Joint Workshop of COST Actions TU0601 and E55
September 21-22 2009, Ljubljana, Slovenia

Robustness of buildings in structural codes

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Summary

Robustness criteria for buildings as provided in current codes are briefly reviewed in this document. Methodological aspects are briefly described first. A summary of state-of-practice regarding robustness in other type of structures i.e. offshore structures, bridges and tunnels is then presented. The criteria given in the Eurocodes and in the widely used U.S. standard ASCE are highlighted. Limitation in code requirements and an outlook for future developments in standards are finally provided.

Keywords

Accidental actions, codes, robustness.

Background / Introduction

The awareness of the significance of the design of structures of structures against accidental loads was intensified some 40 years ago following the partial collapse of Ronan Point. As a consequence of this incident a significant amount of research has been carried out into the various aspects of robustness and has resulted in a number of useful recommendations on how to achieve robust structures. In this document the implementation of robustness in practice is summarized based on the experience of the author.

One of the important things while dealing with the robustness of structures is to estimate to which level the structure can be regarded as robust. Also the consideration of system effects is particularly important when modeling robustness. Building code criteria primarily focus on designing individual elements or subsystems of a larger engineered system. This design philosophy has generally been successful, except in those instances where systems have suffered cascading system failures due to a lack of robustness. Considerations for future developments are therefore included herein.

Terms and definitions

Robustness: Robustness is the insensibility of a structure to local failure. From this definition follows that the robustness is a property of the structure.

General collapse*:* The immediate, deliberate demolition of an entire structure by a triggering event (e.g. explosion).

***Limited local collapse**:* Failure of a structural member without affecting the adjacent members (e.g. destruction of one or two columns in a multibay structure).

***Progressive collapse**:* The spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or disproportionately large part of it.

Problem statement / Key issues

A guiding principal in the design of structures is to maximize its reliability i.e. the reliability of its structural system. It is simple to optimize structures for maximum reliability without regard to properties such as redundancy or robustness. However, experience shows that the analytical models are only approximate, they omit factors such as human error, fail to identify cascading failures, or underestimate the probability of occurrence of accidental loads. In these cases criteria related to robustness are important. National and international standards have developed guidelines to consider robustness and progressive collapse in structural design. Such criteria are reviewed in this fact sheet and recommendations for future improvements are provided.

Methodology

Methods for assessing the potential of a damaged structure to withstand damage without the development of a general structural collapse and for designing to withstand such damage can be developed using concepts of structural reliability analysis and probability-based risk assessment. Such procedures require probabilistic models of normal and abnormal loads; material properties under static, dynamic and impact load conditions; and computational platforms to support the analysis of damaged structural systems at limit states involving nonlinear material behaviour and large deformations.

The problem of global failure can be expressed with a probabilistic formulation using the probability, *P(C)*, of a progressive collapse, *C*, due to an abnormal event, *E* as follows:

$$P(C) = P(C|LE)P(L|E)P(E) < P_A \quad (1)$$

Where:

C	event of structural collapse
$P(E)$	probability of occurrence of hazard E (Accidental action),
$P(L\|E)$	probability of local damage, L, given that E occurs,
$P(C\|LE)$	probability of collapse given that E and L both occurs
P_A	acceptable probability of global failure

The breakdown of the collapse probability into various events makes it possible to focus attention on strategies to prevent global failure of the structure. The probability of occurrence of the accidental event is basically independent of the design strategy, it can be controlled by the setting of the building, by the implementation of protection measures, etc. In many cases site specific studies are performed to analyze the factor *P(E)* and if it results for an event E smaller than the acceptable failure probability P_A, then the event is not further considered. It is also noted here that in many cases the supporting statistical data, derived form experience and observation, are rare. Therefore qualitative or semi-quanitative analyses are frequently used. Thereby probabilities of accidental events are classified in categories from frequent to improbable.

It is further observed that the aforementioned neglect of very rare events *E* is performed independently of the degree of robustness of the structure and would lead to inhomogeneous designs. Finally models for accidental actions can be found in various sources for example in CIB (1992) or in the probabilistic model code presented by the JCSS (2009). Probabilities of accidental events are reported for example by Ellingwood and Dusenberry (2005) and demonstrate that accidental events in buildings are rare but not as rare that they should not been taken into account:

- Gas explosions (per dwelling): $2\text{x}10^{-5}$ per year
- Bomb explosions (per dwelling): $2\text{x}10^{-6}$ per year
- Vehicular collisions (per building): $6\text{x}10^{-4}$ per year
- Fully developed fires (per building): $5\text{x}10^{-8}$ per m^2 per year

The condition probability of local damage *P(L|E)* given the event *E*, can be considered in two different ways. In many cases local damage is accepted and consequently *P(L|E)* is equal to 1.0. In other cases local strengthening is preferred in order to reduce the probability of local damage. It is noted here that local damage needs specific definition in each case (also for the computation of the conditional probability *P(C|LE)*) and is mainly related to failure of specific components of the structural system (for example column).

