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Robustness of Civil Engineering Structures – A Modern Approach in Structural Design

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ABSTRACT

The awareness of the significance of robustness of structures has gradually intensified over the years due to experiences with failure and collapse of many structures. Recent events caused by terrorist actions in different parts of the world have further emphasized the urgent need for development of rational approaches to ensure that risks to people, environment, assets and functionality of the societal infrastructure and built environment are acceptable and affordable to society. A significant amount of research has been invested into the various aspects of robustness resulting in a number of useful recommendations on how to achieve robust structures.

However, despite many significant theoretical, methodical and technological advances, structural robustness is still an issue of controversy and poses difficulties with regard to its interpretation as well as regulation.

The aim of the present paper is to present some aspects regarding the assessment of the structural robustness based on the knowledge of the failure mechanisms and on the collapse avoiding methods. The currently used methods of designing for robust structural systems according to the Eurocodes are also specified.

Keywords: robustness of structures, reliability, structural integrity, residual load-bearing capacity, structural failure, disproportionate failure.

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1. INTRODUCTION

Structural robustness is an issue discussed by the civil engineers and by the scientists mostly during the last decades. In fact, the importance of robustness as a property of structural systems has been recognized following several structural failures, such as that at Ronan Point in 1968, UK, where the consequences were deemed unacceptable relative to the initiating damage.

A variety of research efforts in the recent decades have attempted to quantify aspects of robustness such as redundancy and identify design principles that can improve the robustness of structures [1], [2].

Robustness of structural systems has gained renewed interest following the bombing of the Alfred P. Murrah Federal Building in Oklahoma, USA in 1995 and the collapse of the World Trade Center towers on September 11, 2001 [1]. This disaster happened at a time when regulatory requirements related to disproportionate collapse were considered to be adequate and related research was slowing down. As a result of those incidents stakeholders worldwide have now begun to re-examine relevant issues, including destructive attacks, holistically by incorporating associated risks. Another reason for increased interest in robustness is that most failures of structures are due to unexpected loads, design errors, errors during execution, unforeseen deterioration and poor maintenance during the life span of the construction which is not possible to design against using conventional code based design [2].

2. STRUCTURAL FAILURES

2.1. Generalities

Knowing and understanding the failure types and mechanisms of the existing structures represent an essential educational tool for all civil and structural engineers necessary for the designing of robust structures with adequate strength and rigidity to different loads. In addition, scenarios of possible causes which do not induce the structural collapse but a certain structural deterioration should also be included.

Although structural designers are not keen to discuss their shortcomings and mistakes from their activity a detailed analysis of failure cases is an instructive way of preventing similar events.

A first step for the design of a robust structure resistant to different loading is the knowledge of the failure mechanism of existing constructions.

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Experience and judgment, which play an important role in structural design, receive less attention in technical literature than the description of new and efficient structural designs. Technical literature on the failures of the past is scarce; however a full discussion and analysis of failure cases can as useful as presentations of great engineering achievements.

The experience from previous failure of different constructions generally provides a valuable knowledge base. Firstly, the accumulated information gives an overview of the safety and the reliability of the structures and may indicate possibilities of improving the design codes in this regard. If this information is carefully studied it can provide the understanding ways of the most important hazard scenarios and generally of the possible risk situations which can affect the engineering structures.

The concept of failure is mainly related to the ultimate limit state and not to the loss of serviceability. Thus, failures are defined as events which directly or indirectly have or could have implied risk for human lives.

Generally, the collapse or the failure of the civil engineering structures may occur in some situations, like the following ones:

- deterioration of some of the principal structural members or connections;
- fatigue of the structural members after a large number of alternating loads;
- buckling of the main structural members;
- blasts or impact.

Numerous investigations of structural failures that have been occurred in practice have been carried out during the years. Such investigations show convincingly that with few exceptions structural failures are due to human errors and almost never as a result of unfavorable combinations of random events. The purpose of these studies has been to quantify sources of error and to indicate their relative importance in the building process [3].

