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STRUCTURAL ROBUSTNESS PROVISIONS IN MODERN DESIGN CODES AND REGULATIONS

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Abstract. The concept of structural robustness received significant attention for the first time about forty years ago, after the partial collapse of Ronan Point building in UK. In the recent years, the interest for studying the robustness of structures has intensified and significant research activities have been carried out for achieving a better understanding on the various aspects implied by this new concept in civil engineering domain. These efforts resulted in a set of several useful recommendations regarding the possibilities to achieve robust structures. The need for studying the concept of robustness appeared from the fact that structural design codes are predominantly based on the design of structural members or the consideration of individual member failure modes. Modern structural design codes and regulations contain only some general requirements for robustness, beside the more specific provisions regarding the structural safety, serviceability and durability. These robustness requirements generally state that the consequence of damages to structures should not be disproportionate to their causes. Although the robustness concept is very important for structural design, specific requirements are actually still not underlined in such a comprehensive way in current building codes.

This paper summarizes the revised definitions and provisions regarding the structural robustness implemented in some modern design codes and regulations.

Key words: structural safety; disproportionate collapse; vulnerability; risk assessment; theoretical framework.

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1. Introduction

The main objective of the modern codes is to provide a basic design framework to asses and ensure a suitable degree of structural safety by efficient and cost effective material using. The requirements necessary to answer this aim must have a standard safety format. They have to include models of material and structural behaviour and appropriate safety factors, but also provisions for an adequate degree of robustness. A further category of the existing robustness related stipulations in the design codes is needed to improve the general strategy actually used to achieve structural safety and robustness.

A review of the European standards dealing with the various aspects related to the robustness of structures has been carried out and is summarized in the present paper. The robustness provisions in the current design standards are classified using different aspects of risk management in structures: risk treatment, risk control, causing event or structure exposure, risk reducing possibilities and the structure life cycle phase at which the provision is suited to be applied.

2. Definitions of the Concept “Robustness”

One of the main issues related to the robustness of structural systems is that its description varies so much with context that it is very difficult to put in an order all its diverse aspects, relationships and ramifications. The most used definitions of robustness are quite similar to each other, especially those provided by the design codes, where there are used different related terms like structural robustness, structural integrity or vulnerability of buildings, but also prevention of progressive collapse phenomenon.

Robustness is an inherent property of systems that enables them to survive unforeseen or unusual events without excessive damage or loss of function. This is a requirement of the modern building codes, but there is not provided a precise guideline on how to achieve structural robustness. Also, the design codes may not always include all relevant exposure or design situations which may affect the integrity of the structural performance (Ioniță *et al*., 2010).

Discussions on robustness issue frequently occurred in different papers related to the progressive or disproportionate collapse of buildings. A selection of definitions is listed in Table 1. It is necessary to make a clear distinction between these two different concepts: *collapse resistance* and *robustness*. Both terms are illustrated in more detail in Fig.1 (Starossek & Haberland, 2010).

Table 1
Definitions Related to the Concept Robustness in Civil Engineering Domain (Starossek & Haberland, 2010)

Source	Definition
Eurocode 1. Part 1-7, 2006	"Robustness. The ability of a structure to withstand events like fire, explosions, impact or the consequences of human error without being damaged to an extent disproportionate to the original cause".
GSA, 2003	"Robustness. Ability of a structure or structural components to resist damage without premature and/or brittle failure due to events like explosions, impacts, fire or consequences of human error, due to its vigorous strength and toughness".
JCSS, 2008	"The robustness of a system is defined as the ratio between the direct risks and the total risks (total risks is equal to the sum of direct and indirect risks), for a specified time frame and considering all relevant exposure events and all relevant damage states for the constituents of the system".
Agarwal and England, 2008	"Robustness is […] the ability of a structure to avoid disproportionate consequences in relation to the initial damage".
Biondini *et al.*, 2008	"Structural robustness can be viewed as the ability of the system to suffer an amount of damage not disproportionate with respect to the causes of the damage itself".
Bontempi *et al.*, 2007	"The robustness of a structure, intended as its ability not to suffer disproportionate damages as a result of limited initial failure, is an intrinsic requirement, inherent to the structural system organization".
Val & Val, 2006	"[…] ability of a structure to absorb […] the effect of an accidental event […] without suffering damage disproportionate to the event that caused it". "[…] ability of the structure to withstand local damage without disproportionate collapse […]".
Vrouwenvelder , 2008	"The notion of robustness is that a structure should not be too sensitive to local damage, whatever the source of damage […]".

