Assessment and determination of robustness of structures

Working Paper

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Publication date:
2012

Permanent link:
https://doi.org/10.3929/ethz-a-007362042

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Originally published in:
IBK Bericht 337
ASSESSMENT AND DETERMINATION OF ROBUSTNESS OF STRUCTURES

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May 2012
Foreword

Robustness of structures has been a research topic of significant scientific and practical interest and relevance for the last 4-5 decades and moreover a topic associated with controversy and strong opinions among engineers in the structural engineering community. Modern design codes include a number of provisions aiming to ensure that structures are robust. However, in spite of this, structural failures disproportional to their cause still take place. Among the causes of relevance count exceptional load events such as explosions, impacts and fires; however in many cases where structures collapse, human and organisational errors are also involved.

There are several challenges associated with the topic of structural robustness. First of all, dealing with the topic of robustness of structures necessitates an understanding of structural systems with respect to their performance and with respect to how to influence these by design provisions. Additionally, the issue on how to decide on the adequate level of robustness must be dealt with. However, even if these issues may be resolved at an academic level there remains the problem on how to introduce the findings into practice. How can we codify the process of structural design such that the robustness is consistently and adequately accounted for? And by which means of structural analysis can we support the design verifications?

The present thesis takes basis in the recent developments in risk and reliability assessments for engineered facilities and systems and builds on this in addressing all but the last of the above mentioned issues. I believe that the contributions of the thesis are of interest to both the research community working on structural performance in general and robustness in particular, as well as the industry that in effect is responsible for ensuring adequate robustness of the built environment. In particular, the present thesis outlines a new perspective on how robustness explicitly can be incorporated into the next generation of structural and building design codes, which is why the thesis would be highly relevant for pre-normative and normative committees.

Kongens Lyngby, Denmark, May 2012          Michael Havbro Faber
Abstract

Robustness in structural engineering is widely considered to be a desirable ‘must-have’ property and commands significant recognition as a hallmark of best practice structural system design. Robust structures are commonly understood as structures for which the consequences arising from possible damages and failures in the structures are not disproportionate to the causes of the damages and failures. The failures of several high profile buildings and societal infrastructure especially over the past two decades followed by their wide-ranging consequences and the resulting heightened adverse societal perception have propelled the awareness of the significance of the robustness of structures to momentous levels.

Despite this degree of importance accorded to structural robustness, current structural design codes and standards do not spell out suitable approaches for achieving adequate robustness in specific, transparent or explicit detail. This situation exists partly due to the responsibilities of the design codes in catering to the need for a highly standardised and widely and easily implementable design process and the predominantly structural component-centric design philosophy used in practice. As a result of assumptions and simplifications introduced in the design process, certain aspects of structural performance and safety are not given adequate attention. This results in a lack of a systematic and integrated engineering understanding of all the requirements and considerations necessary to ensure adequate safety in structures and the implications arising from structural design practice that have a bearing on the integrity of the overall structure. The absence of a systematic approach for the establishment of holistic and well-informed safety requirements particularly at the structural system level can be seen as a major gap in the realm of code-based structural design practice. Pure risk-based design philosophies provide a strong conceptual platform to address these issues; this however comes at the cost of significant rigour and detail, thereby making it unwieldy for use in common structural design practice.
The issue of robustness is examined in this thesis from a fundamental perspective as well as from a practical viewpoint. At a fundamental level, a risk-informed approach for the consideration of robustness is developed that integrates the essential ingredients from a holistic risk and lifecycle performance understanding of structures together with code-based structural design. A differentiated architecture to ensure adequate robustness in structures is proposed as the viable design basis for a future format for structural design codes and standards which comprises:

- a well-defined and separated code standard safety format that accounts for most component related (direct) risks in structures, and
- a set of clearly stated principles and application rules to ensure appropriate robustness that account for most structure/system related (indirect) risks.

The implementation of this architecture is facilitated by the development of a framework that enables a comprehensive consideration of factors that influence the robustness of structures from a lifecycle performance perspective. The framework is organised using a system of generic categorisation and mapping for the different factors associated with robustness in structures. A generic treatment of the implications arising from code-based structural design that impinge upon the robustness of structures and their ensuing evolution in the form of failures and consequences in structures is then provided. This establishes a strong foundation and identifies the principal needs that necessitate the development of suitable generic strategies to ensure robustness in structures. The specification of robustness provisions from these generic strategies is guided through the development of a multi-level risk-oriented organisation and categorisation scheme. This scheme also forms the basis for the establishment of a systematic and differentiated mapping of the current consideration and treatment of robustness in European standards.

At a practical implementation level, a guidance platform based on the developed risk-informed approach is established which channels engineering design thinking towards i) a logical and systematic consideration of situations and scenarios that necessitate the consideration of robustness and ii) the planning of suitable strategies and provisions to ensure adequate robustness in structures. The use of the guidance platform is illustrated through a design
example which typifies its use for improved decision making in the assessment and management of structural robustness in different situations and circumstances.

A broad range of factors and considerations can be seen to influence the robustness of structures. These include the occurrence of hazards and their effects on structures, the evolving structural performance, the ensuing consequences and the effectiveness of strategies for the management of safety and integrity in structures. A structured and flexible manner to systematically and more importantly visibly account for such factors and considerations in the process of provision of robustness in structures is provided in this thesis.

The developed risk-informed approach aims to supplement and enrich existing code based structural design practices by providing a better understanding and transparent handling mechanisms for risks in the context of robustness. This approach can also be seen to establish a clear pre-normative foundation and a viable structure for the development of revised structural design code formats in which the consideration of structural lifecycle performance with regard to robustness is facilitated in a systematic, visible and explicit manner in the structural design, execution and maintenance processes for structures. It is envisaged that the work described in this thesis will ultimately contribute to a paradigm shift in engineering design thinking from component-based to system-based thinking and also from considerations of deemed-to-satisfy (implicit) risk to tolerable (explicit) risk.
Zusammenfassung


In der vorliegenden Arbeit wird die Robustheit von Tragwerken sowohl grundlegend als auch von einem praktischen Standpunkt aus betrachtet. Auf der grundlegenden Ebene wird ein Risiko-informierter Ansatz zur Berücksichtigung der Robustheit entwickelt, der die wesentlichen Grundsätze
eines ganzheitlichen Verständnisses der Risiken über den gesamten Lebenszyklus von Tragwerken mit Normen-basiertem Tragwerksentwurf zusammenbringt. Um eine adäquate Robustheit von Strukturen zu erreichen, wird ein differenzierter Ansatz als Basis für den zukünftigen Aufbau von Normen und Richtlinien vorgeschlagen. Dieser Ansatz enthält:

- Einen wohldefinierten separaten Standard-Sicherheits-Nachweis, der die meisten Bauteil-bezogenen (direkten) Risiken in Strukturen abdeckt, und

- klar definierte Prinzipien und Anwendungsregeln, die eine angemessene Robustheit garantieren und die meisten auf das System bezogenen (indirekten) Risiken behandeln.


Auf der Ebene der praktischen Umsetzung des neu entwickelten Risiko-informierten Ansatzes wird eine Richtlinie vorgestellt, die das Denken von Ingenieuren im Entwurfsprozess auf die folgenden Punkte fokussiert: i) Eine logische und systematische Berücksichtigung von Situationen und Szenarios, die die Betrachtung der Robustheit erfordern und ii) die Planung von geeigneten Anforderungen und Strategien, die eine ausreichende Tragwerks-Robustheit garantieren. Die Verwendung der Richtlinie wird anhand eines Bemessungsbeispiels illustriert, das die verbesserte Entscheidungsfindung bei
der Beurteilung und Beeinflussung der strukturellen Robustheit in unterschiedlichen Situationen und Umständen verdeutlicht.


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Chapter 1

Introduction

1.1 Background

Robust structures are commonly understood as structures for which the consequences that arise from possible damages and failures in the structures are not disproportionate to the causes of the damages and failures. The awareness of the significance of the robustness of structures has gradually intensified especially over the past two decades principally due to experiences with failure and collapse of several high profile structures and buildings and their wide-ranging consequences and heightened adverse societal perception. The issue of robustness first received significant attention following the partial collapse of the Ronan Point building (UK) in 1968. Events of terrorism and malevolence such as the Oklahoma City bombing (USA) in 1995 and the attack on the New York World Trade Center towers (USA) in 2001 have resulted in renewed international resources being devoted to better understand the different issues and challenges concerning robustness. Also, the colossal damages and losses suffered during events of natural disasters such as the Indian Ocean tsunami in 2004, the Sichuan earthquake (China) in 2008, the cyclone Nargis (Myanmar) in 2008 and the Haiti earthquake in 2010 have served to strongly precipitate this interest in robustness and safety of structures. Structural robustness has therefore attained a never-before-seen significance in today’s global environment.

More recently, there has also been an increased focus on the performance of entire structures as systems; this has been brought about primarily through rising public awareness and concern about the condition and criticality of societal infrastructure. Events such as the I-35W Mississippi River bridge collapse (USA) in 2007 and the Fukushima Daiichi nuclear disaster (Japan) in 2011 have been major wake-up calls in this respect. Due to an ever increasing
complexity of infrastructure development, the long overdue need for clear systems considerations in design, construction and lifecycle management of structures has become critical.

Further, an ever growing awareness of the need for sustainable development has placed significant importance on the judicious use of the available limited societal resources with due consideration of the needs of the future generations. Given the primacy of infrastructure development for societal progress, this has meant increased standards of responsibility and greater appreciation of the balance between resources and performance in activities involving the design, construction and maintenance of societal infrastructure.

Continued events of terrorism and malevolence and growing public awareness of infrastructure safety and sustainable development across the world have therefore emphasized the urgent need for the review and development of rational, transparent and holistic approaches to ensure that risks to people, environment, assets and functionality of the societal infrastructure and the built environment are acceptable, affordable and sustainable to society. With several high profile building and structural failures, robustness is now recognized as a property of great significance in structural engineering and good system design as well as a vital benchmark of system performance due to its importance for structural safety and integrity. Research efforts and developments towards a better understanding, assessment and adequate provision of structural robustness hence provide a vital contribution to the overall efforts in ensuring a safe and sustainable development of the built environment.

1.2 Research problem

Modern codes and standards for structural design consider robustness through requirements which typically state that the consequence of damages to structures should not be disproportionate to the causes of the damages. Despite the importance of robustness for structural design, such requirements are, however, not substantiated in further explicit or transparent detail; nor has the engineering profession been able to agree on an interpretation of robustness that facilitates its assessment, quantification and use in practice.
Introduction

This situation exists partly due to the responsibilities of the design codes in catering to the need for a highly standardised and widely as well as easily implementable design process and the predominantly component-centric design philosophy in structural design practice. Certain aspects of structural performance and safety are therefore not given adequate attention as a result of the assumptions and simplifications introduced in the process. Further, codes and standards dealing with structural design are based largely on the design of structural members and the consideration of individual member failure modes. When the overall ability of a structure to sustain damages or failures is considered, existing design practices are seen to be ambiguous and much less specific or direct, with some exceptions. This approach therefore ensures a certain satisfactory and optimal level of performance for the individual members and connections of a structure. However, the extent to which the failure of these individual members and connections and other factors influence the performance and behaviour of the entire structure leading to its possible failure is not directly or completely accounted for and considered.

The general consensus in the structural engineering community is that robustness is of extreme importance and the present situation with regard to ensuring sufficient structural robustness as enshrined in codes and standards is unsatisfactory. There is a general agreement and understanding on the broad attributes that contribute to robustness in structures. However there is a clear lack of a systematic approach for a transparent evaluation, assessment and provision of structural robustness.

It has therefore become essential for design practices and codes and standards for structural design to directly and effectively consider and address approaches aimed at evaluating the robustness of a structure as a system. This is essential in order to eventually establish and ensure an adequate baseline level of safety for the structural system, in a manner broadly analogous to the provision and assurance of an appropriate level of safety for structural components and connections. The absence of such a systematic approach and the establishment of safety requirements at the structural system level can be seen as a major research gap in the realm of code-based structural design practice.
The developments pointed out in Section 1.1 have imparted a greater sense of significance and commitment towards work in this direction. It is therefore of utmost importance to first establish a viable foundation for the consideration and treatment of structural robustness in structural design codes and standards. This requires work at a strategic and pre-normative level which will lead towards a) the establishment of a design code format that provides due consideration to robustness in structural design and lifecycle performance management and b) its eventual use in design practice.

1.3 Philosophical basis and hypothesis

The current societal development environment is characterised by growing complexity (in requirements, designs, materials and technologies), increased perceived dangers to societal infrastructure and rising concerns over sustainable development. In this climate, a clear and holistic understanding of risks and the underlying uncertainties in the built environment together with a greater focus on overall system performance is fast emerging as the sine qua non of structural design and sustainable lifecycle performance management. This focus on systems has also found recent parallels in other sectors – following the global financial crisis in 2008-09, there has been a growing attention on the health of the overall financial system and system-wide characteristics and not just the health and state of individual banks and institutions (Haldane & May, 2011).

Recent developments in the area of engineering risk assessment (JCSS, 2008) have taken the perspective that the ‘system’ subjected to assessment in the context of structural design may be represented in terms of i) the exposures (actions or hazards) acting on the structure, ii) the damages which may occur on the individual components of the structure and the immediate (direct) consequences of the exposures and iii) the impact of these damages on the overall structural system integrity and performance and the ensuing follow-up (indirect) consequences. This principle is illustrated in Figure 1.1.
Here, exposures may be understood as any effects acting on the structure with the potential to cause damage and consequences to the structure and include the occurrence of natural or human-induced hazards. The vulnerability of a structure is described by the degree to which the individual constituents (members and connections) of the structure are damaged by the effects of the exposures. Such structural damages may include the loss of one or several structural members or the reduced performance of individual members or joints. The robustness of the structure is understood as the ability of the structure to sustain the damages resulting from the exposures without failure or loss of functionality of the entire structure. The use of indicators at every stage in this framework provides a quantifiable basis necessary for the assessment of risk.

The consideration and assessment of robustness is a vital ingredient of any risk-based decision making process for structural design and lifecycle performance management. A risk-based approach considers robustness from a

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### Figure 1.1 Illustration of system representation in an engineering risk assessment framework for structures (Source: JCSS, 2008).