More specific, the objectives for undertaking the survey of building failures are to get a picture of:

- the underlying reasons for the observed failures;
- which type of components are most prone to fail;
- which failure modes are most frequent;
- what can be done to avoid or reduce the number of failures;
- the way the collapse of the entire construction can be avoided [3].

For a more appropriate analysis of failure causes, structures can be ranged in different categories by destination, as it follows:

- civil and industrial buildings;
- bridges;
- dams;
- offshore structures;

- pipelines;
- nuclear power plants
- chemical facilities.

2.2. CASE STUDIES

The interest of civil and structural engineers is many times focussed on the inevitable decay caused by material aging, which occurs in time and on the effects of some accidental events which can affect the structural integrity. Thus, earthquakes, winds, slumps, fires, floods, explosions, chemical agents and fabrication processes are only some of the factors causing damages. Another cause occurring even more frequently is related to the dynamics of possible functional alterations [4].

Very frequently, construction decay is caused by material aging in its various forms: exceeding its life time, fatigue, creep, yield, multiple load cycles or the action of the chemical agents [4].

Exposure of concrete to high temperature for a long period of time leads to its hastened aging and, consequently, the material becomes much more brittle. A very relevant example of this kind is the building of a board factory where furnaces were placed too close to the central column and no measures of thermal insulation were taken, figure 1. The columns broke down when a strong earthquake occurred [5].

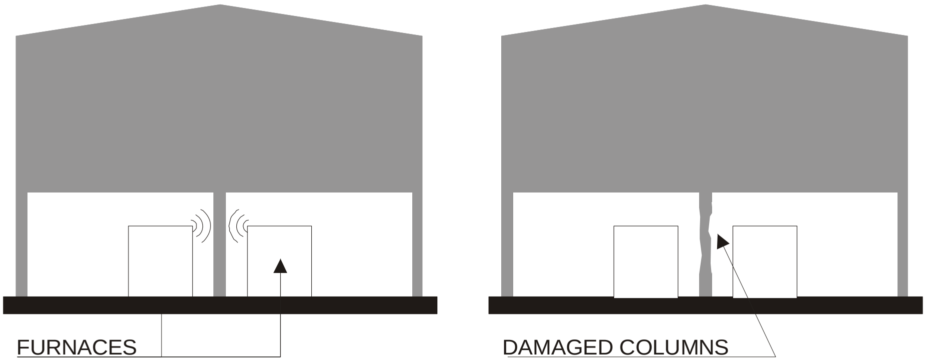

Fig. 1 Concrete aging as a result of its subjection to high temperatures for a long period of time

Design errors should not be neglected either. There are cases when the design engineer accepts improper structural systems created by architects or when the investor changes the destination of the building at a later stage leading to a loading underestimation [4].

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In some thermoelectric power plants constructed in Romania between the 1950s and 1960s, the boiler rooms have been designed in such a manner that the structure of the boilers supports the hall roof as well. The magnitude of the seismic action was ignored in the design phase, so that, during the 4th of March 1977 earthquake, the failure of some component elements of the boiler produced important degradations to the structure of the boiler room, figure 2. As a result, the truss was pulled out by the boiler and the most important effect was the failure of the joints with the intermediate section of the building [6].