Finally a main problem in the formulation of Eq.(x.1) is that the underlying probabilistic concept requires specification of an admissible probability of global failure P_A. The target failure probabilities of probabilistic design codes are usually derived for single failure modes from calibration with previous deterministic design codes and on the basis of cost-benefit considerations. Targets for global failure are usually not specified. Human safety and societal risk criteria are important when global failure acceptability criteria are established and the risk is obtained as:

$$R_c = P(C) \text{ x } C_C \tag{2}$$

with C_C the consequences of collapse. Safety measures are frequently necessary in order to satisfy the risk acceptance criteria. They can classified as follows:

- Prevention measures influencing P(E) such as site layout, access control, fire detectors etc.
- Mitigation measures influencing P(L|E) and P(C|LE) and C_C such as protective cladding, barriers, fire-fighting systems etc.

Experience in other fields

In this section the implementation of robustness requirements for other structures than buildings, in detail offshore structures, bridges and tunnels, is examined under consideration of accidental loads to show their importance for the design of robust structures.

Robustness of offshore structures

Progressive collapse analysis is implemented in offshore design since 30 years. The accidental actions (impact scenarios, fire and explosion, flooding, etc.) are usually determined through risk analyses and by accounting for the relevant factors of influence. The magnitude of the accidental event can be controlled by using passive or active measures. For passive measures there are recommendations given, for example fenders can be installed to reduce the damage due to impact.

In principle an offshore structure can be designed to resist the accidental action. It must be decided whether a local damage may be avoided or is tolerable. For this case it is crucial to provide alternate load paths to ensure that a small damage does not lead to disproportionate consequences through a progressive collapse. This design criterion leads to a robustness of the structure and ensures that loss of stability and capsizing can be avoided within an acceptable probability.

For verification of these accidental events the NORSOK (2004) standard can be used. It provides an Accidental Limit State (ALS) for the consideration of accidental loads. The ALS applies to all relevant failure modes. The structural integrity criterion in NORSOK is a two-step procedure. The first step is to analyze the resistance of the structure against accidental loads, i.e. the structure must be checked whether it can maintain its intended load carrying function. The second step is to check the structure for the damaged condition. Hereby is important that the damaged condition is analyzed for defined (reduced) load combinations (e.g. for steel structures load and resistance factor is set to 1.0). A summary of design of offshore structures against accidental actions is presented by Moan (2007). The consideration of accidental loads to obtain a robust offshore structure is essential. The accident rates for platforms demonstrate the need for more robustness of the structures. The ALS criteria of NORSOK is a first step to implement global failure modes and progressive failure in structural design.

Robustness of bridges

The requirement to avoid progressive collapse in case of local failure is an important design criterion for multi-span bridges. It can have strong impact on both conceptual design, including choice of structural system, and detailed design. The triggering events of collapse are manifold. This extraordinary event could either be a ship impact, strong ice formations collision on a pier or fire and explosion.

In view of the accidental nature of imaginable and unimaginable circumstances, in relation to structural robustness, it would be unrealistic to design against progressive collapse just by preventing local failure at any expense. In case of bridges it is more reasonable to allow local failure (e.g. loss of pier) and investigate the behavior of the damaged structure. It must be demonstrated that a progressive collapse due to the local failure can be avoided. It can be seen that not only the redundancy (ensures alternate paths) is important for the robustness as shown in the design of the Confederation Bridge (Starossek, 2006). The reducing of a system’s degree of static indeterminacy may be used to avoid progressive collapse caused by accidental events, thus increase the robustness of the entire structure.

Current design codes do not strictly require the prevention of progressive collapse of bridges. Recent disasters and theoretical considerations on the basis of risk theory indicate that codes should be improved to more clearly address this problem.

Robustness of tunnels

Robustness of tunnel structures is implemented mainly through fire resistant materials. Accidental loads include internal and external hazard scenarios. Accidental loads are usually derived based on a site specific study. Outcome of such studies are protective measures such as protective layers. The tunnel with the protective layer shall namely be able to resist, without puncturing of an exterior waterproofing membrane or spalling of interior concrete, the accidental loads specified for the project. Only one of the accidental loads is thereby assumed to act at any time on any session of the tunnel.

Codified approaches for buildings

European approach (Eurocode, 1991)

The basic European document for structural design is the EN 1990. This code indicates that sufficient structural reliability can be achieved by suitable measures including ensuring an appropriate degree of structural integrity, i.e. structural robustness. In the EN 1991-1-7 (Eurocode, 1991) 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 general the code states two strategies for the extraordinary design condition. The first is for identified extreme events, the second is a strategy to limit local failure. The first strategy is based on identified extreme events (internal explosions, impact) and includes:

a) design the structure to have sufficient robustness

b) prevent or reduce the action (protective measures)

c) design the structure to sustain the action

The second strategy is based on the limiting extent of local failure, i.e:

a) enhanced redundancy (alternative load paths)

b) key element designed to sustain additional accidental load

c) prescriptive rules (integrity, ductility)

For these strategies the Eurocodes provide three consequence categories (CC) for the design of structures under extraordinary events.