<table>
<thead>
<tr>
<th>Scenario representation</th>
<th>Physical characteristics</th>
<th>Indicators</th>
<th>Potential consequences</th>
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<tbody>
<tr>
<td><strong>Exposure</strong></td>
<td>Flood</td>
<td>Use/Functionality</td>
<td>Direct consequences</td>
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<td>Ship impact</td>
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<td></td>
<td>Explosion/Fire</td>
<td>Environment</td>
<td>Material losses</td>
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<td>Earthquake</td>
<td>Design life</td>
<td>Injuries and fatalities</td>
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<td>Vehicle Impact</td>
<td>Societal importance</td>
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<td><strong>Vulnerability</strong></td>
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<td>Indirect consequences</td>
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<td>Rupture</td>
<td>Design target reliability</td>
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<td>Erosion</td>
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<td>Corrosion</td>
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<td>Damages to environment</td>
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<td><strong>Robustness</strong></td>
<td>Partial collapse</td>
<td>Design codes</td>
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lifecycle perspective to be a product of the design together with strategies for operation, maintenance and control as well as appropriate emergency response measures. The assessment of robustness for a structure therefore necessitates the systematic consideration of the possible scenarios leading to failure of the structure, their probability of occurrence as well as the corresponding consequences. This more differentiated and risk-oriented perspective of robustness provides a viable basis for the establishment of a consistent and rational approach so that structural design codes and standards may:

- provide guidelines and methodologies for the sound assessment and optimal improvement of structural robustness, and
- set minimum requirements for a level of adequate and acceptable robustness

for a given set of attributes and indicators for a structure.

A future platform for the assessment and improvement of structural robustness can therefore be based on considerations of risk using the above described framework illustrated in Figure 1.1 where the different decision alternatives with regard to improving structural robustness are assessed and ranked in terms of their total risks. In its conceptual form, this framework can be seen to provide risk-based decision support at a strategic level. For use at a normative level and eventually at a practice implementation level for structural design, the framework needs to be seen within the domain of code-based design. In this context, the provision of adequate safety in structures can be set out in the form of requirements that comprise:

- a code standard safety format that incorporates models of material and structural behaviour and the underlying uncertainties with the use of appropriate factors of safety, and
- a set of provisions to ensure adequate robustness.

These requirements need to be fulfilled individually and independently in an adequate manner. The standard safety formats (such as the load and resistance factor design (LRFD) approach and the partial factor system used in the Eurocodes) used in codes and standards dealing with structural design can
be considered to be well organised and developed and also optimised though the use of code calibration methods. However there is a clear lack of a systematic, organised and transparent approach in codes of practice to deal with robustness; the prevalent rules and provisions in this regard are not formulated on a rational or explicit basis in a manner consistent with the optimisation of the overall performance and safety of structures. Further, a well-defined separation does not presently exist in modern codes of practice between the standard safety format and the set of robustness provisions. Robustness related provisions primarily exist in the form of prescriptive rules, the beneficial impact of which in ensuring robustness is taken to be implicit and are occasionally interspersed among other provisions in codes and standards.

With respect to the risk assessment framework illustrated in Figure 1.1, the standard safety format may be seen to deal with the predominant aspects associated with the vulnerability (and the corresponding component related or direct consequences) of the structure and the set of robustness provisions aim to ensure adequate robustness (and the corresponding system related or indirect consequences) of the structure. In order to establish sound assessment procedures and ensure adequate robustness in structures, a differentiated approach is therefore advocated as the basis for a future format for structural design codes and standards which comprises:

- a well-defined and separated code standard safety format that accounts for most component related (direct) risks in structures, and

- a set of clearly stated principles and application rules to ensure appropriate robustness that account for most structure/system related (indirect) risks.

The development of the structure of such a code format is carried out following a ‘risk-informed approach’ that aims to enhance existing code-based structural design practices through the broader consideration of necessary insights from a risk-based and lifecycle performance oriented approach. Through a logical and workable process, such consideration is used to establish optimal, adequate and acceptable robustness measures for structures commensurate with their use, safety, performance and economy.
A holistic identification of relevant considerations or factors that influence the robustness of structures from a lifecycle performance oriented perspective is first carried out. This includes the consideration of relevant exposures, their ensuing consequences and the necessary strategies required in response to the effects of the exposures and consequences. These can be seen as the different components of a utopian ‘complete risk model’ that can be established for a structure. A system of generic categorisations and mapping is developed for the different components of this ‘complete risk model’. A viable platform for the establishment of optimal provisions for robustness in structures is made available through this categorization and mapping.

A clear identification of the present code requirements towards safety and their separation into the standard safety format and the set of robustness provisions are then carried out. Towards this end, a scheme for systematic categorisation of robustness provisions using attributes related to risk management is proposed. The attributes considered include the approach to risk treatment, nature of risk control, relationship with event (independent or specific), focus domain of risk reduction and applicability with respect to the lifecycle of the structure. Using this scheme, a systematic and differentiated mapping of the current treatment of robustness in European standards is also established.

This facilitates the development of a guidance platform for structural engineering design that takes into account the considerations already established within the standard safety format in codes and provides a structured approach using information from the developed generic categorisation for providing and ensuring adequate robustness. Considering that the standard safety format is already optimised, the optimisation of the identified robustness provisions can be separately carried out based on considerations of lifecycle cost efficiency and investments into life safety.

Using holistic considerations of risk and lifecycle performance, this approach provides a clear pre-normative basis as well as a working structure for the establishment of a revised structural design code format in which the consideration of structural lifecycle performance with regard to robustness is more clearly, systematically and explicitly introduced in the structural design, execution and maintenance processes. Further the development of a guidance
platform is aimed at a practice implementation level in order to enhance decision making in the assessment and management of structural robustness in different situations.

1.4 Organisation of thesis
This thesis consists of six chapters. Chapter 2 provides a discussion on the current treatment of robustness in code-based structural design and a review of the different approaches developed and reported in literature for the assessment and quantification of robustness. A risk-informed approach that serves as the underlying basis for the establishment of a modified code format for the assessment of robustness is developed in Chapter 3. The different steps involved in the development of this modified code format approach are elaborated in Chapter 4. Chapter 5 provides an illustration of the proposed approach described in the preceding chapters. The conclusions of this thesis and the future outlook are discussed in Chapter 6.
Chapter 2

Current treatment of robustness in code-based structural design

2.1 General understanding of robustness

In common parlance, the term ‘robustness’ means different things to different people and in different contexts. The online Oxford dictionary (http://www.oxforddictionaries.com/) defines ‘robust’ as:

1. (of an object) sturdy in construction
   
   strong and healthy; vigorous

   (of a system, organization, etc.) able to withstand or overcome adverse conditions

   uncompromising and forceful

2. (of wine or food) strong and rich in flavour or smell

Different fields of science, engineering and technology provide essentially contextual definitions and understanding of the concept of robustness, generally emphasising its importance as a system-wide property. From the above dictionary meanings, the reference to the ability to withstand or overcome adverse conditions seems to be the most pertinent in the context of systems. Broadly speaking, robustness can be therefore considered as a measure of the degree to which certain performance objectives, properties or performance of a system are affected by extreme, unexpected, hazardous, ambiguous or abnormal conditions.

As discussed in Chapter 1, robustness in structural engineering is now widely considered to be a desirable ‘must-have’ property and is well recognised as a
Current treatment of robustness in code-based structural design

hallmark of best practice structural system design. Several different perspectives and opinions exist on the understanding, interpretation and assessment of structural robustness. Robustness is generally considered to be a structure-wide characteristic and seen to be associated with several indicators or properties that include risk, redundancy, ductility, variability of loads and resistances, probabilistic descriptions of extraordinary loads and environmental actions, performance of structural members and connections, dependencies of failure modes, consequences of structural component and system failures, strategies for structural monitoring and maintenance, emergency preparedness and evacuation plans and general structural coherence and integrity. A commonly accepted understanding of a robust structure is one in which the consequences resulting from an initiating event or cause are not disproportionate to the initiating event or cause; this is based on the requirements stipulated in the head standard (BSI, 2002) in the family of European standards for structural design or the Eurocodes. This broad understanding forms the basis of discussion in this thesis.

2.2 Philosophy of structural design

The term ‘structural design’ (hereinafter also referred to as design) can be seen to have different connotations. In this thesis, structural design refers to an entire range of activities and processes for a structure that include the planning and conceptualisation phases, feasibility studies, structural analysis, formulation of detailed design proposals and preparation of the execution plan for the design proposals and the maintenance plan for the structure over its lifecycle. The structural design process straddles between the considerations and requirements related to use, safety, performance and economy for a structure. The primary requirements or expectations of a structure that can be realised through its design process are associated with these considerations and can be identified as:

- Appropriate fulfilment of use or functionality, without the need for abnormal maintenance during its lifetime (use)
- Provision of adequate safety (safety)
• Ensuring sustainable lifecycle performance through sustainable practices in design, execution, use and maintenance (performance)

• Minimising damage to qualities of the environment (performance)

• Provision of the above at an optimal overall lifecycle cost (economy)

During this process, an optimal and acceptable balance needs to be achieved between the considerations and requirements related to use, safety, performance and economy. The basic approach in achieving this balance and in fulfilling the primary requirements specified for a structure is enshrined in the ‘design concept’ for the structure. The design process is facilitated through the use of suitable codes of practice and standards for structural design. In this setting, structural engineers and designers draw upon their knowledge, experience, skill and judgement to realise the above requirements and make suitable design decisions with a certain degree of freedom afforded to them in this process.

### 2.3 Code-based structural design: implications for robustness

#### 2.3.1 Assumptions, idealisations and major considerations and their implications and validity

The code-based structural design process can be seen as a means of providing efficient rules for the design of the broad range of structures that fall within the validity range of the codes. The design codes fundamentally aim at providing a viable basis for the design of structures which on the one side provides adequate structural safety through an efficient use of materials and technologies and on the other side sufficiently caters to the need for a highly standardized and efficient design process.

For the purpose of standardising structural design and design verification through the use of practically applicable structural design codes, present best practice of structural analysis and design involves a number of idealisations and simplifications introduced in different aspects of relevance for the design. Some of these include:
• The loading situations explicitly considered by the design codes can at best be understood to represent an idealisation of the real loads and envelope the actual load effects in the structures during their service life. Actually occurring loads are therefore represented by a set of enveloping loads and suitable load combinations specified in design codes.

• The performance of structures is addressed with regard to a set of specified design situations referred to as limit states.

• Design values are defined to account for relevant uncertainties associated with loads, materials, models, deterioration phenomena and execution.

• Design verification is focused on the performance of individual failure modes of structural elements, connections and to a limited extent also selected (specific scenario-based) failure modes of structural systems. Structural failure modes are generally considered by addressing critically loaded cross sections, components and details.

• Dependencies between failure modes as well as other possible jointly contributing effects which may lead to damages and failures in the structures are generally not accounted for.

• Design equations for different limit state design verifications are based on simplified physical representations of the real structural performance.

• Consequences of failure and damage are marginally considered in setting criteria to acceptable failure probabilities. Consequence reduction in case of warned structural failures and accidental load cases are only implicitly considered through the criteria for acceptable failure probabilities.

• Most structural deterioration effects are assumed to i) exist within certain but generally unspecified boundaries and ii) remain under control through best practice inspection and maintenance strategies.

• The assumptions made with regard to the use of the structures at the time of design are generally assumed to remain valid throughout the service lives of the structures.
Assumptions are also made in design codes and standards with regard to material and product use and quality as well as personnel competencies associated with the use of codes and standards – these include (BSI, 2002):

- The quality of materials, design verifications, drawings, manufacturing, workmanship and future maintenance is assumed to fulfil certain standards and specifications. The performance of materials is described in terms of a few selected parameters.
- The structural design and execution processes are carried out by appropriately qualified and experienced personnel.
- Adequate maintenance of the structure is carried out as laid out in the design concept and maintenance plan.
- The design, execution and maintenance processes are carried out under adequate supervision and quality control. Gross errors are assumed to be identified and generally taken care of by means of suitable quality control procedures.
- The structure is used in accordance with the design concept.

In addition, several specific idealisations and simplifications are assumed and used in the evaluation of different aspects of structural behaviour and also within the scope of the degree of freedom given to the personnel involved in the design, execution and maintenance processes. For instance, some assumptions made in the context of alternate load path analyses and member removal analyses include (Cormie et al. 2009):

- The structural bay above the ‘removed’ column responds as a single, discrete point mass if the structural response is characterised by a dominant deformation mode.
- The rate at which the ‘column loss’ load is redistributed is taken to be instantaneous in the estimation of an upper bound solution to the dynamic response.

The use and understanding of such assumptions, simplifications and idealisations are deemed to be made through the exercise of sound judgement.
and due diligence by the personnel involved in the design, execution and maintenance processes in accordance with their knowledge, experience and technical skills. This applies both with regard to the implementation of the codes and standards as well as to the degree of freedom given to the personnel involved in the various processes.

The set of assumptions, simplifications and idealisations made in the design, execution and maintenance processes therefore influence:

- the degree to which the combined outcome of these processes represents the actual envisaged structure.
- the balance between the considerations and requirements related to use, safety, performance and economy

and impose a set of boundary conditions or constraints for the design, execution and maintenance processes.

2.3.2 Principal structure of modern design codes and the design envelope

Modern code based structural design is based on a set of documents typically comprising:

- a code on general principles which defines the code standard safety format
- codes on the specification of actions including loads which prescribe appropriate load combinations for the structure
- codes on the specification of (generally material specific) resistances, design equations and limit states
- standards for the production of materials
- standards for execution, protection, maintenance and repair
- standards for quality control

Code-based structural design is typically based on a philosophy wherein the individual structural components are assessed and designed to ensure that their
resistance or load carrying capacity is sufficient to resist loads or the effects of actions corresponding to different relevant load scenarios. The load scenarios are established by considering, in turn, the different relevant loads as being the leading load and combining their extreme effect with the corresponding factored effects of other relevant loads.