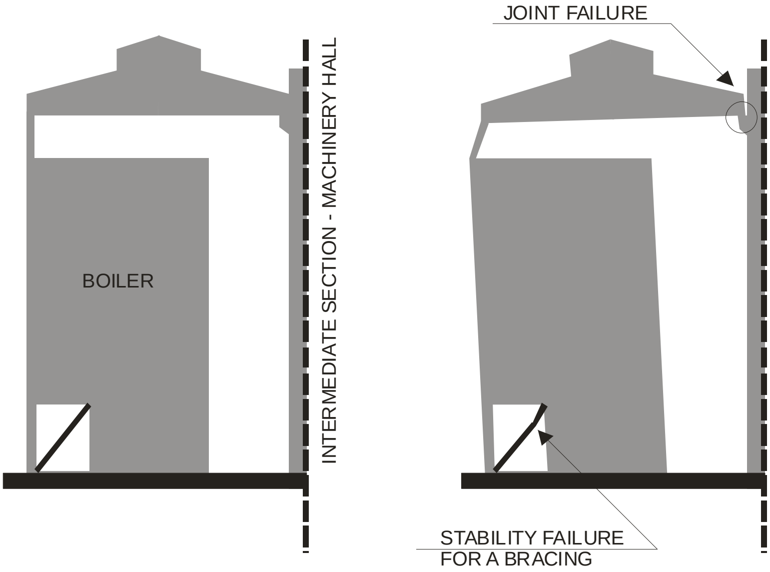

Fig. 2 The bracing failure into a boiler in the thermoelectric station

In most cases the design errors become obvious when extraordinary actions occur. Through their secondary effects, these may lead to important deteriorations.

Even though the hall in figure 3 for a paper factory was well built, an earthquake weakened it and it has failed, mainly due to a conceptual error. Since the contiguous components supporting the roof had very different degrees of stiffness, they didn't work together, the joints of the caissons weakened and the resulted displacement led to their partial collapse. Part of the caissons fell over the rolling girder; others broke and fell over the paper machine [4].

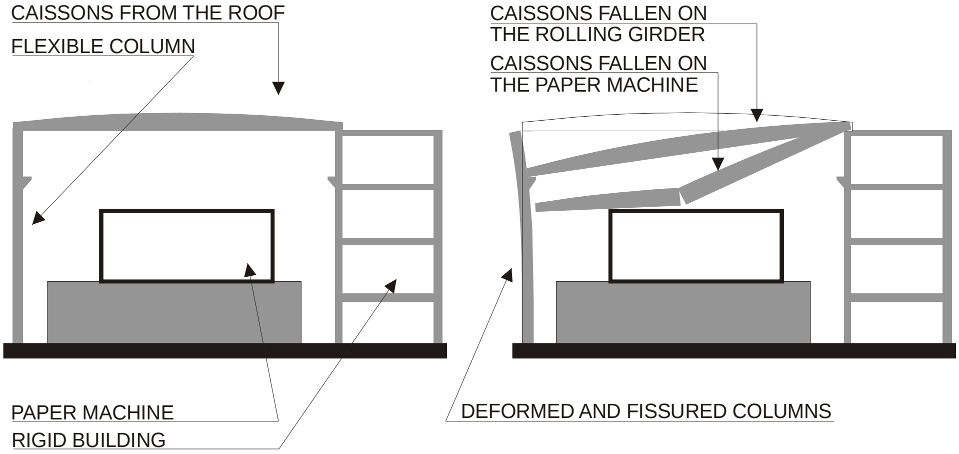

Fig. 3   The collapse of the roof caissons of a hall after an earthquake because of the different stiffness of contiguous structures

There are many situations where water leakage from the water-supply network systems decreases the load-bearing capacity of the foundation soil. A relevant example is a framed structure block of flats located in Iasi, supported on a network of foundation beams (figure 4.a). The building leant during the execution phase due to the soil failure caused by a water leakage coming from one of the adjacent ducts. This event damaged the basement floor, figure 4.b.

The building has been rehabilitated by eliminating the water leakage (preventing a potential future soil failure) and digging in the opposite area for balance. After bringing the structure back to its vertical position, a mat foundation including the existing beam network has been built, figure 4.c [4].

Excluding the fact that the applied seismic design load had not covered the total spectrum of dynamic characteristics other causes for structural damages have been detected, most of them design errors. Among these, the lack of measures to obtain suitable ductility for structural elements needs to be particularly mentioned.

Fig .4 Failure of foundation soil due to sewage water infiltration: a. initial stage, b. soil failure, c. rehabilitated structure

Although there are many other examples, we would like to mention the reinforced concrete block of flats located in Valea Calugareasca, figure 5. The ground floor was conceived for commercial purposes and the other three floors for residential spaces divided into flats. Due to insufficient steel stirrups, the ground floor columns failed and the building shrank by one floor during the 4th of March 1977 earthquake [7].