- CC 1 Low consequences

- CC 2 Medium consequences
- CC 3 High consequences

By consideration of these categories the defined strategies lead to an adequate robustness of the structure to minimize a limited amount of damage and failure without collapse. Thus the structure can withstand the effects of undefined extraordinary events. Thereby sets the code the minimum period of time that the structure must resist after such an event as the time which is necessary to safely evacuate persons from the damaged building and its surrounding area. For structures with dangerous goods, public affairs, or for reason of public security longer time frames are required.

Furthermore the Eurocodes provide some constructional measures to obtain robustness in buildings. These measures are for example active vertical and horizontal traction anchors. For main structural elements, that are capable of carrying an extraordinary action, the verification should be done under consideration of the effect for the main element and the adjacent components and their joints. For this case it is thus necessary to consider the entire structure and not only the single elements. The extraordinary design load according to EN 1990 should be applied as single load or uniformly distributed load. For structures in CC3 group a systematical risk assessment is required under consideration of predictable and unpredictable hazards. For this case an analytical model for damaged structures is recommended.

Robustness provisions are also provided in various national codes of European countries, e.g. U.K., Denmark, Italy etc. but they will not discussed herein, since the Eurocodes build the basis for standards in Europe (see for example for U.K. Harding and Carpenter, 2009)

U.S. approach (ASCE 7- 02, 2005)

The main document is the ASCE 7-02 standard which assumes that triggering events, accidents, misuse, or sabotage are normally unforeseeable events and can therefore not be defined precisely for the design. Likewise, general structural integrity is a quality that can not be stated in simple terms. The ASCE standard does not intend to establish specific events to be considered during design. Also the standard does not provide specific design criteria to minimize the risk of progressive collapse.

However in the ASCE standard is a commentary that provides the user with precautions in design to limit the effects of local collapse. This is realistic and can be satisfied economically. For this reason the ASCE recommends design alternatives for multistory buildings, so these structures can posses the same structural integrity than inherent in properly designed conventional frame structures. There are a number of ways to obtain resistance to progressive collapse. In the ASCE 7-02 is distinguished between two ways of design: direct and indirect design.

The *direct design* considers *explicit* the resistance to progressive collapse during the design process. This can be obtained by the *alternate path method* which allows local failure to occur, but seeks to provide alternate load paths so that the damage is absorbed and major collapse can be averted. The structural integrity of a structure may be tested by analysis to ascertain whether alternate paths around hypothetically collapsed regions exist. In addition the Standard recommends the *specific local resistance method*. This method seeks to provide sufficient strength to resist failure from accidents or misuse. This may be provided in regions of high risk since it may be necessary for some elements to have sufficient strength to resist abnormal loads in order for the structure as a whole to develop alternate paths.

The *indirect design* considers *implicit* the resistance of progressive collapse during the design process through the provision of minimum levels of strength, continuity, and ductility. Alternate path studies may be used as guides to develop rules for the minimum levels of these properties needed to apply the indirect design approach to enhance structural integrity. Furthermore the ASCE standard provides specific constructional guidelines to achieve a resistance to progressive collapse (ties, compartmentalization, etc). The requirements are entirely threat-independent. A discussion of American standards regarding structural robustness can be found in Shankar (2004).

Limitations and outlook

In order to develop reliability based criteria for global failure of structures subjected to abnormal events the following topics should be further investigated:

- Data on accidental frequencies and classification of the data in frequency categories.
- Consensus on risk analysis method for important buildings (category CC3 according to Eurocodes).
- Performance based criteria reflecting risk acceptance as discussed by Hamburger et. al. (2003) in case of earthquakes or by Diamantidis and Bazzurro (2007) in which the difference between new and existing structures is emphasized.

	Consequence Categories				
Hazard Level	Insignificant	Marginal	Critical	Severe	Catastrophic
Frequent	ALARP	NAL	NAL	NAL	NAL
Occasional	ALARP	ALARP	NAL	NAL	NAL
Remote	AL	ALARP	ALARP	NAL	NAL
Improbable	AL	AL	ALARP	ALARP	NAL
Incredible	AL	AL	AL	ALARP	ALARP

Notes:AL: Acceptable Level; ALARP: As Low As Reasonably Practicable (Level); NAL: Not Acceptable Level

Table 1: Risk acceptability matrix

A first step could be the development of a widely recognized performance or so-called risk acceptability matrix as shown in Table 1 (see also Hardening and Carpenter, 2009) compatible to state-of-practice in risk analyses. For that purpose specified hazard probability levels are combined with specified hazard severity levels, both associated to quantitative ranges. The principle of the risk classification matrix has been used in various projects such as tunnels, chemical plants, bridges etc.

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