By summarizing these definitions, robustness refers to the ability of a structure to resist without disproportionate damage to either abnormal events or an initial damage. For the assessment of robustness it is necessary to take into consideration the possible scenarios which may lead to collapse, their probability of occurrence as well as their consequences. The probability of disproportionate collapse, $P[C]$, caused by the exposure to an abnormal event, E, may be split according to Fig. 1. It represents in fact the product of the following partial probabilities: $P[E]$ – the probability of occurrence of an abnormal event, E, that may affect the structure; $P[D|E]$ – the conditional probability of initial damage, D, produced by the abnormal event E; and $P[C|D]$ – the conditional probability of a disproportionate spreading of structural failure, C, as a consequence of the initial damage, D (Starossek & Haberland, 2010).

As illustrated in Fig. 1, in order to achieve robustness, the *disproportionate failure spreading* has to be prevented by controlling the global system behaviour. The structural vulnerability is associated with the failure initiation prevention by controlling local component behaviour.

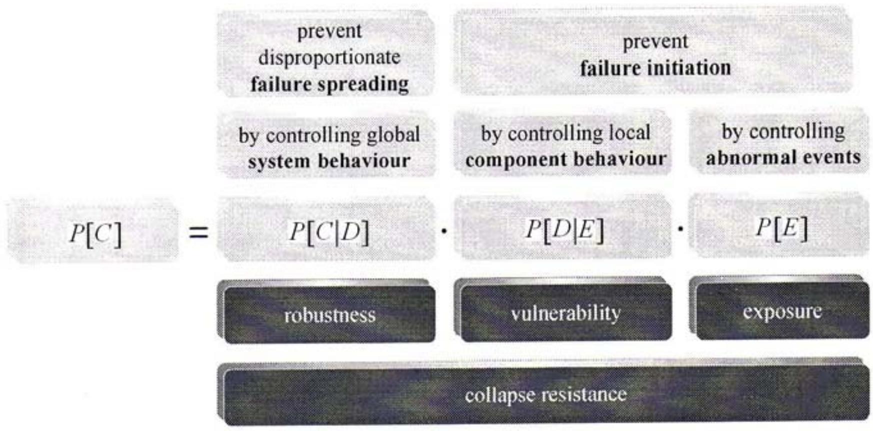

Fig. 1 – Design strategies to achieve collapse resistance.

Consequently, it can be stated that the robustness is a desirable system property which may be assessed as the product of another indicators. It represents in fact a way of ensuring structural safety above the existing provisions from the traditional design codes.

3. Implementation of Structural Robustness in the Design Codes

The study of structural robustness issue and of the associated aspects has attained an increased interest, especially because of the serious consequences related to failure of different types of structures.

The fundamental design specifications in many building codes are related to the design and check of each structural component, element or connection to have sufficient reliability. It should be noted that systems redundancy is closely related to robustness. Robustness is required in those situations in which exposures produce local damage to the structural system, and where this damage may further lead to disproportionate collapse of the structure (Kirkegaard & Sorensen, 2011).