The code standard safety format provides an explicit quantifiable basis to ensure an adequate margin of safety between the set of actions on the one hand and the set of resistances on the other. This is done through, for example, the use of the load and resistance factor design (LRFD) approach and the partial factor system in the Eurocodes. The implementation of this set of codes and standards in the design process provides a design envelope for the structure which aims to encompass and represent the design concept (defined in Section 2.2) together with the different possible interactions between the design concept and the totality of its external environment. The design envelope attempts to take into account considerations and requirements related to use, safety, performance and economy together with possible constraints and provides suitable design criteria with respect to identified and explicit design situations typically in the form of limit states.

Modern codes of practice and standards for structural design such as the Eurocodes are generally based on a probability-based partial factor design approach. Safety and performance (such as those pertaining to serviceability) requirements in Eurocodes based on identified design situations are considered to be fulfilled through the application of the partial factor method (BSI, 2002; Vrouwenvelder, 2008). The formal link between the set of partial factors and probabilistic methods of structural design can be established through code calibration. The partial factors used for actions and resistances aim to account for possible unfavourable deviations of the actions and resistances from their characteristic values, possible inaccurate assessment of the action effects and resistances and their significance for safety and the reduced probability of combinations of actions all occurring at their characteristic values (Beeby, 1999).

On the basis of the assumptions, idealizations and simplifications made in the design process, the set of design codes and standards facilitate a relatively
simple design verification process through the use of standard safety formats. Subject to the considered assumptions, simplifications and idealizations, the safety formats are calibrated such that the reliability of the structures with respect to the explicitly considered structural performance states is appropriately high. Reliability analysis of structures in general and its applicability especially for the purpose of code calibration (Faber and Sørensen, 2003; JCSS, 2003; Sørensen et al., 1994) in the context of structural component design has undergone strong development over the past few decades and can now be considered as a well-established tool in structural engineering.

It is very important to fully appreciate that the structural reliability assessments performed for the purpose of code calibration are indeed performed under the same best practice simplifications and idealizations that exist in the code-based structural design verification regimes. In this perspective it needs to be realised that the reliabilities are dependent on a number of assumptions which may or may not be fulfilled. Optimal code-based design therefore strives to achieve a balance between use, safety, performance and economy within this framework whose boundary conditions are partly established by the set of assumptions, simplifications and idealisations.

The considerations and the procedures associated with the standard safety format and the design envelope mostly cater to design situations at the level of individual members of a structure. In addition to the identified design situations considered in the standard safety formats and the design envelope, design codes and standards also specify provisions and measures aimed to ensure robustness in structures for design situations beyond the design envelope. The understanding of robustness here is that of a system-wide characteristic with the consequences resulting from possible initiating events or causes being not disproportionate to the initiating event or cause, as discussed in Section 2.1. Such provisions are typically in the form of requirements for tying of structural components, performance of joints, ductility considerations, design for member removal situations and key element design procedures. These additional prescriptive provisions specified by most design codes aim to ensure robust structural performance mostly in an implicit manner as opposed to the more explicit considerations in the standard safety format. In some select cases,
design codes also provide some explicit requirements and design situations for certain types of structures subject to specific extreme load conditions; for instance, a separate code in the Eurocodes system (BSI, 2006) is provided for the consideration of accidental loads with particular focus on impact and internal explosions. However, the more general and explicit code basis and requirements for ensuring sufficient structural robustness remain largely unspecified; this largely leaves the structural designer with the problem and the responsibility of understanding and dealing with robustness in an appropriate manner.

In this manner, the set of codes and standards for structural design stipulate the required reliability towards the fulfilment of safety and lifecycle performance (involving considerations for serviceability, durability and other criteria) of structures. This approach is illustrated in Figure 2.1.

2.3.3 Treatment of uncertainties

As with any engineering decision problem, structural design involves several uncertainties whose consideration and treatment play an influential role in shaping the success or failure of the process. In the field of engineering risk assessment, it has become standard to differentiate between uncertainties due to inherent natural variability, model uncertainties and statistical uncertainties. Uncertainties due to inherent natural variability and randomness are referred to as aleatory (or Type 1) uncertainties whereas uncertainties associated with modelling, statistical and lack of appropriate knowledge are referred to as
epistemic (or Type 2) uncertainties (JCSS, 2008). The differentiation in uncertainties is primarily introduced for the purpose of setting focus on how uncertainty may be reduced.

In the context of structural design, the primary mechanism to deal with aleatory and most epistemic uncertainties is through the use and implementation of methods such as the partial factor system in the structural Eurocodes. This covers the different components used in the standard safety format pertaining to, for instance, the values of relevant actions and resistances for structural components. However questions arise over the treatment of other forms of predominantly epistemic uncertainties which arise due to the deviations from the design concept of the structure and the implications and validity of the assumptions, idealisations and simplifications made in the design, execution and maintenance processes, overall understanding of the structure and its behaviour as well as due to the occurrence of gross errors in the process. These uncertainties are presently addressed through recommendations of a general guidance nature on quality control and in a rather cyclical manner through further assumptions regarding the competencies of the personnel involved in the design, execution and maintenance processes. Such treatment poses serious and critical questions, particularly in the context of robustness and performance associated with the overall structure.

2.4 Robustness in standards and codes of practice – A review study of European codes and standards

As discussed in Section 2.3, the conceptual formulation of code-based structural design requires the stipulation of provisions and measures to ensure robustness in addition to the considerations arising from the standard safety format. In order to ascertain a systematic understanding of the current consideration and provision for robustness in codes and standards, a comprehensive review of European codes and standards dealing with the design, execution, material aspects and maintenance of concrete and steel structures has been carried out. The robustness related provisions in the standards are identified and categorised according to the following attributes related to risk management:
• Approach to risk treatment
• Nature of risk control
• Relationship with event
• Focus domain of risk reduction
• Phase in the lifecycle of the structure in which the provision is applicable

The details concerning the categorisation scheme are covered in Section 4.2.8.3 (for reasons of better consistency and continuity in discussion). A complete listing of all the identified robustness related provisions in the reviewed standards together with their categorization can be found in Appendix A.

The basis and understanding for achieving robustness is provided at a strategic level in the head Eurocode for structural design namely EN 1990 – Eurocode: Basis of Structural Design (BSI, 2002). Most of the implementation level strategies and measures to ensure robustness are covered in EN 1991-1-7 Eurocode 1: Part 1-7 Accidental Actions (BSI, 2006). A few provisions dealing with robustness also exist in other standards relating to design, execution, material and maintenance aspects. The absence of an organised, direct and performance-based approach to deal with robustness is clearly seen in the set of reviewed codes and standards. The lack of such an approach means that potential synergistic effects that could lead to damages and failures in structures and the impact of possible relevant aggregation of measures to ensure robustness in the different codes and standards are not completely accounted for. Robustness related provisions primarily exist in the form of prescriptive rules, the beneficial impact of which in ensuring robustness is taken to be implicit. Further, such rules are occasionally interspersed among other provisions in codes and standards. There is also no direct link or relationship between the implementation of these measures and the achieved level of robustness (which is essentially expected and considered at the system level).

Strategies and rules to ensure robustness are usually provided with regard to design for what are termed ‘accidental design situations’ which could arise due to identified as well as unidentified or unforeseen accidental actions; this is
shown in Figure 2.2. Structures or (more specifically buildings) are categorised under different consequence classes which are primarily based on the use, occupancy and dimensions of structures. Strategies and measures to ensure robustness are then specified for each consequence class. The principal robustness provisions in the Eurocodes (BSI, 2006) are given in Table 2.1 with a brief commentary.

Figure 2.2 Strategies specified in BS EN 1991-1-7:2006 for accidental design situations (Source: BSI, 2006).

The design situations arising from identified accidental design situations are seen to be dealt with in an explicit manner through the consideration of suitable partial factors and limit states, in a manner principally similar to the consideration of design situations arising from the standard safety format (such as the persistent or transient design situations used in the Eurocodes). The common provisions particularly those that deal with the unidentified or unforeseen actions include the provision of tying systems and increased local resistance for selected components. The use of segmentation as a strategy for risk control is not recommended, except in the context of fire protection design where segmentation is linked to the performance criteria of integrity.
### Table 2.1 Principal robustness requirements in the structural Eurocodes.

Several other provisions to deal with robustness are seen to be either of a general guidance nature (e.g. avoidance of errors through quality management) or those that deal with event specific or identified accidental actions (e.g. provision of adequate clearances to guard against impact). The possible merits, demerits and limitations associated with the implementation of these provisions in different environments and conditions are not covered, leaving open questions over their broader relevance and applicability. The context and
relevance of different measures specified for ensuring robustness are not clearly spelt out and hence their (mostly implicit) intent may not be well understood. This is related to the commonly raised questions of whether the use of structural ties is appropriate under all circumstances and whether segmentation can be a robustness relevant strategy outside the scope of fire protection design.

A majority of the measures need to be implemented during the planning, design and execution phases of a structure. It is implicitly assumed though not visibly demonstrated that if these measures are adequately and efficiently implemented, a sufficient though not specified level of robustness remains during the life of the structure. There are no provisions for some form of ‘robustness monitoring’ over the lifecycle of the structure. This has implications therefore for the assessment and improvement of robustness in existing structures.

With regard to the manner or risk reduction for overall structure or system failure, the effect of measures such as limits for localised failure, incorporation of redundancy and provision of tying systems that aim to minimise the occurrence of system failure is again seen to be implicit in intent and not elaborated or spelt out explicitly. This can also be said of measures such as the provision of ductility and avoidance of brittle failure that help to contain consequences arising from a system failure.

2.5 Inadequacies and limitations of current code-based practices in dealing with robustness

2.5.1 Focus on a component-centric approach

Modern codes and standards for structural design are based predominantly on the design of structural members and the consideration of individual member failure modes (ASCE, 2010; BSI, 2002; BSI, 2005; BSI, 2006; JCSS, 2001a; NBCC, 2010). The focus is therefore on the quantification of performance, assurance of safety and optimisation of reliabilities at the level of structural members and connections. When the overall ability of a structure to sustain damage/failure is considered, the codes and existing design practices are
visibly less specific. There exist only a few considerations of relevance at the structural system level – these include, for instance, the provision of effective length factors in the stability analysis of low-rise frames and the use of response modification coefficients to account for inelastic behaviour and energy dissipation in earthquake resistant design (Ellingwood, 2000).

One of the basic needs to consider the concept of robustness stems from the component centric thinking enshrined in modern standards and codes of practice for structural design. Such an approach aims to ensure the satisfactory performance of structures mostly through a consideration of the individual components of a structure. Against this backdrop of component centric thinking, relevant design scenarios of importance for the integrity of the overall structure and considerations relating to system effects and gross errors are not given commensurate consideration. At the level of the entire structure, design codes typically require structures to be robust through the implementation of specified prescriptive rules, without providing a direct and transparent demonstration or verification of whether these are sufficient and adequate. Considerations pertaining to the performance of the overall/entire structure are generally either not directly considered or deemed to be accounted for through such prescriptive rules which are mostly implicit in their intent. The implementation of such rules for robustness also does not possibly allow for a rational optimisation of resources and performance at the system level, similar to reliability-based code optimisation that currently exists at the structural member design level. Since robustness has a meaningful and complete association at the level of the entire structure, the very conceptual component-focused formulation of structural design codes and standards can be considered to be an inadequacy or mismatch with regard to the establishment of optimal and adequate provisions for robustness.

2.5.2 Implications of assumptions

In order to facilitate an efficient implementation of the code-based structural design process, several assumptions, simplifications and idealisations are made during the course of the process – these have been discussed in Section 2.3.1. Structural performance mostly at the member level is deemed to be directly
accounted for through the consideration of appropriate limit states. This is done within the frame of the different assumptions, idealisations and simplifications, giving a corresponding idealised and simplified model representation of the designed component. System performance however is not directly accounted for in the code-based design process.

Due to these assumptions, simplifications and idealisations and possible inadequacies in the design process, certain aspects associated with safety and performance of the structure particularly those associated with system performance are not adequately or demonstrably accounted for – this can be seen as one of the principal reasons behind the need for the requirement of sufficient structural robustness in addition to the requirements for reliability. The deviations from the structural design concept and the validity and the implications of possible deviations and violations of these assumptions, simplifications and idealisations (which may arise due to the use of imprecise models, insufficient data, inherent natural variability or subjective experience and judgement) also pose serious questions with regard to system performance and system integrity, some of which, though not all, may be answered through an appropriate treatment of uncertainties in the design process.

2.5.3 Ambiguities and shortcomings in robustness provisions
The head Eurocode for structural design (BSI, 2002) prescribes the following requirements that may be seen as establishing the basic understanding of robustness without the explicit use of the word ‘robustness’ itself:

- A structure shall be designed and executed in such a way that it will not be damaged by events like explosion, impact and the consequences of human errors, to an extent disproportionate to the original cause.

- In the case of fire, the structural resistance shall be adequate for the required period of time.

Even though the information and intent contained in the above requirements is substantial and well-intentioned, it may be seen as being highly ambiguous. As a result, structural engineers and users of such design codes have little
practical or specific guidance on the understanding, implementation and implications of such provisions for structural robustness.

The shortcomings and limitations associated with code provisions that aim to ensure robustness have been well documented in Section 2.4. In essence, the design code approach to robustness does not provide for the quantification of robustness of a structure akin to the quantification of component reliabilities but is based on ensuring a notional level of robustness through the application of specified prescriptive rules that aim at risk mitigation through different means. Therefore, a set of such robustness provisions can at best be seen to provide a useful contribution to the robustness level of a structure. There is no demonstration and verification mechanism to show that sufficient robustness has been provided.

2.5.4 Understanding of overall system behaviour

The organisation of the code-based structural design process leaves open possible avenues in which several considerations, particularly those associated with system effects are not considered. This translates to a lack of a holistic understanding of structural performance and robustness, particularly under different unfavourable situations and environments. A clear influence is also exerted by the degree of communication, knowledge transfer and continuity through the planning-design-execution-maintenance chain. This continuity is particularly relevant for system behaviour and can be expressed in the form of the following basic requirements (Beeby, 1999):

- The system visualised by the designer must be a structurally valid system and it must be complete.
- The quantitative model representation must adequately represent the system.
- The intentions of the designer with regard to the design of the structural system must be accurately and unambiguously communicated to the execution team.
- The structure must be executed in accordance with its structural design.
• The structure must be used and maintained as intended during its lifetime.