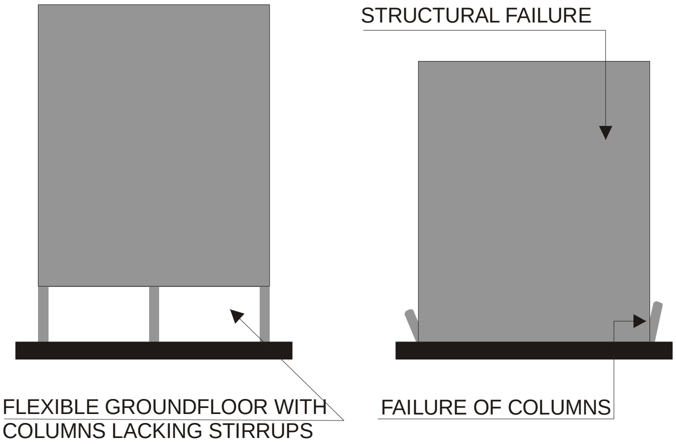

Fig. 5 Failure of insufficiently reinforced columns of a block of flats during an earthquake

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2.3. CAUSES OF STRUCTURAL FAILURES

The majority of the structural failures happened during the years could have been avoided if available knowledge had been utilised in a correct way. About half of the failures are caused by errors in design or lack of design. One quarter of the failures was due to errors made on the building site. This fact more or less confirms the conclusion made by Kaminetsky [8] that for structures of all types of materials, almost all failures occur due to human errors. According to Kaminetsky [8], human errors can in turn be related to one or several of the following categories:

1. *Errors due to ignorance*: Humans responsible for various tasks in the building process have inadequate training in relation to the tasks they have to fulfil. This can be improved by education and training.
2. *Errors due to carelessness and negligence*: The performance of humans in the building process is non-professional and they do not perform their tasks seriously enough. This may be improved by independent control measures.
3. *Errors by "intent"*: Responsible personnel consciously decide to take short-cuts and risks in order to save money and/or time in the building project.

In figure 6 the distribution of causes of the failures and errors is illustrated. It can be seen that ignorance and insufficient knowledge are the most important contributions to failures and errors, followed by causes as underestimation of effects, failing to remember, incorrect transfer of responsibility and simply not knowing.

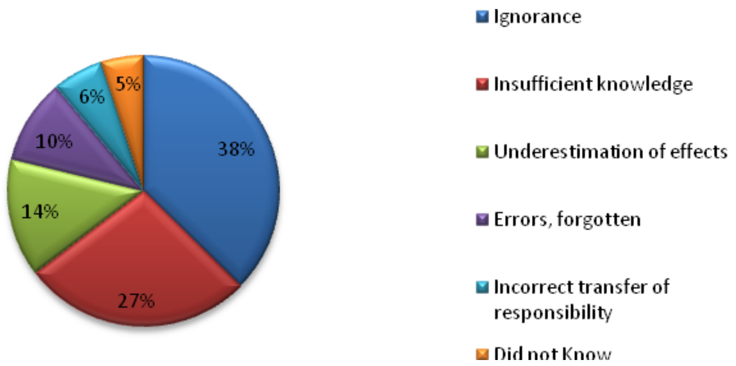

Fig. 6 Distribution of causes of the failures and errors [9]

It should be noted that failures due to human errors cannot be counteracted by increasing safety factors or safety levels in structural codes.

It is more or less impossible to eliminate the risk of human errors completely but their frequency can be reduced by improving building process management, where an important element is to assign or commission personnel with adequate experience and education as well as with the right attitude to the tasks at hand.

Training, education and control measures should be especially focused on those technical aspects found to be the most common causes of failures. Training of engineers and control in the design phase should have high priority, since the most frequent errors are made in this phase.

In figure 7 it is illustrated whether and how the failures and errors might have been avoided. From this figure it is evident that control is one of the most important risk treatment measures, a fact, which is generally realized by most engineers, but unfortunately not fully appreciated. Often, control is considered an obstruction of the routines of the daily work. However, normal care or precaution also plays an important role. It is seen that a smaller part of the failures and errors is actually unavoidable. Thus, the potential for improvements is large.

