,

$$I_{\mathrm{rob}} = \frac{\sum_i R_{\mathrm{dir}_i}}{\sum_i R_{\mathrm{dir}_i} + \sum_j R_{\mathrm{ind}_j}}. \tag{4}$$

4. Conclusions

Despite many significant theoretical, methodical and technological advances in the recent years, structural robustness is still an issue of controversy and poses difficulties with regard to its interpretation as well as regulation.

The perception of risks may be significantly influenced by information about the risks themselves. Information can and should be used as a targeted means of reducing potential losses caused by reactions to events beyond what is rational, seen in the perspective of normative decision making. Being provided with transparent information regarding the nature of exposures, possible precautionary actions, information on how risks are being managed and the societal consequences of irrational behavior reduces uncertainties associated with the understanding of risks of individuals. This, in turn, adds to rational behavior and thereby reduces follow-up consequences. For this reason, schemes for targeted, transparent and objective information concerning the stakeholders are a highly valuable means of risk treatment.

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"Gheorghe Asachi" Technical University of Iaşi
Department of Civil and Industrial Engineering
e-mail: ionita@ce.tuiasi.ro
and
* *"Politehnica" University, Timisoara*
Department of Civil Engineering

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EVALUAREA ROBUSTEŢEI STRUCTURALE PRIN INTERMEDIUL RISCURILOR

(Rezumat)

Una dintre preocupările principale ale proiectării structurale este aceea de a conferi siguranţă structurilor. Acest obiectiv este atins in manieră tradiţională prin proiectarea elementelor structurale componente în condiţiile unor anumite stări limită. Cu toate acestea, aşa cum a demonstrat colapsul structurii Ronan Point din UK în anul 1968 când o explozie datorată acumulării de gaze care s-a produs într-unul din apartamentele de la nivelul al optsprezecelea al clădirii rezidenţiale a condus la cedarea unei întregi secţiuni a clădirii, acest mod de calcul nu este suficient. Abordarea aceasta nu exclude riscul provocat de o degradare locală a unei structuri datorită acţiunilor de tip accidental care se pot manifesta pe durata de exploatare a structurii. Dar în timp ce probabilitatea de apariţie a unor astfel de evenimente pentru structurile uzuale este redusă şi, astfel, acestea nu sunt luate în considerare în mod explicit în proiectare, efectul lor asupra siguranţei structurale devine semnificativ în cazul în care structura nu este una robustă. Această situaţie are loc atunci când o degradare locală poate provoca o reacţie în lanţ de cedări conducând la colapsul întregii structuri sau a unei porţiuni însemnate a acesteia, aşa-numitul *colaps progresiv*.

Obiectivul esenţial al acestei lucrări este acela de a evidenţia care sunt premizele de bază ale aplicării tehnicilor de evaluare a riscurilor în vederea evaluării ulterioare a robusteţei structurale. În lucrare evaluarea robusteţei este percepută ca un proces de decizie bazat pe evaluarea riscurilor.