The increasing complexity of structural design and the fragmentation of the design process have increasingly endangered the sustenance of this continuity. Any deviation in this chain of continuity has possible implications for system performance and robustness which may not be adequately factored in the planning, design, execution and maintenance processes.

Further, the absence of a standard safety metric at the level of a structural system is also seen in structural design practice. In the absence of such a metric, it is not possible to quantify and ensure a certain degree of safety for a structural system or to evaluate the effectiveness and robustness of system designs through a comparison of the safety levels of different systems, as can be done in the case of different possible design options for structural elements.

### 2.5.5 Quality management

The degree (or possible lack) of adequate quality control in following and implementing the relevant codes and standards during the design, execution and maintenance processes has a profound impact on the success of these processes and may be seen to be instrumental in the possible generation of synergistic effects and gross errors at the structural system level that significantly influence the robustness of the structure. This is clearly influenced by the knowledge, competence, skill, experience and judgment of the personnel involved in the design, execution and maintenance processes. Further, another important issue is associated with the degree of freedom given to the personnel in the design, execution, maintenance processes in the use of the codes and standards. This becomes crucial when it involves the interpretation of the intent of the codes and standards in cases where only qualitative and general normative guidance is available – a situation that can be very relevant for robustness.

In view of the above concerns detailed in Sections 2.5.1 to 2.5.5, a significant amount of research has been carried out into the various aspects of robustness resulting in a number of useful recommendations and approaches on the assessment and provision of robustness in structures. However, despite these
significant theoretical, methodological and technological advances over the recent years, structural robustness still poses difficulties with regard to its interpretation, regulation and provision.

2.6 Approaches for the assessment and quantification of robustness and associated properties

Several approaches can be found in the literature for the assessment and quantification of robustness and associated properties that include vulnerability, redundancy and reserve capacity. The approaches can be deterministic, probability-based or risk (probability and consequence)-based in their conceptual formulations. There also exist divergent perspectives with regard to whether robustness should be considered as an inherent property of a structural system or whether it should also include external effects relating to the consequences of possible failures as well as the options for managing the integrity of structures over their lifetime.

2.6.1 Risk-based assessment of robustness

A risk-based approach for the assessment of structural robustness is proposed in Baker et al. (2008) based on a risk assessment framework for engineering decision making developed by the Joint Committee on Structural Safety (JCSS, 2008).

![Event tree representation for the quantification of robustness](Source: Baker et al., 2008).
The assessment is facilitated by the consideration of an event tree representation shown in Figure 2.3. The procedure begins with the consideration and modelling of exposures \((EX)\) that have the potential to cause damage to the components of the structural system. Exposures could include extreme values of design loads, accidental loads and deterioration processes. Damage here refers to reduced performance or failure of individual components of the structural system. After the exposure event occurs, the components of the structural system either remain in an undamaged state \((D)\) as before or change to a damage state \((D)\); a number of different damage states can be generated depending on the exposures. Each damage state in combination with other relevant damage states can then either lead to the failure of the structure \((F)\) or no failure \((\overline{F})\). The modelling of the relevant damage and failure states is followed by a holistic consideration of the consequences resulting from the damage and failure states. Direct consequences \((C_{DIR})\) are considered to result from damage states of individual components of the structural system. Indirect consequences \((C_{IND})\) are incurred due to loss of system functionality or failure and can be attributed to lack of robustness. The direct risks \((R_{DIR})\) are then determined by considering all direct consequences along with the respective probabilities of the occurrence of the exposures and the occurrence of damages given the occurrence of the exposures:

\[
R_{DIR} = \int_{z} C_{DIR} p(D|EX) p(EX) \, dz
\]  

(2.1)

The indirect risks \((R_{IND})\) are similarly determined by considering all indirect consequences along with the respective probabilities of the occurrence of the exposures, the occurrence of damages given the occurrence of the exposures and the occurrence of system failure given the occurrence of the exposures and damages:

\[
R_{IND} = \int_{z} C_{IND} p(F|D,EX) p(D|EX) p(EX) \, dz
\]  

(2.2)

For a complete risk analysis, the evaluation of the direct and indirect risks needs to be carried out considering all possible and relevant exposures, damage states and failure states for the structure and integrating over the vector of all random variables \((Z)\) associated with the structure.
The index of robustness ($I_{ROB}$) is then defined as:

$$I_{ROB} = \frac{R_{DIR}}{R_{DIR} + R_{IND}}$$  \hspace{1cm} (2.3)

The index takes values between zero and one depending upon the source of risk. A robust system is considered to be one in which indirect risks do not contribute significantly to the total risk. When there is no risk due to indirect consequences, the structural system is regarded to be completely robust and the index of robustness equals one. An important caveat to be borne in mind is that this index measures only the relative risk due to indirect consequences. This means that the acceptability of the direct risks should be determined through other criteria (such as reliability associated with structural members) prior to the acceptability of the indirect risks or robustness being considered.

Several scenario specific applications of this risk-based approach for the assessment and quantification of robustness can be found in literature. The assessment of robustness for a highway overpass structure for vehicular impact has been presented in Schubert and Faber (2007); here the effect of different engineering measures on the structural performance and robustness of the bridge structure are studied. A time variant assessment of robustness involving the consideration of structural deterioration and the implementation of inspection and repair actions during the lifetime of a structure can be found in Schubert (2006). The evaluation of robustness of a post-tensioned highway bridges has been reported in Von Radowitz et al. (2008) where the effect of different deterioration caused damage states such as stress-corrosion cracking, chloride induced corrosion as well as creep and shrinkage on the structural robustness are studied. Further, a quantitative evaluation of structural robustness for a high rise building structure has been presented in Narasimhan and Faber (2008) illustrating the use of the risk-based approach in collapse assessment. Here different scenarios are analysed to study the effect of parameters such as intensity of exposure, degree of ductility of structural elements, location of damaged elements with respect to height and orientation in the structural frame on the probability of system failure and robustness.

It is recognised that probabilistic risk assessment can be used to assess robustness in a general manner (Ellingwood, 2005). This risk-based approach
can therefore be seen to provide an ideal in-principle approach for the consideration of all possible exposures, damages and consequences relevant for a structure; however its use in this complete form poses practical implementation difficulties in common structural design practice.

### 2.6.2 Vulnerability and robustness

The concept of vulnerability and its understanding have been used in the assessment of robustness of structures. The vulnerability of a structural system can be understood to be its degree of susceptibility to damage. It is the inability of a system to resist a hazard or to respond to an adverse action and provides a contrasting perspective to appreciate the concept of structural robustness. A useful insight into the lack of robustness can hence be gained by identifying how a system is vulnerable. The focus is to determine the most likely failure scenarios and identify events which may expose the lack of robustness – reliability analysis may be useful for such applications. Having identified what makes a system vulnerable facilitates the design and implementation of appropriate remedial actions.

A simple but useful probability-based measure of vulnerability and damage tolerance that can be associated with robustness is presented in Lind (1995) and Lind (1996). Here the degree of damage tolerance of a structure is related to its integrity to withstand unforeseen disturbances without any undesirable response. Vulnerability and damage tolerance are considered to be complementary concepts. The measure of vulnerability is developed using the loading or exposure exerted on the structure and the corresponding system state of the structure. The probability of failure of the structure \( P(r, S) \) in a system state \( r \) for a considered loading or exposure state \( S \) is considered. If the undamaged or pristine system state of the structure is denoted by \( r_0 \) and a certain damaged system state is denoted by \( r_d \), then the vulnerability \( V \) of the structure in a system state \( r_d \) for a loading state \( S \) is defined as:

\[
V = V(r_d, S) = \frac{P(r_d, S)}{P(r_0, S)} \quad (2.4)
\]
For the considered case, the vulnerability of the structure is one if the probability of failure is the same in the damaged and undamaged system states. If transition from \( r_0 \) to \( r_d \) increases the probability of failure by a factor \( f \), then the associated vulnerability is equal to \( f \). This measure of vulnerability therefore provides a simple working means of evaluating the adequacy of a structural system with respect to robustness and also other performance characteristics associated with a structure. However such an evaluation is conditional on the considered exposure or loading states and the corresponding definition of the system state for the considered structure and also does not account for consequences of the system states that may have a significant bearing on the robustness of the structure.

### 2.6.3 Redundancy and robustness

The concept of redundancy in structures has also been used to relate to the evaluation and quantification of robustness. Frangopol and Curley (1987) and Fu and Frangopol (1990) have considered the use of probabilistic indices to measure structural redundancy based on the relationship between (component) damage probability and (system) failure probability. A probability-based redundancy index \( RI \) for the representation of system redundancy has been defined in Fu and Frangopol (1990) as:

\[
RI = \frac{P_{f(dmg)} - P_{f(sys)}}{P_{f(sys)}}
\]  

(2.5)

Here \( P_{f(dmg)} \) denotes the probability of occurrence of damage due to component failure and \( P_{f(sys)} \) denotes the probability of failure of the structural system. The occurrence of damage due to component failure can be related to performance limit states associated with the members of the structural system. The difference between the probability of occurrence of damage due to component failure and the probability of failure of the structural system is considered to represent the system residual strength. A structural system is then considered to be non-redundant if the redundancy index is zero or if the probability of occurrence of damage due to component failure and the probability of failure of the structural system are equal (which may be the case, for instance, for a
perfect series system). On the other hand, if the probability of occurrence of
damage due to component failure is greater than the probability of failure of the
structural system, this indicates that the system possesses certain residual
strength which can be quantified through the redundancy index. The
redundancy index is seen to be highly dependent on the specific damage states
considered for the component failures and also does not consider the influence
of the consequences arising from the damage and failure states. Questions
therefore remain over its applicability for a wide range of damage and failure
states relevant for a structure. Furthermore, a one-to-one correspondence
between redundancy and robustness may not be applicable in all the
considered contexts and scenarios for structures.

2.6.4 Other measures and studies

Several other studies found in literature have considered the evaluation of
robustness and associated properties for specific classes of structures
subjected to specific damage scenarios. A relatively well-studied case is the
progressive collapse of frame structures (Ellingwood & Leyendecker, 1978;
Vlassis et al., 2006). The robustness studies of overpass structures in
Switzerland has been reported in Stempfle and Vogel (2005) and Stempfle and
Vogel (2006). The vulnerability of flat slab structures has been studied and
presented in Müllers and Vogel (2005). Studies of this nature are important for
characterizing failure probabilities for specific scenarios but it may be difficult to
generalise the obtained findings to other types of systems or other forms of
damage.

Stiffness and energy-based measures for the quantification of robustness have
been proposed in Starossek (2009). General methods that are applicable to any
engineered system have also been considered for quantification of robustness.
Information-gap theory has been applied to the problem of robustness in Ben-
Haim (1999) and although it can be applied to general systems, challenges
remain in using the method to balance robustness improvements with their
associated costs.
The evaluation of structural system reliability or system probability of failure is essential for most approaches that aim to quantify robustness and associated properties. Such assessment typically involves the consideration of different combinations of numerous possible failure modes for the components of the structure together with their associated dependencies and interactions and can be technically challenging and computationally demanding. Several approximations and numerical approaches have been proposed to overcome these challenges; however, issues concerning their universal applicability and comparison of evaluations remain. The challenges and demands posed by such evaluations of system reliability can be seen to be relevant particularly in the context of standard structural design practice.

### 2.6.5 Summary

The different approaches in literature are seen to appeal to their respective constituencies or specific contexts and scenarios during application and are accompanied by their own complexities, implementation issues and limitations. Such approaches have therefore not gained universal applicability for wider use in structural design practice as reflected in codes and standards.

### 2.7 Outlook

It is important to visualise and assess the safety and performance of a structure in association with its environment, function and use. With this understanding, robustness can be appreciated as a performance attribute of an overall structural concept which encompasses the structure, its design, execution, function, operation and condition management over its entire lifecycle. A robust structural concept can ensure that consequences arising from any event of deviation from the structural concept are either zero or reduced to the consequences commensurate with the event itself. The importance of the consideration of robustness in structural design and lifecycle performance management has been brought out in Section 1.1. There exist several inadequacies and limitations in current code-based practices to deal with robustness – these have been discussed in Sections 2.4 and 2.5. Further, the
development and emergence of several approaches for the assessment and quantification of robustness and associated properties described in Section 2.6 have not provided adequate answers sought by the structural engineering community to the questions on handling robustness in structures.

It has therefore become necessary to think and deal with structural robustness through a better organised, direct and explicit approach. The approach needs to be of a generic nature applicable to both common structures as well as extraordinary structures but also specific enough to be adapted and used for different cases and practically manageable from the perspective of structural design practice. Therefore, it is first necessary to develop a sound foundation for the treatment of structural robustness in future structural design codes. This will lead to the establishment of a normative basis for a future design code format in which robustness is systematically and more explicitly considered with regard to lifecycle performance. This will ultimately pave the way for a seamless incorporation of adequate and optimal robustness considerations and strategies into structural design procedures and future design codes and standards.

A holistic assessment of robustness requires a clear consideration and modelling of not only the occurrence of events of relevance such as exposures, damage states and failure states but also their ensuing consequences. The risk-based approach provides useful lessons and a strong basis in this regard and will be revisited in the next chapter.
Chapter 3
Towards sound assessment and improvement of robustness of structures

3.1 Introduction
An ideal optimal structural design can be considered to be one wherein it is possible to establish a perfect risk model for a given structure for which all information about exposures, consequences of failures (both component related and system/structure related) as well as a complete probabilistic model of knowledge (aleatory as well as epistemic uncertainties) is available. Such a utopian ‘complete risk model’ adequately accounts for and provides optimal solutions for all design scenarios or events including those that are concerned with the robustness of the structure. An ideal optimal design of a structure can then be based on this model, with the total risk being used as a means to rank different possible design alternatives.