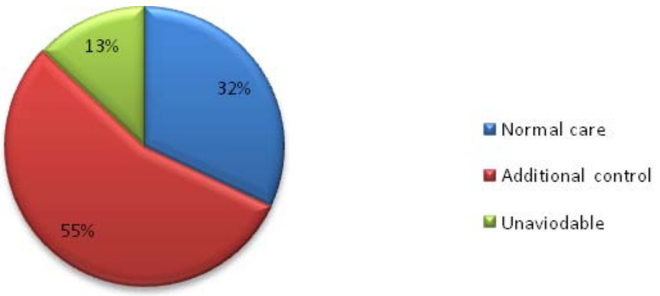

Fig. 7 Relative distribution of the risk treatment measures [9]

3. THE ROBUSTNESS CONCEPT

Robustness definitions used for technical applications vary greatly starting from the engineering domain up to the similar concepts from the control theory, statistics, linguistics, etc.

The robustness of a structure has to be defined as being the capacity of the system to keep its structural integrity for any kind of action that may occur during its service life.

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 (which also includes the infrastructure), closings, finishes and ending with the installations.

A robust system has to keep its integrity even in the case of accidental actions like powerful earthquakes, landslides, storms, explosions, etc.

Robustness must not be understood as an over dimensioning 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 unfavorable situation.

The robustness of a structure can be improved through periodical inspections as well as adequate maintenance measures during its service life. In this context we have to keep in mind the maintenance or repair costs, too. So, a robust system has to call for minimum maintenance costs during its life span and for reduced costs to put into service again in case of an accident.

In a perceptual context, something is robust if it is "*vigorous*", meaning that it gives to the person watching it a sense of safety and it doesn't create states of physical discomfort, although sometimes the appearances can be misleading through the lack of perception upon the defects. If we extend this aspect to the buildings domain, robustness means the achievement of a "clear" structural system which can be easily apprehended and which can give a sense of safety. Complex structures, with hidden load bearing elements, even if from aesthetic point of view are appreciated, can lead to deficient behavior to particular actions.

4. DISPROPORTIONATE FAILURE

Disproportionate failure of a structural system can be described as the situation where the total damage (or risk) resulting from an action is much greater than the initial damage caused by the action which acted upon only locally or on a component of the structural system.

Progressive collapse, where the initial failure of one or more components results in a series of subsequent failures of components not directly affected by the original action is a mode of failure that can give rise to disproportionate failure, like a "domino" game [2].

Fig. 8 Progressive collapse simulation through a domino game

Progressive collapse issues came to the fore of engineering thinking following the partial collapse of the Ronan Point building in London in 1968, due to an internal gas explosion. The explosion resulted in a loss of support for the five stories above, and the weight of the fallen top floors caused the subsequent collapse of the floors below. Thus, the entire collapse of one corner of the building was produced. Although progressive failure, especially on structures during construction, had occurred previously, they had not interested engineers and regulators in the way the failure of the occupied 22-storey Ronan Point building did. The main reason for the sudden importance was not only the potential for fatalities and injuries during failure of residential building of this kind, but also the public perception issues given rise to by the major parliamentary inquiry that took place [2].

Following the recommendations of the official inquiry into the Ronan Point failure, the world's first-ever robustness related regulations came into force in the UK. Although those requirements had been developed in relation to the hazard of internal gas explosions, they were also considered to provide a minimum safety level under impact actions and other extraordinary action situations [2].

The principles behind the robustness related requirements currently implemented in various countries originated from the UK requirements which were developed via much theoretical and experimental studies and professional debate. The UK's robustness requirements have also been later tested on some full-scale building for specific disaster situations. These requirements have been also indirectly and successfully tested with respect to a new hazard, bomb explosions [2].

Whereas renewed interest in robustness was generated by the bombing of the Alfred P. Murrah Federal Building in Oklahoma, USA in 1995, it was the 2001 World trade Center incidents (9/11) that created, like no other in the past, a significant interest on robustness and progressive collapse issues.

The 9/11 incidents disaster has made engineers and regulators ask questions on:

- the adequacy of national building regulations;

- the adequacy of current knowledge in relation to severe destructive attacks and combinations of serial extraordinary actions;
- decision making in the presence of alternative solutions;
- public perception issues related to safety [2].

