Robustness: key property of modern structures

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Abstract

Recent developments of high-performance materials, construction technologies and methods of structural analysis facilitate design of increasingly complex and slender structures. These structures may be vulnerable to unfavourable effects of extreme events including man-made hazards. In most cases, failures of structures exposed to such events may hardly be completely prevented. However, for sufficiently robust structures, failure consequences can be significantly reduced and safety of occupants essentially increased. The paper summarises present achievements in present codes and technical literature. Appropriate structural models, exposure conditions and construction measures for design of new structures and assessment of existing structures are discussed. It appears that structural robustness can become a key concept in design of modern structures. Despite significance of structural robustness, its quantification and methods of assessment are not yet sufficiently developed and further improvements are urgently needed. Available experience indicates that decisions concerning structural robustness can be efficiently based on methods of risk assessment and on the theory of reliability.
Keywords: construction safety, robustness, risk analysis.

1 Introduction

Developments in high-performance materials, 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 and safety of occupants increased. Despite many significant theoretical and technological advances, structural robustness is still an

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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 a better understanding of the aspects related to robustness. The paper, partly based on working materials of the Action, attempts to summarise findings concerning structural robustness concepts.

2 Definitions

EN 1990 [1] 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 [2], 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 the document of SEI/ASCE [3], robustness is understood as 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.

In general, 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). Therefore, robustness is a complicated concept that is not understood uniformly and precise definition is urgently needed. Figure 1 illustrates the basic concept in robustness:

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.

Robustness requirements are primarily related to steps b) and c).

3 Quantification of robustness

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

1. Deterministic, such as the deterministic reserve strength ratio, ISO 19902 [5],
2. Reliability-based, such as the redundancy index derived from failure probability of a damaged and intact structural system [6],
3. Risk-based. Baker et al. [4] 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 Figure 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 either lead to the failure of the structure (F) or not $(\overline{F})$.

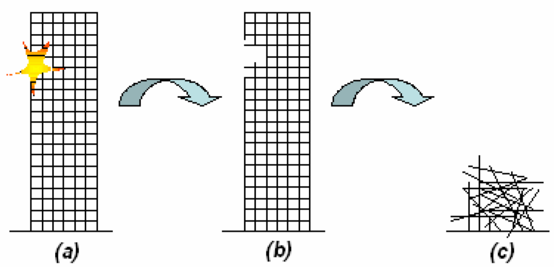

Figure 1: Illustration of the basic concept in robustness, EN 1991-1-7 [2].

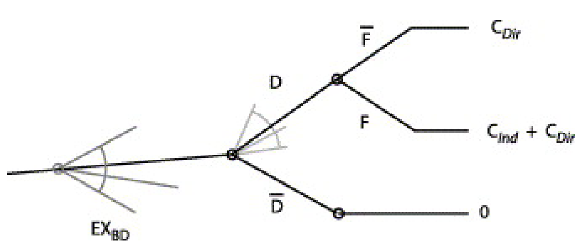

Figure 2: Event tree for quantification of robustness [4].

4 Exposure conditions

Modelling of the relevant exposures, described in detail in [7], 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 in [8].
- 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, help categorise failure causes as unforeseen or unforeseeable 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 Table 1.

Table 1: Indicative probabilities of exposure occurrence and removal of a column anywhere in the building in 50 years, given exposure, [7] and [9].

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 structures, large cracks, plastic and large deformations, catenary or membrane actions, high temperatures, dynamic effects, etc.

For practical design, the 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 a 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 Table 1.

No universal approach to assure structural robustness exists due to many potential means by which a local collapse in a specific structure may propagate [10]. SEI/ASCE [3] 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 or retaining devices resisting and shielding from impact, heat or blast).
- Increased local resistance, reducing the vulnerability (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 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 Robustness of existing structures

6.1 General aspects

Uncertainties in the assessment of robustness of existing structures may be significantly different from those considered in design of new structures. Some of them may be less significant than for new structures (modelling uncertainties, deviations from specified dimensions and strengths), some of them may be more significant (data on inaccessible members and connections) [11].