Anyway, additional requirements and measures are needed to ensure that the structure considered as an intrinsic system has sufficient reliability. Supplementary provisions are also necessary to minimize or even to eliminate the effect of design errors, execution errors, unexpected deterioration of components etc. Until now, the researchers and the structural engineers could not agree on a common interpretation of robustness so that to facilitate its quantification. Robustness requirements in modern codes should cover these issues in parallel with quality assurance terms and best practices application in the design, execution, operation and maintenance phases as illustrated in Fig. 2 (Dean *et al.*, 2011).

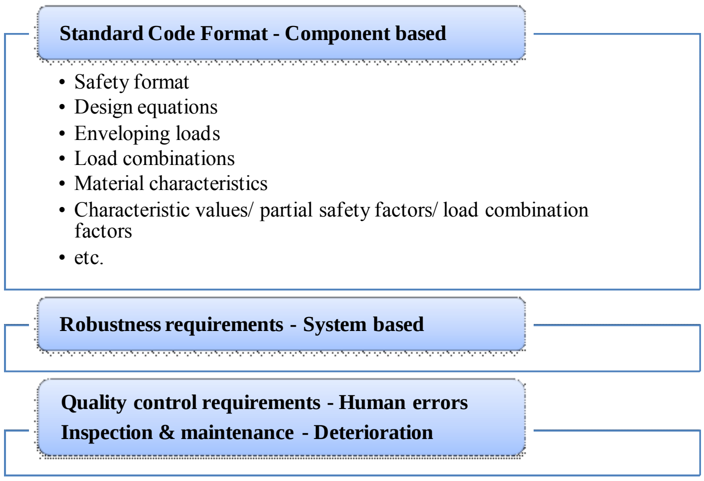

Fig. 2 – Code based design steps.

3.1. Implementation of Structural Robustness in UK Codes

Robustness has been considered a desirable property of structures after several high structural system failures, such as the Ronan Point Building in 1968, when the consequences have been considered to be unacceptable related to the initiating damage. The UK regulations related to structural robustness have been implemented following the progressive partial collapse of one corner of Ronan Point building. The event had a significant effect on the engineering community in UK and this led to some revisions and changes in the Building Regulations. The 1976 Building Regulations stipulated that a building should be so constructed so that the structural failure caused by the removal of any member from a storey should be localized and limited to a certain area of that storey. Additional revisions have been made following the building sensitivity decrease to disproportionate collapse.

The guidelines from the Building Regulations have been included by several structural design codes.

In June 2004, Approved Document A (2004 Edition) has been published. The new provisions could be applied from 1st of December 2004. Section 5 of the document, called "*Reducing the sensitivity of the building to disproportionate collapse in the event of an accident*", added major changes to the previous UK practice code.

The document offers an approach for ensuring that a structure is enough robust to sustain a limited damage or a local failure, depending on the building class, without triggering the overall collapse. It makes a new classification of buildings and the corresponding design requirements for these building classes. All these provisions are closely related to some of the EN1991-1-7guidelines. Therefore, the relevant UK practice code provisions will be next presented through the equivalent EN1991-1-7 recommended design specifications.

3.2. Implementation of Structural Robustness in Eurocodes

The robustness requirements are specified in most building and civil engineering structures design codes like in the two Eurocodes: *EN 1990 —Basis of Structural Design* and *EN 1991-1-7—Accidental Actions*.

EN 1990—Basis of Structural Design describes the fundamental principles regarding the robustness of structures. In this code it is stated that „*a structure shall be designed in such a way that it will not be damaged by events like fire, explosions, impact or consequences of human errors, to an extent disproportionate to the original cause*".

EN 1991-1-7—Accidental Actions provides the potential strategies to assess structural robustness. This design code makes a classification of the identified and the unidentified actions. The actions that should be considered in different design scenarios are the following:

a) *designing against identified accidental actions*;

b) *designing against unidentified actions*. In this second case, the design against disproportionate collapse, or the design for robustness, presents a major importance.

