ROBUSTNESS OF REINFORCED CONCRETE STRUCTURES - BASIS OF ASSESSMENT



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Abstract

Recent developments in high-performance concrete and construction technologies facilitate design of complex structures that may be vulnerable to unfavourable effects of extreme events. Failures of structures exposed to such events may hardly be prevented. However, for sufficiently robust structures, failure consequences can be significantly reduced. The paper attempts to provide summary of present achievements in the assessment of structural robustness. It appears that structural robustness can become a key concept in design of innovative concrete structures, but quantification and methods for assessment of robustness are not yet sufficiently unified.

Keywords: Robustness, Structural models, Design principles

1 Introduction

Developments in high-performance concrete, construction technologies and methods of structural analysis enable to design increasingly complex and slender structures. Such structures may be vulnerable to unfavourable effects of extreme events, human errors or excessive settlements.

Failures of structures exposed to extreme events can hardly be completely prevented. However, in case of sufficiently robust structures, consequences can be significantly reduced. Despite many significant theoretical and technological advances over the recent years, structural robustness is still an issue of intensive research. Requirements and methods for the assessment of robustness in present codes are vague and seem to be insufficient for practical use. Therefore, the European research project COST Action TU0601 has been initiated to establish better understanding of the aspects related to robustness. The paper, mostly based on working materials of the Action, attempts to summarise findings concerning structural robustness concepts. Decision making concerning robustness measures is illustrated in Annex A (attached to the electronic version on CD-ROM).

2 Definitions

EN 1990 (2002) indicates that sufficient structural reliability can be achieved by suitable measures such as ensuring an appropriate degree of robustness (structural integrity). However, the definition of structural robustness and operational rules for its achievement are not provided. In EN 1991-1-7 (2006) robustness is defined as 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. In SEI/ASCE (2010), robustness is a property of the structure and the extent of the initial damage. If the initial damage is specified as a notional damage, its causes are immaterial and robustness becomes a purely structural property. The definitions of robustness used in an engineering society may be divided into the definitions in a narrow sense (indicator of the ability of a structure to perform adequately under accidental situation) and definitions in a broad sense (indicator of the ability of a system containing a structure to perform adequately under accidental situation of the structure).

It follows that robustness is a complicated concept that is not understood uniformly. Precise definition is urgently needed. **Fig. 1** illustrates the basic concept in robustness - robustness requirements are related to steps b) and c):

a) Exposures,
b) Local damage due to exposure - direct consequences,
c) Total (or extensive) collapse following the local damage - indirect consequences that may include societal (fatalities, injuries), economic (structural and demolition costs, business interruption), ecological (release of dangerous substances), psychological (loss of reputation) and other consequences.

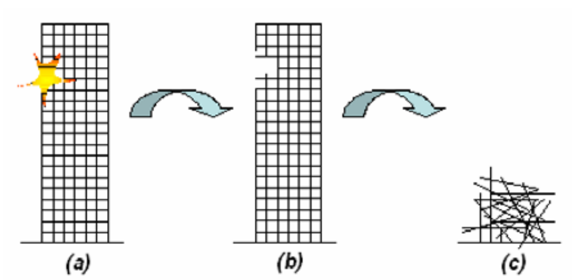

Fig. 1 Illustration of the basic concept in robustness, EN 1991-1-7 (2006)

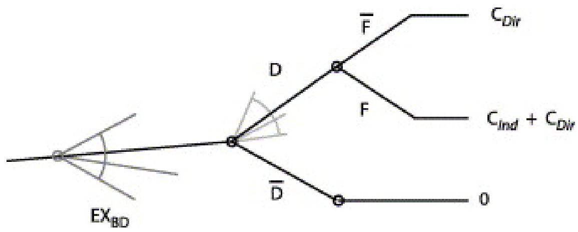

Fig. 2 Event tree for quantification of robustness proposed by Baker et al. (2008)

3 Quantification of robustness

Available robustness indices can be divided in three levels with increasing complexity:

1. Deterministic such as the deterministic reserve strength ratio, ISO 19902 (2007),
2. Reliability-based such as the redundancy index derived from failure probability of a damaged and intact structural system, Frangopol and Curley (1987),
3. Risk-based. Baker et al. (2008) proposed a definition of a risk-based index - ratio of the direct risk over the total (direct + indirect) risk. Consequences are divided into direct consequences (proportional to the initial damage) and indirect (disproportional) consequences.