In general, the following aspects should be taken into account:

- The actual structural system, conditions and actions, including deterioration effects.
- Past overloading and occurrence of irreversible deformations,
- As-built material properties since actual material strengths are usually greater than the design values.
- Realistic models of connections, as they may significantly contribute to structural ductility, influence the ultimate strength and assure the load redistribution. Survey of connections may be necessary to evaluate as-built properties and assess influence of deterioration.
- Advanced theoretical modelling of existing structures that can be often justified by considerable repair cost savings.
- Proof, diagnostic or dynamic load tests that may help update information on structural properties.

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– A cost-benefit analysis as a basis of decision-making concerning robustness measures, such as reduction of exposures, local strengthening and improvements of the redundancy. In many cases of existing structures, such analysis will lead to the application of relatively simple measures, acceptance of the present conditions and/or orderly measures until major rehabilitation for other reasons.

It is emphasised that it may be important to assure robustness also in all phases of rehabilitations. If the decision is to replace a structure or a part thereof, the demolition should be carried out in such a way that human safety will be assured, fire flashover will be prevented and propagation of collapse of the structure or a part thereof will be controlled.

6.2 Examples of material-specific robustness measures

Concrete and masonry members can be often repaired by encapsulating the existing member by additional reinforced concrete, or strengthened by steel, carbon-fibre or glass-fibre reinforced polymers (FRP). The capacity of reinforced concrete beam-column connections can also be increased using FRP. The ductility of precast concrete structures can be achieved using external cables to provide continuity. Such rehabilitations improve strength and ductility of the structure [12]. Figure 3 illustrates selected methods for strengthening of reinforced concrete and masonry members.

For steel members and connections, the addition of cover plates to increase structural capacity is common practice. Examples of strengthening of steel connections are shown in Figure 4, accepted from [13].