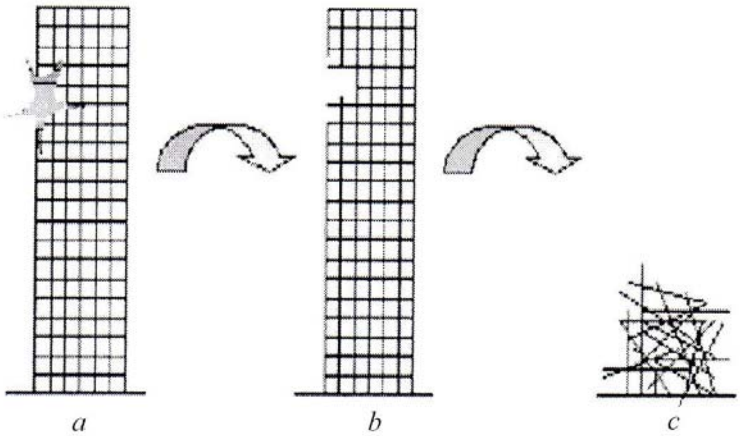

Fig. 3 – Illustration of the basic concepts in robustness.

An illustration of the concept from *EN 1991-1-7—Accidental Actions* is shown in Fig. 3. It suggests that because of an exposure event of any kind, a local damage may occur. This local damage is in fact the direct consequence of the exposure. Starting from this damage state, the structure may survive if it is enough robust or a considerable part of it may collapse.

The basic concepts illustrated in this figure are

a) *the exposure phase*;

b) *the occurrence of a local damage caused by the exposure* – as the direct consequence of the exposure;

c) *the overall or extended collapse of the structure* following the local damage – as the indirect consequence of the exposure.

Robustness requirements are especially related to the last two scenarios. These requirements are concerned on the possibilities of avoiding the overall collapse due to a local damage.

3.3. Implementation of Structural Robustness in Danish Codes

The requirements regarding the robustness in the Danish codes are focused on the reduction of the structures sensitivity when they are exposed to unforeseen loads and damages that are not usually provided in codes. Structural robustness is considered as a general requirement of the structures and not a requirement related to specific loads, such as accidental loads. This happens because it is considered that the structures should be anyway designed to withstand this kind of actions.

Table 2
Measures for Improving the Structural Robustness

Measure	Example
Load determination	Imposed load (*e.g.* operation instructions should specify allowable loads); accidental loads (*e.g*. all imaginable accident scenarios should be considered);
System configuration	Use of parallel systems; non-sensitive systems with respect to settlements of supports (*e.g*. statically determinate systems are normally not sensitive with respect to settlements)
Statically indeterminate systems	Redistribution of internal sectional forces and/or internal stresses
Ductility	Ductile materials and connections
Solidity	Large dimensions and masses; reduced slenderness; over sizing (*e.g.* key elements are given larger dimensions than required by the code; connections are given a capacity similar to the capacities of the adjacent elements although not required)
Coherency	*In situ* cast concrete structures (normally high degree of coherency in horizontal and vertical direction)
Investigation and control	Critical investigations during design in order to identify details and elements important/vital for the reliability and robustness of the system, ensuring accessibility during operation for inspection; quality control during execution; Control during operation (inspection procedures, etc.)

In the Danish code called "*Code of practice for the safety of structures*" DS409 it is stated that a structure is robust

a) if the essential parts of a structure needed for its safety have just a low sensitivity to unforeseen loads and damages;

b) if the failure of a limited part of the structure will not trigger the entire collapse of the structure.

The Danish code also provides a series of measures that may improve the structural robustness. These are summarized in the Table 2 (Sorensen, 2008).

3.4. Implementation of Structural Robustness in Italian Codes

The Italian code called "*Norme Tecniche per le Costruzioni*" (2005) has been developed within a performance-based design philosophy. Specific references to the term robustness are mentioned in Chapters **2** and **4** of this code. Of course, approaches to the concept are found in the entire document. These are related to new constructions, but also to the existing construction or to the foundation works.