5. CURRENT PRINCIPLES OF DESIGNING FOR ROBUSTNESS

Despite the importance of robustness for structural design such requirements are still not substantiated in clear detail, nor have the engineering profession been able to agree on an interpretation of robustness which facilitates its quantification [10]. The structural reliability is the subject of continued intense interest for the structural engineering profession. Over the last half century, developments in the field of structural reliability have been substantial and as a result of this most codes for the design and assessment of structures take basis in quantitative requirements to structural reliability [11].

Design codes have traditionally been developed with the main focus on the structural reliability for individual failure modes or components of structures. System effects and reliability of system failure modes such as full collapse are usually treated only by specifying that structures should be design treated such that they are sufficiently robust. In general, very little guidance is provided by design codes on how to assess *robustness* and also in regard to criteria for sufficient robustness [10].

Typical requirements to structural reliability are provided in terms of maximum acceptable annual failure probabilities in dependency of the consequences associated with structural failure and sometimes also in dependency of the relative costs associated with improvement of reliability. In this way, reliability requirements are identified for both structural components and structural systems [11].

Normally, design codes take basis in a design philosophy where the individual components 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 designs in this way explicitly take into account the relevant load scenarios including environmental extreme loads, accidental loads, earthquake loads and the effect of degradation [11].

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 effect the engineers and the owners of structures have little help on the quantification of robustness and no clear definition on acceptability of robustness [11].

The currently used methods of designing for robust structural systems that originated in the UK have now been adopted by various countries with slight modifications, where appropriate, by other countries and international codes such as the Eurocodes [2].

Nowadays, in Romania, the basic material for the understanding, assessment and improvement of robustness of structures is the national design code CR 0-2005 - "Cod de proiectare. Bazele proiectării structurilor în construcţii". This is the official Romanian version of EN 1990-2002 - "Basis of Structural Design" which provides the fundamental principles for achieving robustness. The strategies and methods to obtain robustness and the actions to consider are provided by EN 1991-1-7 Eurocode 1: Part 1-7 "Accidental Actions" [12-14].

In Eurocode 1991-1-7 (CEN 2006), where designing for robustness is introduced, there are two design situations to be considered:

- designing against identified accidental actions;
- designing against unidentified actions, where the designing against disproportionate collapse, or for robustness, is important [14].

As obvious from their names, these are situations where the designer is aware or not aware, respectively, of the possible hazards that could test the robustness of a particular structural system. The hazard(s) to be considered can be:

- known ordinary and extraordinary actions;
- known and unknown quality and gross errors from human inactivity or activity;
- unknown hazards that may pose a danger to a particular structure or structures in general [14].

The methods used to design for robustness of a structural system can be divided into several levels based on the potential consequences of structural failures, categorized in terms of a building's Consequence Class (CC):

CC1: low consequences - no special requirements;

CC2: medium consequences - handled using simplified equivalent static analysis methods or by prescriptive rules;

CC3: high consequences - case by case reliability or risk analysis. It may require refined methods of structural analysis [14].

The strategies for designing a robust structural system can include one or more of the following:

i. prevent or reduce the action;
ii. design the structure/key elements to sustain the action;
iii. design the structure to have a minimum level of robustness by either providing alternative load paths or using prescriptive rules which provide sufficient redundancy and ductility.

In the third method above, the principle of prevention of disproportionate collapse is utilized. According to this principle, a localized failure due to an (accidental) action may be acceptable, provided it will not endanger the stability of the whole structure and that the overall load-bearing capacity of the structure is maintained and enables necessary emergency measures to be undertaken. The proportionality of failure can be checked in practice by assessing the additional damage that can result when each load-bearing member is notionally removed, one at a time, from the structure. The damage is considered to be disproportional if it exceeds that given in the code. If the damage is disproportional, then the particular load-bearing member is either designed as a strong “key element” or protective measures are undertaken to reduce its probability of failure to an acceptable lower level [2].