In principle, a complete risk model can provide the necessary answers to the questions posed of the structural design with regard to system performance, integrity and robustness. In practice, it is however not possible to realise such a model. However an understanding of the underlying principles in risk-based design provides a viable basis for the establishment of a comprehensive and consistent framework and principles for the assessment and improvement of robustness of structures.
3.2 A risk-based design approach through consideration of component (direct) and system (indirect) risks

3.2.1 Basic principles and framework

The general objective of a risk-based design for a structure is to evaluate and reduce risks associated with the structure with due consideration to the adequate safety and performance of the structure at an economically acceptable cost. Risks may be expressed in terms of the probability of occurrence and the consequences of the different events and scenarios under consideration in the design process. Risk reduction may hence include measures (such as provision of protective barriers) that aim to reduce the probability of occurrence and measures (such as provision of sprinklers and vent openings) whose intent is to reduce consequences. It is however not possible for any design to consider and account for all possible effects that could arise due to different actions, causes and influences during the lifetime of the structure; therefore the underlying principle as enunciated in several design codes and standards in the context of robustness and discussed in Chapter 2 is that the structure should not be damaged to an extent disproportionate to the cause of the damage (BSI, 2002).

The basic principles of a framework for risk-based engineering decision making are described in a guideline document published by the Joint Committee on Structural Safety (JCSS, 2008) and are adapted here to form the basis for discussion in this section. In this context, it is essential to first establish the concept of a system for analysis. Here a system is considered to be a set of logically interrelated constituents established at various levels of detail and scale in time and space. The constituents of the system may be physical components such as structural elements or procedural processes like design, execution and maintenance. The appropriate level of detail or scale depends on the physical or procedural characteristics or any other logical entity of the considered problem as well as the evolving spatial and temporal characteristics. Importantly, the development of a system model facilitates a risk assessment and risk ranking of decision alternatives which is consistent with available knowledge about the system and which enables that risks may be updated according to the knowledge that may be available at future times. Optimal
decisions can then be identified as those that yield the maximum utility or benefit in accordance with the preferences expressed by the concerned decision makers and stakeholders.

Figure 3.1 Generic system representation in risk assessment (Source: JCSS, 2008).

The risk assessment for a given system is facilitated by considering the generic representation shown in Figure 3.1. Following Faber and Maes (2005a), the exposure to a system is represented as a set of different exposure events acting on the constituents of the system. Exposures refer to possible events that have the potential to cause damages and consequences for the system; these can include events of natural hazards, malevolence, deterioration processes and the effect of human activities such as gross errors. The constituents of the system can be considered as the first defence of the facility in regard to the exposures. The damages or failures of the constituents due to the occurrence of the exposures are considered to be associated with direct consequences. Direct consequences may include economic losses, loss of lives, damages to the qualities of the environment or just changed characteristics of the constituents. Based on the combination of events of constituent failures and the corresponding consequences, follow-up or indirect consequences may occur. Indirect consequences are associated with the loss of functionality of the entire system caused by the combined effect of constituent failures. Typically the indirect consequences evolve beyond the spatial and temporal boundaries of
the system. The indirect consequences in risk assessment play a major role and their modelling should therefore be carefully considered (Faber & Maes, 2004).

### 3.2.2 Outline of a risk-based structural design procedure

Based on the framework described in Section 3.2.1, a general outline of a risk-based procedure for structural design is described here.

#### Identification of structural system and relevant exposures, damages and failure states and risk screening

First, a clear identification and definition of a structural system for the purpose of risk analysis is necessary. A structural concept is established through a judicious balance between the considerations and requirements related to use, safety, performance and economy. The spectrum of all relevant exposures for the structure along with the different damage, malfunction and failure modes for structural components as well as structural systems is then ascertained. A thorough consideration of the various components (structural members and connections) within the system and possibly the establishment of a ranking system of components based on their criticality to system integrity and performance may be established. Next, all relevant design and assessment situations are identified and any deviations from the structural concept considered. A risk screening exercise is then carried out and the scenarios relevant for future consideration are identified.

#### Modelling and quantification of exposures, damage and failure scenarios

An assessment and modelling of the probabilistic characteristics of the occurrences and intensities of the relevant exposure events is carried out. Suitable probabilistic models for relevant characteristics of structural components (such as strength and stiffness properties) and connections are also identified. Using these models, a systematic modelling and quantification of the different damage, malfunction and failure modes for structural components
as well as the structural systems identified in the risk screening with consideration of the necessary dependencies and interactions are carried out.

**Modelling of consequences resulting from damage and failure scenarios**

A thorough assessment and modelling of the consequences resulting from the considered component damage and system failure mode are then carried out. This involves the development of a clear and consistent basis for distinction between direct consequences (affecting individual structural components) and indirect consequences (affecting the entire structural system).

**Assessment of risk – quantification, treatment and acceptance**

Following the modelling of the exposures, damage and failure states and consequences, the ensuing risks need to be quantified and evaluated. This involves the combination of the probabilities of the considered domain of scenarios (exposures, (component) damage states and (structure) failure states) and their consequences together with the necessary dependencies and aggregation for the estimation of total direct and indirect risks for the structure. As discussed in Section 2.6.1, a measure of robustness of the structure may then be obtained as the ratio of the indirect risks to the total risks for the structure. Risk treatment and mitigation can be accomplished through measures that result in changes in the characteristics of the structure with regard to exposures, component damage states, system failure states or consequences. These measures may then be considered as possible decision alternatives or design options in a decision optimisation framework, with the objective being to optimize the expected utility to be achieved by the decision making. Finally, suitable risk acceptance criteria for tangible as well as intangible risks are established and evaluated.

The procedure outlined above is illustrated in Figure 3.2. Here, phase 1 denotes the modelling of exposures for the structure, phase 2 corresponds to the modelling of the damage states of the components of the structure and phase 3 symbolises the modelling of the performance of the structure through the failure
states of the structural system and the ensuing consequences. Such a risk-based approach can be seen to constitute an onerous task and pose implementation issues in standard structural design practice.

Figure 3.2 Illustration of a risk-based structural design approach (Source: BSI, 2002; Faber et al., 2004).

3.2.3 Reliability analysis and uncertainty modelling

In the context of structural design, the exposures and the constituent damages for a structural system are respectively modelled as loads and resistances/vulnerabilities for the constituents of the system through the use of reliability methods and uncertainty modelling. This is also the basis of structural design codes and standards such as the Eurocodes. Structural reliability methods presently provide a well-developed basis for engineering decision making in structural design and are also widely used for the purposes of code calibration, assessment/reassessment of existing structures, design of extraordinary structures, inspection and maintenance planning and lifecycle analysis.

Furthermore, basic knowledge concerning the exposures (actions) as well as resistances and material characteristics for structures has gradually improved due to scientific, methodological and technological advances with time. This knowledge has now reached a level where it is now possible to reliably take into account uncertainties in material properties and actions in the assessment of load carrying capacity, resistance, serviceability and service life in structures.
General guidelines for the use of structural reliability methods in practical applications are available (JCSS, 2001a; JCSS, 2001b) which can be seen to constitute the basis for ensuring that the modelling of exposures and resistances is performed on a theoretically consistent basis. These developments have led to an increasingly more consistent, reliable and transparent evaluation of safety and reliability; however this has happened predominantly at the level of members and connections in structures.

3.2.4 System reliability and performance in risk-based design

The use of reliability theory in the design and assurance of structural component safety and performance may be seen as a necessary but not sufficient condition for ensuring robustness in structures. This is particularly evident in its inability to handle considerations such as system effects and gross errors. As seen in Section 3.2.2, the evaluation of indirect risks requires the consideration of failure states of the structure/system and their probabilistic modelling. The occurrence of exposure events leads to the possibility of occurrence of damages in one or more components of the structure. These component-specific damage states, either acting independently and/or in interaction with one another, contribute to the possibility of failure of the structure. The determination of system reliability provides a measure of the probability of failure of the structure. This is, however, not a straightforward task; the existence of numerous possible individual failure modes in a structural system and their interactions act as significant impediments in the determination of a reliable probability of failure of the system. Several methods and software tools have been developed to provide estimates of the system reliability or system probability of failure (Moses, 1982; Thoft-Christensen & Murotsu, 1986; Ditlevsen & Bjerager, 1986; Galambos, 1990; Naess et al. 2009). However the use of such methods has not evolved to a level of standardisation and implementation in common structural design practice and in codes and standards, possibly due of the component-centric design philosophy in codes and standards and also because the work involved in such evaluations can be technically challenging and computationally demanding.
3.2.5 Simple illustration – design of a truss structure

In order to illustrate the use of a risk-based structural design approach and an associated evaluation of robustness, a simple example (Narasimhan et al., 2009; Garrè, 2009) involving the design of a one-bay truss structure shown in Figure 3.3 is discussed here. The design of the structure is demonstrated for three different design approaches:

- Code-based design following the Eurocode approach (BSI, 2005).
- System reliability-based design based on a requirement for the system reliability or system probability of failure.
- Risk-based design explicitly taking into account the probabilities and consequences of failures.

Figure 3.3 Illustration of the truss structure considered for investigation.

A corresponding optimisation problem is formulated for each design. The objective function for minimisation used for the code-based design and the system reliability-based design is taken to be the total construction cost, with a restraint on the value of the annual system probability of failure (an upper bound of $10^{-4}$) included in the system reliability-based design case. For the risk-based design case, the objective function includes the total construction cost and the expected value of the failure costs arising from system as well as component failure discounted over the lifetime of the structure. The modelling parameters considered for the exposures (loads), material properties and resistances are based on the JCSS Probabilistic Model Code (JCSS, 2001a) and shown in Table 3.1.
Towards sound assessment and improvement of robustness of structures

<table>
<thead>
<tr>
<th>Variable</th>
<th>Distribution Type</th>
<th>Mean $\mu$</th>
<th>Standard Deviation $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load $R$</td>
<td>Gumbel</td>
<td>$\mu_R = 24$ [kN]</td>
<td>$\sigma_R = 0.2\mu_L$ [kN]</td>
</tr>
<tr>
<td>Yielding stress $\sigma_y$</td>
<td>LogNormal</td>
<td>$\mu_y = 250$ [MPa]</td>
<td>$\sigma_y = 0.07\mu_y$ [MPa]</td>
</tr>
<tr>
<td>Young’s Modulus $E$</td>
<td>Deterministic</td>
<td>$\mu_L$ [kN]</td>
<td>$\sigma_L$ [MPa]</td>
</tr>
<tr>
<td>Section properties thickness $t$</td>
<td>Normal</td>
<td>$\mu_t = t_{nom}$ [mm]</td>
<td>$\sigma_t = 0.04\mu_t$ [mm]</td>
</tr>
<tr>
<td>width $w$</td>
<td>Normal</td>
<td>$\mu_w = w_{nom} + \text{Uniform}(-1,1)$ [mm]</td>
<td>$\sigma_w = \text{Uniform}(0,1)$ [mm]</td>
</tr>
<tr>
<td>Length of outer element</td>
<td>Deterministic</td>
<td>$3$ [m]</td>
<td>$-$</td>
</tr>
<tr>
<td>Length of brace element</td>
<td>Deterministic</td>
<td>$4.24$ [m]</td>
<td>$-$</td>
</tr>
</tbody>
</table>

*Table 3.1 Modelling parameters for loads, resistances and properties.*

The limit states for component reliability assessment are based on yielding and buckling failure criteria. The failure of the structural system is defined as the formation of a mechanism in the structure. Direct consequences are considered to be associated with the failure of individual components and represented by material and component replacement costs. Indirect consequences associated with the failure of the entire structure are represented as a multiple of direct consequences and considered to be equal to 100 for this example.

The results obtained from the design optimisation for the three design approaches are shown in Table 3.2. The evaluation of total risks provides a rational basis for the selection of the optimal design alternative for the structure.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Cross sections of brace elements (all in mm)</th>
<th>Cross sections of outer elements (all in mm)</th>
<th>Initial Cost (Swiss Francs)</th>
<th>System probability of failure</th>
<th>Total risk (expressed in Swiss Francs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code based design</td>
<td>$60 \times 60 \times 3$</td>
<td>$50 \times 50 \times 2$</td>
<td>$685$</td>
<td>$1.25 \times 10^{-4}$</td>
<td>$820$</td>
</tr>
<tr>
<td>System reliability based design</td>
<td>$70 \times 70 \times 3$</td>
<td>$50 \times 50 \times 2$</td>
<td>$750$</td>
<td>$3.4 \times 10^{-5}$</td>
<td>$790$</td>
</tr>
<tr>
<td>Risk based design</td>
<td>$70 \times 70 \times 3$</td>
<td>$60 \times 60 \times 2$</td>
<td>$810$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$825$</td>
</tr>
</tbody>
</table>

*Table 3.2 Results from design optimisation.*

Further, an evaluation of robustness based on indicators obtained from literature is carried out. The indicators evaluated include the index of robustness (Baker et al., 2008), vulnerability (Lind, 1995) and the redundancy index (Fu & Frangopol, 1990) – these have been briefly described in Section 2.6. The
results from this evaluation are presented in Table 3.3 with the most favourable alternatives for each case highlighted. For the evaluation of the vulnerability and redundancy measures, the dominant damage states that emerge are the buckling failures of an outer element or brace element. The vulnerability and redundancy measures consider robustness to be a measure concerning only the structure and depend on relative values of damage and failure probabilities. The results from the evaluation of the index of robustness provide a useful indication of situations where consequences need to be considered using a risk-based framework.