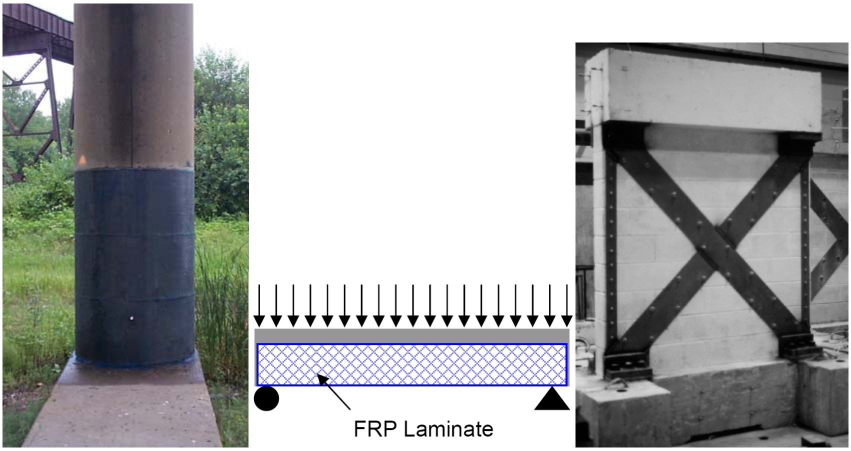
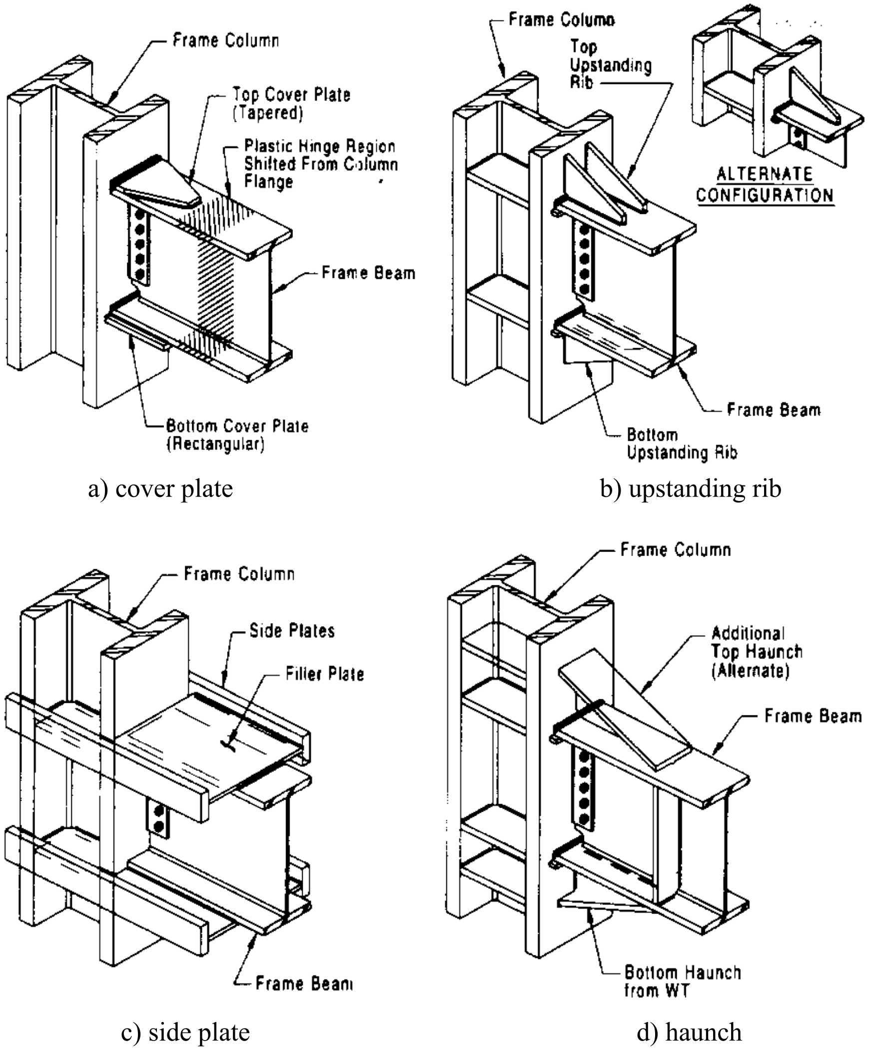


Figure 3: Reinforced concrete column wrapped with carbon composite; sketch of a reinforced concrete beam strengthened with FRP laminates [10]; masonry panel reinforced with steel strips [14].



a) cover plate b) upstanding rib

c) side plate d) haunch

Figure 4: Strengthening of steel connections [13].

7 Case studies

7.1 Case studies from USA and Saudi Arabia

Case studies of several buildings that offer insight into the causes of progressive collapses and mitigation measures are provided in [10]. The examples include major collapses (Ronan Point, Kansas City Hyatt Regency Hotel Skywalks, L'Ambiance Plaza, Alfred P. Murrah Federal Building, Jackson Landing Skating Rink), structures that survived major damage (The Pentagon, 130 Liberty Street) and designs to prevent progressive collapse (Khobar Towers). Lessons learned from these case studies may be summarised as follows:

- Collapses often develop due to insufficient structural integrity and lack of alternate load paths (e.g. statically determinate systems).
- Strong winds and/or fire actions may also cause progressive collapse.
- Special detailing (for instance as used in seismic regions), redundant and alternate load paths, short spans between columns, continuity of bottom reinforcement through supports, and conservative design for persistent design situations may prevent progressive collapse.
- Horizontal progression of collapse may be prevented by proper horizontal bracing that is able to support extreme overloads or by detailing connections.

7.2 Case studies from the Czech Republic

7.2.1 Floods

Hundreds of structures in the Czech Republic were affected by floods in 1997 and 2002. The most significant damage was observed to residential houses, but the floods also affected office buildings, schools, hotels, churches, bridges, subways etc. Masonry was a typical material of the flooded structures. Failure causes included geotechnical causes (insufficient foundation, underground transport of sediments and man-made ground and propagation of caverns, increased earth pressure due to elevated underground water) and structural causes (insufficient robustness, use of inadequate construction materials, material property changes caused by moisture). Figure 5 illustrates failures of structures with low robustness.

a) undermined foundations b) missing ring beams

Figure 5: Failures of structures with low robustness.