In Chapter **2** of the code, three main aspects are stated

a) the design lifetime, which has to be established by the owner and also by the designer of the structure;

b) the class of the construction, which also has to be established by the owner and the designer;

c) the target reliability levels, which are established on a yearly base.

The Italian code also stipulates that in the design phase the requirements from Table 3 (Calzona &Casciati, 2005) have to be met. This is actually the way in which the concept of robustness comes up for discussion.

Table 3

Limit States and Robustness Analysis in the Italian Practice Code

Requirement	Example
Safety with regard to Ultimate Limit States (ULS)	– collapses, loss of equilibrium and serious total or partial instability which may endanger persons or result in the loss of goods, or cause serious environmental and social harm, or put the structure out of service
Safety with regard to Serviceability Limit States (SLS)	– all the requirements which can guarantee the performance levels laid down for the operating conditions
Robustness with regard to accidental actions	– the ability to avoid damage disproportionate to the scale of the triggering cause such as fire, explosion, impact or the consequences of human error

According to the Table 3, the robustness assessment supposes several specifications, such as the conceiving way of the structural system which has to cover a wide range of exposure scenarios.

4. Conclusions

The structural robustness is a desirable system property which may be assessed as the product of another indicators such as structural risks, redundancy, ductility, consequences of structural members damage or of the entire system failure, loads and resistance variability, dependency on the failure modes, joint behaviour characteristics, abnormal loads probability, monitoring and structural maintenance strategies, overall structural consistency.

It is obvious that the robustness is a topic of extreme importance, but the current provisions presented in the design and practice codes and standards are unsatisfactorily. A general agreement on the definition and assessment of structural robustness may be observed in all the design codes provisions. But although there is conformity on the properties of structures which may improve the structural robustness, no specific details could be established for its quantification.

In order to come up these deficiencies, the modern design codes will have to develop a theoretical basic framework with explicit design decisions and assumptions for the assessment of robustness and they have to establish a series of acceptance criteria for structural robustness. A set of acceptance criteria may be very useful for the further development of the corresponding practical methods necessary to ensure reliable levels of robustness, even from the design phase. Design strategies for maintaining the robustness of the existing structures throughout their service life will be also very useful if they will be implemented into the new generation of practice codes.

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PREVEDERI ALE NORMATIVELOR MODERNE DE PROIECTARE CU PRIVIRE LA ROBUSTEȚEA STRUCTURALĂ

(Rezumat)

Conceptul de robustețe structurală a primit pentru prima dată o atenție deosebită în urmă cu aproximativ patruzeci de ani în urma producerii colapsului parțial al clădirii Ronan Point din Marea Britanie. În ultimii ani s-a accentuat interesul cu privire la studierea robusteții structurilor şi au fost investite eforturi semnificative pentru o mai bună aprofundare a variatelor aspecte pe care le implică acest nou termen în domeniul ingineriei civile. Rezultatul acestor eforturi a constat în obținerea unui set de recomandări utile cu privire la modalitățile de proiectare a structurilor robuste. Necesitatea de a studia conceptul de robustețe a fost o urmare a faptului că normativele de proiectare structurală se bazează, în principal, pe proiectarea elementelor structurale sau pe considerarea modurilor individuale de cedare a acestora. Normativele moderne de proiectare structurală cuprind doar câteva cerințe generale despre robustețe, în afara

prevederilor mult mai precise cu privire la securitatea structurală, siguranţa în exploatare şi durabilitate. Aceste cerințe referitoare la robustețe prevăd, de regulă, faptul că urmările degradărilor structurilor nu ar trebui să fie disproporţionate în raport cu cauzele care le-au produs. Deşi robustețea joacă un rol deosebit de important în proiectarea structurală, în normativele actuale încă nu sunt tratate în detaliu asemenea prevederi specifice.

Lucrarea sintetizează definițiile şi prevederile revizuite, implementate în câteva normative moderne de proiectare cu privire la robustețea structurală.