<table>
<thead>
<tr>
<th>Index of robustness</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ratio of Indirect to Direct Consequences</strong></td>
<td><strong>Code based design</strong></td>
<td><strong>System reliability based design</strong></td>
<td><strong>Risk based design</strong></td>
</tr>
<tr>
<td></td>
<td>60 x 60 x 3</td>
<td>70 x 70 x 3</td>
<td>60 x 60 x 2</td>
</tr>
<tr>
<td></td>
<td>50 x 50 x 2</td>
<td>50 x 50 x 2</td>
<td>50 x 50 x 2</td>
</tr>
<tr>
<td>5</td>
<td>0.796</td>
<td>0.731</td>
<td>0.551</td>
</tr>
<tr>
<td>10</td>
<td>0.280</td>
<td>0.617</td>
<td>0.499</td>
</tr>
<tr>
<td>20</td>
<td>0.197</td>
<td>0.460</td>
<td>0.366</td>
</tr>
<tr>
<td>40</td>
<td>0.135</td>
<td>0.305</td>
<td>0.252</td>
</tr>
<tr>
<td>80</td>
<td>0.093</td>
<td>0.194</td>
<td>0.202</td>
</tr>
<tr>
<td>100</td>
<td>0.058</td>
<td>0.121</td>
<td>0.143</td>
</tr>
<tr>
<td><strong>Vulnerability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.572</td>
<td>2.947</td>
<td>3.459</td>
</tr>
<tr>
<td><strong>Redundancy index</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Damage state</strong></td>
<td>Code based design</td>
<td>System reliability based design</td>
<td>Risk based design</td>
</tr>
<tr>
<td>Buckling failure of outer element</td>
<td>0.21</td>
<td>3.29</td>
<td>1.88</td>
</tr>
<tr>
<td>Buckling failure of brace element</td>
<td>0.96</td>
<td>1.79</td>
<td>3.04</td>
</tr>
</tbody>
</table>

*Table 3.3 Evaluation of robustness.*

This simple example serves to illustrate the conceptual usefulness of risk-based structural design in a robustness context and the significance of the consideration of consequences in design. At the same time, there exist practical implementation difficulties in applying the method for real life structures; this points to the need for a more practice friendly approach based at the same time on the principles of risk-based design.
3.3 Basis of a modified format for structural design codes for the assessment of robustness

3.3.1 Background and foundation

With respect to the structure of code-based design, the provision of adequate safety in structures can be set out in the form of requirements that comprise:

- a standard safety format – This provides the basis for consideration of situations within the design envelope through the incorporation of models of material and structural behaviour and the underlying uncertainties with the use of appropriate factors of safety.

and

- a set of provisions to ensure adequate robustness – These aim to cater to situations beyond the design envelope and deviations from the design concept of the structure.

The requirements covered under the above two categories (as well as requirements for adequate quality control and supervision of the design, execution and maintenance processes) need to be fulfilled individually and independently in an adequate manner (Beeby, 1999). The design process involves the use of several assumptions, idealisations and simplifications related to different aspects of design and material and structural behaviour; this possibly results in some aspects pertaining to structural safety and performance not being given due consideration in the process. This nature of the process coupled with the predominantly component-centric thinking in engineering design makes it necessary to consider and provide for structural robustness in addition to the requirements for reliability contained in the standard safety format.

Modern structural design codes and standards however do not have a clearly delineated and well-defined separation between the standard safety format and the set of robustness provisions – this has also been alluded to in Section 2.4.
In the context of current code-based design, the above requirements for adequate structural safety therefore translate to:

- fulfilment of a set of explicit design equations dealing with the design envelope
- ‘deemed to satisfy’ or prescriptive rules for robustness

Several concerns and questions pertaining to robustness and system performance in structures have arisen and present code-based structural design practices have failed to provide adequate answers in this respect – this has been discussed in Section 2.5. Significant resources have been invested towards achieving a better understanding of structural robustness and developing approaches for efficient treatment of safety and robustness in structural design.

At the same time, the wide usefulness of code-based structural design procedures in providing efficient rules for the design of a broad range of structures needs to be acknowledged. This is particularly relevant in the context of the standard safety format of design codes which has evolved and matured with a strong theoretical basis. Code-based structural design practice in its component-centric domain is seen to be well developed, highly standardised as well as widely and easily used. In the pursuit of solutions for assessing and achieving adequate robustness in structures, the underlying structure of code-based design therefore needs to be respected and solutions within this broad frame need to be explored.

As seen in Section 3.2, a quantitative risk-based approach for structural design can be seen to provide a comprehensive, rational and consistent basis for the assessment of structural robustness through the use of the total risk considerations in the ranking and selection of optimal design alternatives. Such a framework is suitable for the design of structures which can be considered as extraordinary and which fall outside the broad applicability domain of the structural design codes. However the level of rigour and detail required for a meaningful risk assessment makes the approach unwieldy for implementation in common design practice.
3.3.2 Development of a risk-informed approach

In the quest towards formulating procedures for the sound assessment and ensuring adequate robustness in structures and their incorporation in structural design codes, a rational and feasible approach to the problem can be considered to be based on integrating the essence from the necessary facets of a risk-based approach into the domain of code-based structural design. Such an approach can be broadly composed of the following steps:

- A holistic identification of relevant considerations or factors that influence the robustness of structures from a lifecycle performance oriented perspective is carried out. This includes the consideration of relevant exposures, their ensuing consequences and the necessary strategies required in response to the effects of the exposures and consequences. These can be seen as the different components of a ‘complete risk model’ that can be established for a structure. As defined in Section 3.1, a complete risk model is considered to be a perfect or ideal risk model for a given structure for which information about all exposures, component related (direct) consequences and structure/system related (indirect) consequences and their corresponding risks as well as a complete probabilistic model of knowledge (aleatory as well as epistemic uncertainties) are available.

- The requirements as contained in the structural design codes are clearly isolated and delineated into the two categories – standard safety format and set of robustness provisions. In line with code-based component-centric thinking, the standard safety format is considered to account for design situations arising out of most direct risks whereas the set of robustness provisions address the predominant indirect risks.

- A system of generic categorisations is developed for the different components of the complete risk model in order to achieve consistency and standardisation and also ensure that the assessment of robustness is carried out at a realistic and practically manageable level. Based on the linkages derived from the categorised considerations, the important scenarios for the assessment of robustness are then established. A viable platform for the establishment of optimal provisions for robustness in structures is thus made available.
On the basis of the system of generic categorisation, a guidance platform for engineering design is established that:

- acknowledges the considerations accounted for within the design envelope through the code standard safety format, and
- provides a structured approach for the identification of suitable robustness provisions using information from the developed generic categorisation for dealing with design situations beyond the design envelope and deviations from the design concept of the structure.

Considering that the standard code safety format is already optimised (in line with best practice code calibration), the identification of the adequate and acceptable set of provisions for robustness is carried out based on an optimisation process involving the consideration of lifetime cost and investments into reduction of life safety risks.

The approach is illustrated in Figure 3.4. In accordance with their respective roles in ensuring adequate safety and performance during the lifecycle of structures, the standard safety format and the set of robustness provisions each account for a certain proportion of the risk information considered in the ideal complete risk model.

Figure 3.4 Illustration of a risk-informed approach for the assessment of structural robustness.
Towards sound assessment and improvement of robustness of structures

The proposed approach can be seen as a ‘risk-informed approach’ that aims to enhance existing code-based structural design practices through the broader consideration of necessary insights from a risk-based and lifecycle performance oriented approach. Through a logical and workable process, such consideration is used to establish optimal, adequate and acceptable robustness measures for structures commensurate with their use, safety, performance and economy.

A future format for design codes developed based on this approach can therefore be envisaged to comprise:

- a well-defined and separated standard safety format that accounts for most component related (direct) risks in structures, and
- clearly stated principles and application rules to ensure appropriate robustness that account for most structure/system related (indirect) risks at the level of:
  - general safety format
  - structural system
  - materials and failure modes
  - quality control
  - monitoring, inspection and maintenance
  - active and passive loss reduction measures

Through the development of design codes based on the above format and their eventual implementation and use, the consideration of structural lifecycle performance with regard to robustness is more clearly and explicitly introduced in the structural design, execution and maintenance processes. Considerations pertaining to the level of detail, validity, logical clarity and transparency and flexibility of use associated with the proposed code format will be crucial for its successful development and implementation.
Chapter 4

Development of a modified code format approach for the assessment of robustness of structures

4.1 Introduction

A risk-informed approach for a more clear and direct consideration of robustness in code-based structural design practice has been proposed in the previous chapter. Based on this approach, the different steps involved in the establishment of a code format for the assessment of robustness of structures that have been listed at the beginning of Section 3.3.2 are elaborated in this chapter.

4.2 A lifecycle performance based framework and system of generic categorisation for assessment of robustness

4.2.1 Brief description of the framework

The theoretical basis of the proposed code format is established through the development of a framework that facilitates a comprehensive consideration of factors that influence the robustness of structures from a lifecycle performance perspective. An illustration of this framework is shown in Figure 4.1.

In this framework, the goals of the structural design process are first established in the form of objectives or targets for safety and performance which can be associated with integrity, deterioration, fitness for use and other performance criteria. Then, a contemplation of the relevant exposures for structures is undertaken – as discussed in Section 3.2.1, this involves the consideration of the actions or hazards with the potential to cause consequences for a structure in combination with the different influences associated with the design concept of the structure. This is followed by a consideration of the effects of the
exposures – effects here are understood as the manifestation of a single or a combination of exposures on structures.

As discussed in Section 3.3.1, the safety requirements for structures in the context of code-based structural design can be laid out in the form of a *standard safety format* and a *set of robustness provisions*; requirements under these categories are however presently not clearly demarcated. The next step in the framework therefore involves the establishment of a well-defined separation of the safety requirements between the two categories in design codes; this can be achieved by the identification and systematic organisation of the current code provisions related to robustness. Following this, the design of the structure is then considered to be carried out according to the standard safety format, meaning that relevant explicit and identified design situations in the design envelope are considered and adequately addressed following code-based design procedures.

The need to consider and ensure robustness then principally stems from the implications of possible incomplete, incorrect or inadequate considerations in such a design; such implications can be considered beyond the design envelope established by the standard safety format. The development and evolution of these implications give rise to possible damages and failures and their consequences in structures. An identification of such implications and the consequences and their evolution in structures is carried out. This is followed by a consideration of strategies for the planning, design and execution of suitable provisions and measures in response to the arising implications and consequences. Finally, a guidance platform is established that provides a structured approach for the identification and treatment of scenarios and situations beyond the design envelope for structures. The optimal set of strategies to ensure robustness is then identified by carrying out an optimisation involving considerations of lifecycle cost and benefits from investments into risk reduction in structures.
4.2.2 Need for a system of generic categorisation

For each stage in the proposed framework, numerous factors need to be considered over different time and space domains and in different states during the lifecycles of structures. Keeping in mind the broad spectrum and scope of such considerations, a system of generic categorisation is devised and used as the instrument for the implementation of the framework. This involves the formulation of generic categories in each stage in order to achieve consistency and standardisation. The identification of such generic categories is also aimed at keeping the assessment at a practice-friendly and practically manageable level.

The fields of categorisation are principally derived by looking at the problem from a ‘lifecycle system performance’ perspective. The categorisation involves a structured hierarchical approach whose use is level adjustable depending on the extent of the current information available for a structure. The categorisation also readily enables an updating of the assessment framework structure through the inclusion of new states or considerations under these generic categories, as and when new information becomes available. In this context, it may be mentioned that the use of a Bayesian approach provides a structured
basis for the consideration of such new information through updating (Faber, 2010).

The development of a system of generic categorisation for use in the framework therefore serves as the basis for a ready reference for the purpose of identification and development of strategies for relevant design scenarios and situations that exist outside the design envelope for a structure.

4.2.3 Identification and development of generic categories

4.2.3.1 Goals

Goals are considered to be objectives or targets that can be related to structural performance during the lifetime of the structure with regard to safety, integrity, deterioration, fitness for use, serviceability and other criteria. These can be expressed as target reliability index values (ISO, 1998; BSI, 2006), annual probabilities of failure for components, systems and structures in different design categories (ASCE, 2005) or as requirements with regard to the consequences or risk of system failure. Performance objectives can also be expressed through the use of hazard severity and likelihood matrices (ICC, 2006). Goals can be seen to influence and shape the design concept of a structure and its associated influences and therefore have a corresponding impact on the considerations pertaining to exposures, effects, design measures, consequences and strategies in the framework.

4.2.3.2 Exposures

Exposures can be represented in the form of possible endogenous and exogenous actions or hazards with the potential to cause consequences for a structure (JCSS, 2008) together with the influences associated with the design concept of the structure. Depending on their particular characteristics, exposures evolve in their distinctive forms over time and space. With respect to the time domain, exposures can, for instance, be seen to be sudden events (such as impact or explosions) or gradually occurring processes (such as deterioration associated with corrosion and fatigue). The characterisation of exposures can be performed through a probabilistic quantification of the
occurrence of the concerned events and supported by the consideration and modelling of indicators associated with the exposures; such indicators include the peak ground acceleration in the case of earthquakes and pressures for explosions. Further a complete description of the exposures for a structure can then be provided in the form of a joint probabilistic distribution of different exposures for the structure that accounts for their relevant characteristics with respect to the temporal and spatial domains. As seen in Section 3.2.2, such characterisation is particularly useful in the context of a risk-based design where it sets up the assessment and modelling of the ensuing possible damages, failures and corresponding consequences caused by the exposures and also facilitates the identification of possible relevant measures for risk mitigation.

In code-based structural design, the exposures relevant for the structure and their corresponding load combinations are considered in accordance with standards on the specifications of actions and loads for structures. Here, the probabilistic quantification is deemed to be taken care of through the use of appropriate partial factors for actions and load combination factors. Such consideration becomes important in the context of robustness in the following situations:

i) The occurrence of exposures is in accordance with normal levels as stipulated in the relevant codes and standards but still leads to occurrence of damages/failures and consequences. This can be due to human errors in the lifecycle of a structure during the design, execution, use or maintenance phases leading to inadequacies with regard to magnitude or even the entire consideration of exposures. No standard methodologies have been established for the modelling of human errors. Simple approaches that can be used for their modelling include either the consideration of factors used as multipliers on the probability of damages and failures in structures or the consideration of the probabilities of occurrence of errors together with the use of error factors on the resistances determined in the design (Vrouwenvelder and Leira, 2011). In the context of risk mitigation, the occurrence of human errors is considered to be reduced through appropriate quality control and review procedures.
ii) The occurrence of exposures is beyond reasonable consideration in the context of code-based design for a structure and can therefore be considered to be extraordinary. The exposures considered in this category include explosions (internal or external), impact, fire or extreme event occurrences of natural hazards such as earthquakes and strong winds. Some of these exposures may possibly be considered in code-based design but not in the magnitudes corresponding to the extraordinary levels of occurrence. One possible approach to model the occurrence of such extraordinary exposures is through the use of a Poisson process (Ellingwood, 2007) characterised by a certain intensity with respect to time and space domains. This is possible in the case of exposures such as fire ignition when the occurrence of the exposure can be considered to be random in time in accordance with the assumptions governing the application of the Poisson process but may not hold true for exposures such as bomb explosions. Values of the mean rate of occurrence for some of such extraordinary or abnormal exposures can be found in Ellingwood (2007) and are given in Table 4.1. These values can be seen to be of an indicative and general nature with no detailed consideration of the different influences (see Section 4.2.3.4) associated with structures and also the consequences (see Section 4.2.7.5) resulting from the occurrence of the exposures.