7.2.2 Snowfalls

In total, 249 failures or collapses of structures were reported in the winter of 2005/2006 in the Czech Republic. The affected types of structures comprised of agricultural structures, residential buildings, industrial structures and public buildings. Failure causes included extraordinary snow load (snow was not removed although required, combination of snow and ice, underestimated design snow loads), errors in design, construction and use (design errors, inadequate quality control, lack of communication, insufficient maintenance, false details). Considerably damaged structures had mostly insufficient robustness (no tying, low resistance of key members or vulnerable structural detailing). Lack of robustness became important particularly in the cases of multiple causes of failures or failures of joints.

A major collapse was that of the light-weight steel-framed ice-hockey stadium in Humpolec [15]. Figure 6 shows the stadium under construction in 2004 and the collapse. The main cause of failure were missing struts for preventing the lateral buckling of the thin-walled I main girders. Some missing struts are indicated in Figure 6, accepted from [15]. This human error affected nearly the whole structure that was almost uniformly loaded by snow. In this case, the robustness strategy may be to make segmentation rather than tie a structure.

7.2.3 Gas explosions

Gas explosions represent relatively frequent accidental actions in residential buildings. Figure 7 shows failures of structures with different levels of robustness due to gas explosions. Note that the limit for extent of the damage as recommended in EN 1991-1-7 [2] is fulfilled for the building in Figure 7a.

7.2.4 Collapses of structures under execution

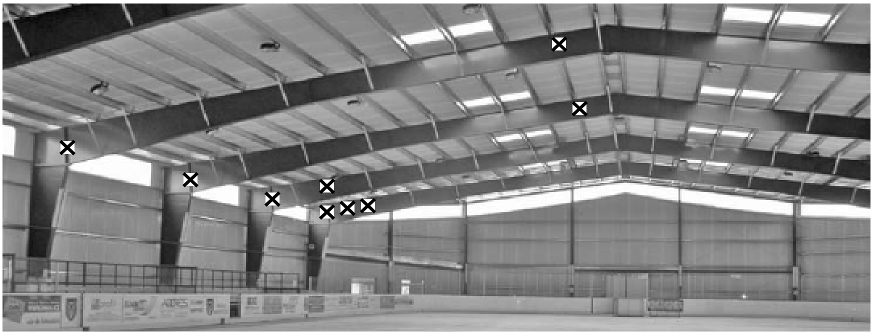
Available data of collapses in the Czech construction industry indicate that most collapses occur in construction (or repair) process. As an example, a collapse within a major repair of the road bridge over an important railway is described. The composite concrete-steel bridge was partly pulled out to one side of the tracks and repaired. During the first steps of the backward traction, the bridge suddenly slipped down from temporary supports on the railway. The main causes include:

- Vertical temporary supports were not provided by appropriate bracing.
- Trestles were not embedded into stiff foundations and not provided by any bracing.
- Inclination of the bridge, unobserved due to lack of geodetical measurements, resulted in redistribution of forces and overloading of some vulnerable temporary structural members.

Figure 8 shows the bridge before the collapse and the trestles without bracing and anchorages after the collapse.

a) under construction

b) collapse



c) missing lateral buckling struts

Figure 6: Stadium in Humpolec.

a) sufficient robustness

b) progressive collapse

Figure 7: Failures of buildings due to gas explosions.

a) the bridge before collapse

b) the trestles without bracing and anchorages after collapse

Figure 8: The collapse of the bridge during repair.

8 Conclusions

In most cases, failures of structures exposed to accidental actions may hardly be completely prevented. However, for sufficiently robust structures, failure consequences can be significantly reduced and safety of occupants essentially increased. Robustness can thus become a key issue in the design of innovative 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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