The assessment begins with the consideration and modelling of exposures (*EX*) that can cause damage to the components of the structural system, see **Fig. 2**. The term “damage” refers to reduced performance or failure of individual components of the structural system. After the exposure, components of the structural system either remain in an undamaged state ($\overline{D}$) or are damaged (*D*). Each damage state can then either lead to the failure of the structure (*F*) or not ($\overline{F}$).

4 Exposure conditions

Modelling of the relevant exposures, described in details by Vrouwenvelder (2010), includes the assessment of probabilistic characteristics of potential hazards:

- Known and dealt with: associated risks are either accepted without additional measures or reduced to an acceptable level. Foreseeable actions may include natural accidental actions, anthropogenic accidental or deliberate actions, and normal loads,
- Known in principle, but unrecognized or ignored: the codes usually formulate a set of generic design requirements for these actions (such as human errors in design, construction and use). Limited information on intensity and frequency of occurrence is usually available. Modelling of human errors is described in detail by Vrouwenvelder et al. (2010),
- Unknown or unforeseeable: no specific information is available for unrecognised actions (kind of human error) and unforeseeable action (shortcoming of the whole profession). Inventory of failed structures may, however, be used to categorise failure causes as unforeseen or unforeseeable at that time and in principle it is possible to estimate frequencies.

Whether or not actions are relevant for the design depends on the nature and location of the structure. Indicative probabilities of occurrence of selected exposures are given in **Tab. 1**.

Tab. 1 Indicative probabilities of exposure occurrence and removal of a column anywhere in the building in 50 years, given exposure, Ellingwood and Dusenberry (2005) and Vrouwenvelder (2010)

Exposure	**P(*EX*)**	**P(*D*|*EX*)**	**Exposure**	**P(*EX*)**	**P(*D*|*EX*)**
Explosion (accidental)	0.002	0.1	Vehicle impact	0.03	not specified
Explosion (deliberate)	0.0001	not specified	Fire	0.02	0.1

5 Structural models and design principles

Appropriate models for structural behaviour are needed to analyse damage scenarios resulting from the exposures and estimate the probability of the total collapse, given occurrence of an extreme load. Such models should be able to deal with partly damaged structure, large cracks, plastic and large deformations, catenary or membrane actions, high temperatures, dynamic effects etc.

For practical design computer models validated with available experimental data are needed. However, computations with such models are time consuming. Depending on material and objectives of the analysis, (justifiable) simplified design rules are required. An example of failure scenario, often considered in codes, is the removal of a column. Indicative probabilities of the removal of a column anywhere in the building given exposure are provided in **Tab. 1**.

Ellingwood et al. (2007) indicate that no universal approach to assure structural robustness exists due to many potential means by which a local collapse in a specific structure may propagate. SEI/ASCE (2010) distinguishes between the following design methods:

- Direct design taking into account the diversity and complexity of structures ensuring collapse resistance in a reliable, verifiable, and economical manner (assessment of the structure for specified performance objectives when subjected to specified hazard scenarios),
- Indirect design aims at increasing the collapse resistance of a structure implicitly by incorporating approved design features without consideration of hazard scenarios and without demonstrating that performance objectives are met (providing tension ties, enabling catenary action, or ensuring ductility).

The following measures are commonly considered:

- Event control reducing the exposure (threat-specific non-structural measures such as control of public access or anti-aircraft defence),
- Protection reducing the vulnerability of a structure (external structural measures such as safety barriers, walls, retaining devices resisting and shielding from impact, heat, or blast),
- Increased local resistance reducing the vulnerability (building columns or bridge piers identified as key elements can be provided with increased local resistance for specified hazard scenarios - either abnormal events (threat-specific) or notional actions (non-threat-specific),

- Alternative load paths enhancing the robustness of a structure by increasing continuity, strength, and ductility (the inversion of flexural load transfer from hogging to sagging above a failing column, catenary action),
- Segmentation producing isolating effects by accommodating: (a) large forces (high local resistance); (b) large deformations and displacements (eliminating continuity or reducing stiffness); (c) large forces and large displacements (high ductility).

6 Conclusions

Robustness can become a key issue in design of innovative concrete structures. However, robustness is not understood uniformly. Some experts perceive the robustness as an indicator of the ability of a structure to perform adequately under accidental situation, the others as an indicator of the ability of a system containing a structure to perform adequately under accidental situation of the structure. Despite its significance, quantification of robustness and methods of assessment are not yet sufficiently developed. A crucial issue is the definition of robustness and consequences that should be included in the assessment.

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