<table>
<thead>
<tr>
<th>Exposure / Hazard</th>
<th>Mean rate of occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire ignition</td>
<td>$0.2 \times 10^{-6}/\text{m}^2/\text{year}$ to $1 \times 10^{-6}/\text{m}^2/\text{year}$</td>
</tr>
<tr>
<td>Fire with potential to cause significant</td>
<td>$10^{-8}/\text{m}^2/\text{year}$</td>
</tr>
<tr>
<td>structural damage</td>
<td></td>
</tr>
<tr>
<td>Internal gas explosions in dwellings</td>
<td>$2 \times 10^{-5}/\text{dwelling unit/year}$</td>
</tr>
<tr>
<td>Vehicular collisions with buildings</td>
<td>$10^{-4}/\text{building/year}$ (for data from USA)</td>
</tr>
<tr>
<td>Bomb explosions against buildings</td>
<td>$2 \times 10^{-6}/\text{building/year}$ (for data from USA)</td>
</tr>
</tbody>
</table>

*Table 4.1 Mean rate of occurrence of exposures (Source: Ellingwood, 2007).*
In this framework, the classification of exposures is carried out using the following generic fields of categorisation:

- **Origin** – Exposures can arise from different sources that include:
  
  - structural use (self-weight and loads related to human and other activities related to functionality and hazards arising during use such as internal gas explosions)
  
  - events of natural hazards (including wind, snow, earthquakes)
  
  - human (and other) errors during the different stages in the lifecycle of the structure
  
  - human and other activities not related to structural use that directly affect or are focused on the structure (intentional – malevolence, terrorism and vandalism or accidental – impact)
  
  - environmental actions affecting the environment of the structure in which the structure is placed (such as proximity to sea water spray/tidal splash, exposure to contaminated soil, human activities such as industrialisation and emissions in the vicinity)

- **Time related considerations** – Here categories pertaining to the duration of the exposures and their variability with respect to time during the lifecycle of the structure are identified; these include (BSI, 2002 and JCSS, 2001a):
  
  - duration – permanent, seasonal, transient or accidental
  
  - variability in magnitude with time – negligible or non-negligible

- **Space related considerations** – The classification of exposures with regard to spatial considerations is based on:
  
  - location – entire structure (self-weight), variable or vulnerable areas (explosion, chemical attack)
  
  - variability in magnitude with space – negligible or non-negligible
• Other considerations – These include considerations, for instance, related to the nature of load build-up which can be classified as static, dynamic or cyclic, and possible dependencies and correlations between exposures.

Table 4.2 illustrates the above categorisation scheme for selected exposures.

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Origin</th>
<th>Time related considerations</th>
<th>Space related considerations</th>
<th>Others – Nature of load build-up</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Duration</td>
<td>Variability</td>
<td>Location</td>
</tr>
<tr>
<td>wind</td>
<td>natural hazard</td>
<td>seasonal</td>
<td>non-negligible</td>
<td>vulnerable</td>
</tr>
<tr>
<td>self-weight</td>
<td>structural use</td>
<td>permanent</td>
<td>negligible</td>
<td>entire</td>
</tr>
<tr>
<td>explosion</td>
<td>malevolence</td>
<td>exceptional</td>
<td>non-negligible</td>
<td>vulnerable</td>
</tr>
<tr>
<td>sea water</td>
<td>environmental</td>
<td>variable</td>
<td>non-negligible</td>
<td>vulnerable</td>
</tr>
<tr>
<td>spray</td>
<td></td>
<td>human error</td>
<td>permanent</td>
<td>variable</td>
</tr>
</tbody>
</table>

*Table 4.2 Classification of exposures.*

4.2.3.3 Effects

Effects can be understood as the manifestation of a single or a combination of exposures in the form of forces, displacements and stresses in the structure. Effects can be seen at different levels from the structural member level to the system level. Examples of effects include the development of bending and shear in structural members, global deflections in structural frames or deterioration processes such as corrosion. The development of effects is accounted for in the structural design process through appropriate resistance mechanisms and the planning and execution of suitable measures. Effects result in damage or failure states which can be established based on the exceedance of defined limit states (possibly due to inadequacy of the resistance mechanisms) and loss of functionality. The categorisation of effects is carried out using the following fields:

• Limit state and/or resistance mechanism – Here, the corresponding limit states and/or resistance mechanisms developed in response to the effects are identified. Simple examples include bending (in response to development of internal moment) and tensile cracking (in response to development of tensile forces).
• Applicability – Effects may be classified based on whether they are applicable for structural members or connections (in the form of internal forces or moments) or for the entire structure (in the form of global deflections and structural collapse).

• Safety criteria – The identified limit states are classified based on safety considerations and their descriptors into:
  
  o Ultimate limit states that can be related to overall or partial loss of equilibrium, exceedance of strength limits, elastic or plastic instability, fracture, etc. (JCSS, 2001a; Nethercot, 2001). These may include member related states or system related states such as collapse.
  
  o Serviceability limit states that can be related to deformation, cracking, vibration, etc. (JCSS, 2001a; Nethercot, 2001).
  
  o Limit states related to deterioration processes such as corrosion, fatigue and chemical attack.

• Nature of resistance mechanism – On the basis of the nature of the resisting mechanism, effects can be categorised using:
  
  o Basic criteria – This can be force, deformation (displacement/rotation) or energy related.
  
  o Level of loading – Here categorisation corresponds to primary resistance mechanisms (such as flexure) and secondary resistance mechanisms (such as catenary action) which are usually activated at loading levels higher than those corresponding to primary resistance mechanisms and which can be seen as particularly relevant in the context of structural robustness.

• Nature of exposure – Some aspects associated with the classification of exposures can be useful in their corresponding form for the classification of effects. These include:
  
  o Path of load transfer – While it may not be possible to establish categories in this case, this can be related to the magnitude and direction of loading and the degree of continuity.
- Nature of load build-up – This can be classified as static, dynamic or cyclic.

An illustration of the above categorisation scheme for selected effects is shown in Table 4.3.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Limit state and/or resistance mechanism</th>
<th>Applicability</th>
<th>Safety criteria and descriptors</th>
<th>Nature of resistance mechanism</th>
<th>Nature of exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>development of internal moment</td>
<td>bending</td>
<td>structural member</td>
<td>Ultimate (exceedance of strength limits)</td>
<td>force</td>
<td>static or dynamic</td>
</tr>
<tr>
<td>development of tensile forces</td>
<td>tensile cracking</td>
<td>structural member</td>
<td>Serviceability (occupant discomfort, aesthetics, warning)</td>
<td>force</td>
<td>static</td>
</tr>
<tr>
<td>development of internal movements</td>
<td>global deflection</td>
<td>whole structure</td>
<td>Serviceability (warning, occupant discomfort)</td>
<td>deformation</td>
<td>static or dynamic</td>
</tr>
</tbody>
</table>

*Table 4.3 Classification of effects.*

### 4.2.3.4 Influences

Influences can be understood as factors that play a role in promoting, preventing or mitigating certain exposures, effects and failures and consequences in structures and also correspondingly evolve during this process. Influences arise from the design of the structure and its environment and are classified into the following families for use in this framework.

**Use**

The use or functionality provided by the structure plays a major role in shaping its design concept so that it satisfies the requirements expected of the structure. Its importance can be appreciated by the fact that it is one of the primary factors in establishing classification systems for structures such as the consequences classes in the Eurocodes (BSI, 2002; BSI, 2006) and occupancy categories in the American standards (DoD, 2009). These classification systems are then
used as the basis for prescribing differentiated safety and robustness requirements in structures.

The factors considered here are:

- **Primary use or purpose of the structure** – Structures can be categorised into:
  - Strategic infrastructure facilities and assets (such as transportation and communication facilities)
  - Public facilities and buildings (including schools and hospitals)
  - Commercial and institutional buildings
  - Special-purpose structures (such as cleanrooms)
  - Residential buildings
  - Structures involving temporary or occasional use (such as storage areas and warehouses)

- **Use-related susceptibilities and restrictions** – The use associated with a structure can be related to the degree of criticality of continuity of operations and use during the lifecycle and also to a propensity for being a potential target for certain types of exposures and failures, examples of which include:
  - Industrial and laboratory facilities – vulnerable to chemical attacks, internal gas explosions
  - Institutional (financial and government buildings) and strategic infrastructure facilities – targets for terrorism and malevolence

- **Importance of the structure and value** – This can be related to the extent and impact of the follow-up consequences associated with the failure of the structure as well as to societal perception of its value.

- **Use and occupancy profile** – Factors related to the activities and occupants associated with the use of the structure in its lifetime are considered here.
**Environment**

The considerations here arise due to the environment in which the structure is placed and are primarily related to possible susceptibilities to certain types of exposures and failures which may be significant for a robustness assessment and consideration; such susceptibilities can include:

- Climate related factors such as corrosion related deterioration due to sea water spray or tidal splash and repeated wetting and drying.
- Location related factors such as accessibility to structure and susceptibility to terrorism and malevolence related attacks due to the location of the structure in or in the vicinity of a vulnerable area (such as financial centres, nuclear facilities, etc.) or a densely populated area (urban centre).

**Spatial characteristics**

The focus here is on the factors or possible restrictions and limitations associated with the spatial characteristics of structures that make them more (or less) vulnerable to certain forms of actions and failures. Such factors are grouped into the following categories:

- **form and configuration** – This includes:
  - type of structural load-bearing system/frame
  - structural layout and arrangement
  - primary direction of spatial orientation
  - restrictions and constraints (such as column spacing, percentage of glazing and sizes of components)
- **dimensions**
  - height (overall and floor height, where applicable)
  - area
  - floor space index
**Time related characteristics**

The service life of structures and structural components can be seen to have a significant influence on the lifecycle performance of structures through their role in the evolution of deterioration patterns and necessitation of maintenance, replacement and repair actions during the lifetime of structures. Such considerations become crucial when they impinge upon the safety and integrity of structures. Other time related issues can be associated with the development and emergence of new knowledge with regard to different aspect of structural behaviour and possible changes in codes, standards and regulations over time.

The factors considered here include:

- age of structure
- period in which the design and execution have been carried out (for an indication of the prevailing practices and regulations)
- information pertaining to (technical and economic) service life of components

**Material behaviour and other aspects**

The strong influence of material behaviour on robustness in structures can be seen in its important role in shaping the structural response and the generation of appropriate resistance mechanisms to counter the effects of exposures acting on the structures. Under this family, factors arising from material behaviour of different components of a structure at different phases and in different situations as well as material use and production are considered. Here, considerations are categorised into:

- material behaviour – consideration of deterioration, ductile-brittle behaviour, non-linearity and plasticity are relevant.
- material use – restrictions or requirements in using certain materials.
- material production – correlations in the material production processes.
Among the several aspects pertaining to material behaviour, an important factor in the context of robustness is the consideration of ductility (commonly understood as the ratio of the maximum deformation to the elastic deformation in structures), particularly in the context of member-to-member connections. A detailed ductile connection design needs to adequately consider the interaction of all connection components and relevant effects in order to ensure that the weakest component is always ductile under the overall loading sequence for the connection (Kuhlmann et al., 2011).

Traditional structural analysis procedures are generally based on the assumptions of linear elastic material response and geometric linearity with the application of static loads. Dynamic effects are deemed to be accounted for through the use of dynamic load factors in static analysis. In the case of situations where the robustness of the structure is called into question, the assumptions underlying such analyses based on small-deflection theory may not hold when displacements become large relative to the dimensions of the structure. Therefore, a clear appreciation of the behaviour and integrity of the structure under such large deformations is not obtained.

Possible analysis procedures that can be more relevant for robustness problems involve non-linear approaches with the non-linearity arising from the inclusion of material plasticity and/or second order geometric non-linearity (Izzuddin et al., 2007; Cormie et al., 2009). Figure 4.2 shows the different response and behaviour phases that can be identified in such an analysis. The initial linear elastic phase is succeeded by a non-linear phase due to geometric non-linearity. Material plasticity considerations then take effect followed by the development of robustness relevant resistance mechanisms including catenary or membrane actions. Material properties beyond the elastic range are therefore utilised in such approaches and reasonably satisfactory results with respect to robustness may be obtained if sufficient ductility is provided.
The role of material ductility and development of plastic deformations is also evident in the absorption and dissipation of energy and the redistribution of forces to reduce force concentrations that could arise due to dynamic actions. Reductions are possible in the values of the dynamic load factors used for such cases when there is sufficient development of ductility; as an example, it is reported in Val and Val (2006) that if the ductility (measured as the ratio of the maximum deformation to the elastic deformation) is around 6, the dynamic load factor can be reduced from 2.0 (usually taken for a linear elastic system) to 1.1. The resulting redistribution of forces either at the level of a structural member (local) or at the level of the structural system (global) requires large deformations. Large deformations of the structural system result in correspondingly large plastic material strain rates, activating the available plastic material reserves. Such activation of plastic reserves may be seen as an indicator of redundancy capabilities at a local (member) level. At a system or global level, the existence of redundancy facilitates the formation of alternate load paths through, for instance, the mobilisation of catenary action which may be essential in a robustness situation.

The inherently ductile nature of steel readily enables the consideration and use of plastic reserves and force redistribution in steel structures. While such material behaviour may not be natural in the case of reinforced concrete,

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**Figure 4.2 Stages of structural material response for a non-linear static approach (Source: Cormie et al., 2009).**
possible practical approaches such as the variation of the placement of reinforcing steel have been suggested (Decan & Taerwe, 2009). Further, in situ reinforced concrete construction can also be seen to provide answers in this respect with the monolithic nature of concrete contributing to the development of alternative load paths and the use of tying resistances.

Another aspect of material behaviour that may be important in the provision of robustness is the consideration of strain hardening. The development of strain hardening can be understood as an increase in stiffness with increasing levels of deformation (Knoll & Vogel, 2009) and is most relevant for mild steel. The benefits of strain hardening are prominently seen in the form of reductions that result in the redistribution of load to possible alternative load paths in the structure and the development of substantial visible deformations before failures that could be useful in risk mitigation.