6. CONCLUSIONS

As previously stated, the robustness of structures first received significant attention 40 years ago. Also the recent terrorist attacks have resulted in renewed international interest and resources being devoted to the topic. Despite its importance, the engineering profession has yet to reach consensus on quantification of robustness for use in design codes and construction projects. The only specific requirements are relating to the increasing of the safety factors which should compensate for a multitude of real causes to generate a reliable system.

It should be noted that robustness should be distinguished from accidental loads although some of the design procedures and measures are similar. As described above all structures should be robust regardless on the likelihood of accidental loads.

The Eurocode and the other national building codes such as the *UK Building Regulations* (ODPM 2004) and the *Danish Code* (DS409 2006) provide comprehensive details for designing structures against disproportionate failure and consider consequences indirectly, but no guidance is available in them for conducting comprehensive analyses of structural systems and the consideration of risks on a probabilistic basis.

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

In this context, the COST Action "TU 0601: Robustness of Structures" aims to develop a foundation for treatment of structural robustness in future structural design codes. Building on the expertise and experience of European experts and close coordination with the European and international engineering associations such as IABSE, ECCS, CIB, fib, Rilem, ISO and the Joint Committee on Structural Safety (JCSS), a new risk-based approach for assessing robustness will be developed and a model code will be produced to guide improvements in future Eurocode revisions. This should greatly improve the efficiency of structural design, ensure the rational treatment of structural safety, safeguard the qualities of the environment, protect societal functionality and economical assets and is expected to increase the international competitiveness of the European building and construction sectors.

References

1. http://www.cost-tu0601.ethz.ch/
2. Canisius, T.D.G., Sorensen, J.D., Baker, J.W. (2007). "Robustness of Structural Systems - A new focus for the Joint Comitee on Structural Safety (JCSS)", in 10th International Conference in Aplication of Statistics and Probability in Civil Engineering (ICASP10), Tokyo, Japan. ISBN 978-0-415-45211-3.
3. Frühwald, E., Serrano, E., Toratti, T., Emilsson, A., Thelandersson, S., (2007). "Design of Safe Timber Structures- How can we learn from structural failures in concrete, steel and timber?"; Report TVBK-3053, ISSN 0349-4969, ISNR: LUTVDG/TVBK-3053-SE (228), Division of Structural Engineering, Lund University, 1-8.
4. Budescu, M., Ţăranu, N., Ciongradi, I.P., Lungu, I., Ciupala, M.A., Isopescu, D., Oprişan, G.; Gavrilaş, I.
5. (2003). "Building Rehabilitation", Editura Societăţii Academice "Matei-Teiu Botez", Iaşi. ISBN 973-7962-26-5.
6. Orlovschi, N., Leonte, C., Ionescu, C., Budescu, M., (1978) "Efectul acţiunii seismice a variaţiilor de temperatură asupra comportării unei structuri în cadre de beton armat", Simpozionul naţional - Interacţiunea construcţiilor cu mediul înconjurător V, 13, Iaşi.
7. * * *, CET Borzeşti, Expertiză tehnică, ISPE, 2000.
8. * * *, Cutremurul de pământ din Romania de la 4 martie 1977, Editura Academiei, 1982.
9. Kaminetzsky, D., (1991). "Design and Construction Failures – lessons from forensic investigations", McGraw-Hill, New York.
10. Matousek, M., Schneider, J., (1976). "Untersuchungen zur Struktur des Sicherheitsproblems bei Bauwerken"; Inst. für Baustatik und Konstruktion, ETH Zürich, Switzerland.
11. Faber, M. H. (2007). "Risk and Safety in Civil Engineering" – lecture notes. ETH Swiss Federal Institute of Technology, Zürich, Switzerland.

12. Faber, M.H., Maes, M.A., Straub, D., Baker, J. (2006). “On the Quantification of Robustness of Structures”. Proceedings of OMAE2006, 25th Offshore Mechanics and Arctic Engineering Conference, Hamburg, Germany, June 4-9 [OMAE2006-92095].
13. CR 0-2005 – “Cod de proiectare. Bazele proiectării structurilor în construcţii”.
14. EN 1991-2002 – “Basis of Structural Design”.
15. EN 1991-1-7 Eurocode 1: Part 1-7 “Accidental Actions”.