Other relevant aspects associated with material behaviour include the consideration of time dependent and evolving effects such as creep, shrinkage and fatigue. From a lifecycle perspective, the influence of these aspects on system integrity and robustness in a structure can mostly be seen to be important when considered in interaction with other effects and exposures associated with the structure (see Section 4.2.3.2 and 4.2.3.3).

**Process related considerations**

Here, the factors associated with the nature and activities involved in the design, execution and maintenance processes are considered. These include:

- choice of approaches, methods and technologies for design, execution and maintenance processes.
- the effect of human (and other) errors and their manifestation in the form of inadequate or improper design, inadequate or poor degree of quality of work during execution, absence of or insufficient inspection and maintenance and others associated with communication.
- the influence of deviation from the design concept of a structure as well as from assumptions made in the design, inspection, maintenance processes.
• the impact of changes in codes and standards as well as the emergence of new knowledge.

• the effect of lack of complete knowledge and the use of inadequate, imperfect or incorrect models, possibly resulting in a failure to perfectly understand structural behaviour.

4.2.4 Separation of safety requirements in structural design codes and standards
The next step in the framework is the separation of the safety requirements laid out in the structural design codes between the standard safety format and the set of robustness provisions. The requirements covered under these two categories can be considered to be independent and need to be fulfilled individually (Beeby, 1999). Further, in line with the risk-based design thinking described in Section 3.3.2, this separation regulates that the standard safety format accounts for design scenarios within the design envelope that arise out of most direct risks whereas the set of robustness provisions take care of design scenarios beyond the design envelope that pose the predominant indirect risks.

A feasible approach to achieve this separation is through the identification and systematic organisation of the current design code provisions related to robustness, the understanding of a robust structure being a structure in which the consequences resulting from an initiating event or cause are not disproportionate to the initiating event or cause. Towards this end, a comprehensive review of European codes and standards dealing with the design, execution, material aspects and maintenance of concrete and steel structures has been carried out.

The robustness related provisions in the standards have been identified and categorised according to the following attributes related to risk management:

• Approach to risk treatment

• Nature of risk control
• Relationship with event/exposure
• Focus domain of risk reduction
• Phase in the lifecycle of the structure in which the provision is applicable

This provides a systematic and differentiated mapping of the consideration and treatment of robustness in European standards. The details concerning the categorisation scheme are covered later in Section 4.2.8.3 (for reasons of better consistency and continuity in discussion). A complete listing of all the identified robustness related provisions in the reviewed standards together with their categorisation can be found in Appendix A.

4.2.5 Measures – baseline design according to standard safety format

The design of structures is then considered to be carried out according to a separated code standard safety format and the design situations stipulated therein. The planning and design of suitable measures commensurate with the corresponding set of considered effects and exposures provides a certain baseline design envelope for the structure which accounts for a proportion of the total risks associated with the structure. Such a design can be seen to place the structure in a state of equilibrium with respect to the standard safety format.

4.2.6 Implications arising from baseline design and the need to consider robustness

Any form of disturbance to the state of equilibrium achieved with respect to the standard safety format can result in possible damages, failures and consequences for the structure.

Such disturbances can be understood as the possible implications arising from an:

• inadequate,
• incorrect, or
• incomplete
consideration of factors associated with the exposures and effects together with the design, execution and lifecycle consideration of measures in the baseline design according to the standard safety format. This poses the principal need to consider and account for robustness in structural design. With respect to the baseline design envelope, the implications can be in the form of:

- an occurrence of new exposure(s) or effect(s),
- changes in currently considered exposure(s) or effect(s),
- changes in influences, or
- inadequacy of measures considered in the baseline structural design to account for the corresponding effects
- synergistic/combined impact of:
  - several existing exposures
  - several existing exposures and new exposure(s)

The above changes may occur due to:

- Anticipated or foreseen considerations (which can pertain to exposures, effects or measures) – These refer to the considerations foreseen in the baseline design envelope but:
  - inadequately accounted for.
  - ignored in the design (judged to be not important and hence ignored).

- Not anticipated (unforeseen or unforeseeable) considerations – These include considerations beyond the baseline design envelope.

These changes can be seen to arise from:

- human errors or lack of understanding/knowledge during the lifecycle of structures – These can involve the inadequate consideration (computational or conceptual mistakes) or understanding of exposures, effects and design measures in the structural design process, poor workmanship and deviations from design during execution, unsatisfactory material production
or fabrication, improper maintenance and monitoring or deviations in the use of the structure.

- limitations posed by the prevailing state of the art of knowledge and best practices – These include limitations and ambiguities in prevailing codes, standards and lifecycle practices and lack of complete understanding of considerations pertaining to the use of certain materials, methods, technologies and systems.

- circumstances beyond reasonable control and consideration for the baseline design of the structure – These include the occurrence of extraordinary exposure events as discussed in Section 4.2.3.2.

Some useful lessons in this regard can be learnt from past experiences with failures. A historical appreciation of the relative importance and relevance of some of the above factors in the context of robustness and structural failures can be gained from Table 4.4 which provides a frequency indication of the primary causes of failure (in reducing frequency) based on a study of structural and constructional failures in the USA (Eldukair and Ayyub, 1991).

<table>
<thead>
<tr>
<th>Primary cause</th>
<th>Frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor erection procedures</td>
<td>54.3</td>
</tr>
<tr>
<td>Inadequate load behaviour</td>
<td>45.2</td>
</tr>
<tr>
<td>Inadequate connection elements</td>
<td>27.0</td>
</tr>
<tr>
<td>Unclear contracts information</td>
<td>23.5</td>
</tr>
<tr>
<td>Contravention of instructions</td>
<td>21.8</td>
</tr>
<tr>
<td>No information</td>
<td>15.5</td>
</tr>
<tr>
<td>Unforeseeable events</td>
<td>7.1</td>
</tr>
<tr>
<td>Errors in design calculations</td>
<td>2.5</td>
</tr>
<tr>
<td>Reliance on construction accuracy</td>
<td>1.8</td>
</tr>
<tr>
<td>Complexity of project system</td>
<td>1.2</td>
</tr>
</tbody>
</table>

*Table 4.4 Primary causes of structural failure (Source: Eldukair and Ayyub, 1991).*

In current code-based structural design, the above situations are deemed to be mostly covered by either prescriptive or guidance rules whose intent is implicit, which are not demonstrably derived from their causative factors and whose beneficial impact is generally not known quantitatively. The proposed framework for the assessment of robustness aims to address these shortcomings through an approach that advocates a more direct and visible consideration of robustness in the design process from a lifecycle performance perspective.
4.2.7 Failures and consequences

The situations covered in Section 4.2.6 with regard to deviation from the baseline design for structures can be better appreciated and understood through the use of available historical knowledge and the utilisation of the benefit of hindsight of past failures in terms of causal relationships, susceptibilities and planning of mitigation measures. A collection from failure case studies selected from Delatte (2009) has therefore been studied and lessons learnt from these case studies are presented in Table 4.5. The case studies are ordered according to their year of occurrence.

<table>
<thead>
<tr>
<th>Case information</th>
<th>Principal Causes</th>
<th>Lessons learnt</th>
</tr>
</thead>
</table>
| Quebec bridge collapse | • Defective design of members and wrong load assumptions | • Implications on safety due to lack of full understanding of behaviour  
• Precedence for safety over economy and other factors  
• Necessity of clear chain of responsibility or command  
• Importance of design verification and peer review |
| St. Lawrence River, Canada | | |
| 1907 | | |
| Execution | | |
| Austin Concrete Dam failure | • Inadequate foundation design  
• Poor quality of material (concrete) construction | • Necessity of precedence for safety before time and economic factors  
• Implications of lifecycle continuity and implications |
| Pennsylvania, USA | | |
| 1911 | | |
| Use | | |
| Tacoma Narrows bridge collapse | • Exceptional flexibility coupled with extreme wind action | • Consideration of lack of knowledge about behaviour  
• Significance of non-consideration of past failures of similar structures |
<p>| Washington, USA | | |
| 1940 | | |
| Use | | |</p>
<table>
<thead>
<tr>
<th>Case information</th>
<th>Principal Causes</th>
<th>Lessons learnt</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Point Pleasant bridge collapse</strong></td>
<td>• Lack of sufficient redundancy</td>
<td>• Difficulties in verification and validation due to unique and state of the art nature of structures and designs</td>
</tr>
<tr>
<td>Ohio River, USA</td>
<td>• Combination of stress corrosion (stress due to traffic loads and environmental effects) and corrosion fatigue</td>
<td>• Impact of lack of knowledge about combination of failure modes, synergistic effects and unfavourable circumstances</td>
</tr>
<tr>
<td>1967</td>
<td>• Compounded by lack of accessibility for inspection of failed components and low temperatures during collapse</td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ronan Point collapse</strong></td>
<td>• Lack of redundancy</td>
<td>• Updating of codes and standards</td>
</tr>
<tr>
<td>London, UK</td>
<td>• No fail-safe mechanisms</td>
<td>• Implications of use of methods, systems or technologies beyond tested use</td>
</tr>
<tr>
<td>1968</td>
<td>• Poor workmanship</td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hartford Civic Center stadium collapse</strong></td>
<td>• Gross design errors (underestimation of dead loads, overloading of members, violation of slenderness ratios)</td>
<td>• Importance of warning signs during lifecycle of structures</td>
</tr>
<tr>
<td>Connecticut, USA</td>
<td></td>
<td>• Effect of over reliance on technologies and methods without complete understanding of their basis, use and implications for the structure</td>
</tr>
<tr>
<td>1978</td>
<td></td>
<td>• Implications of fragmentation and importance of single point responsibility for integrity of structure with division of work based on proper competencies</td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Willow Island Cooling Tower collapse</strong></td>
<td>• Imposition of loads during execution before development of sufficient strength in the structure</td>
<td>• Role of safety standards during execution</td>
</tr>
<tr>
<td>West Virginia, USA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Execution</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Hyatt Regency walkway collapse</strong></td>
<td>• Lack of redundancy</td>
<td>• Design verification</td>
</tr>
<tr>
<td>Kansas City, USA</td>
<td></td>
<td>• Peer review of concept and design details</td>
</tr>
<tr>
<td>1981</td>
<td></td>
<td>• Importance of management of change in personnel</td>
</tr>
<tr>
<td>Use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case information</td>
<td>Principal Causes</td>
<td>Lessons learnt</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------</td>
<td>----------------</td>
</tr>
<tr>
<td><strong>L'Ambiance Plaza collapse</strong>&lt;br&gt;Connecticut, USA&lt;br&gt;1987&lt;br&gt;Execution</td>
<td>Possibly due to deficiencies arising from the use of lift-slab construction</td>
<td>Role of lack of complete knowledge about methods, systems or technologies</td>
</tr>
<tr>
<td><strong>Murrah Federal building bombing</strong>&lt;br&gt;Oklahoma City, USA&lt;br&gt;1995&lt;br&gt;Use</td>
<td>Excessive forces from explosion&lt;br&gt;Non-ductile construction&lt;br&gt;Inadequate alternate load paths&lt;br&gt;Inadequate continuity of reinforcement</td>
<td>Focus on use of unfavourable materials&lt;br&gt;Focus on special detailing practices</td>
</tr>
<tr>
<td><strong>Pentagon attack</strong>&lt;br&gt;Washington DC, USA&lt;br&gt;2001&lt;br&gt;Use</td>
<td>Damage due to extraordinary airplane impact</td>
<td>Considered as a positive benchmark case&lt;br&gt;Importance of favourable design characteristics (continuity of reinforcement, redundancy, energy-absorbing capacity and reserve strength)</td>
</tr>
<tr>
<td><strong>World Trade Center towers collapse</strong>&lt;br&gt;New York, USA&lt;br&gt;2001&lt;br&gt;Use</td>
<td>Inability of buildings to withstand severe structural effects caused by follow-up fire after airplane impact</td>
<td>Focus on protection and consequences control and overall robustness – consideration of occurrence of extreme follow-up hazards</td>
</tr>
<tr>
<td><strong>New Orleans Levee failures due to Hurricane Katrina</strong>&lt;br&gt;New Orleans, USA&lt;br&gt;2005&lt;br&gt;Use</td>
<td>Design errors in design of protection structures – inadequate consideration of unfavourable soil conditions and non-consideration of certain effects</td>
<td>Full appreciation of system risk&lt;br&gt;Transparent communication of risks to stakeholders&lt;br&gt;Importance of single point overall responsibility&lt;br&gt;Implications of lack of external peer review&lt;br&gt;Impact of non-integrated consideration of components in a system</td>
</tr>
<tr>
<td><strong>Boston Big Dig tunnel collapse</strong>&lt;br&gt;Boston, USA&lt;br&gt;2006&lt;br&gt;Use</td>
<td>Incorrect use of material&lt;br&gt;Failure to detect damage during inspections</td>
<td>Impact of inadequate understanding of material behaviour and its influences and its impact on all lifecycle processes – design, execution and maintenance&lt;br&gt;Requirement of different sets of standards and quality control for new and untested materials</td>
</tr>
</tbody>
</table>
Table 4.5 Lessons learnt from past failures.

The following general insights from studies of past failures stand out in terms of their importance for the consideration of robustness in structures:

- The failures and collapses of overall structures generally involve a sequence of events influenced by different factors and considerations associated with the structure and its environment. The importance of unfavourable and complex interactions and dependencies in this process is often crucial. Dependencies can exist with respect to exposures, effects, materials, failure modes and design measures associated with the design of the structure.

- The degree of quality control during design, execution and maintenance provides an important contribution in ensuring adequate lifecycle safety and performance. This involves the use of peer and independent review and verification procedures during design, adequate supervision and management during execution and maintenance, independent testing and control for materials and due diligence and care during use.

- Useful lessons may be learnt from the awareness of similar experiences in past failures (and non-failures). These can be in the form of identification of possible vulnerabilities or adoption of favourable characteristics seen in similar situations.

- The lack of adequate knowledge with regard to the use of materials, designs, methods and technologies which are new or beyond their tested
domains gives rise to the possible emergence of situations which may act as triggering events leading to wider consequences and failures in structures.

- Precedence or greater importance given to economy and other considerations (such as ease of use, time pressures, etc.) over safety is seen as a key contributing factor to the evolving sequence of events and unfavourable circumstances culminating in overall structural failures.

- A single point overall responsibility for ensuring safety and integrity in a structure is essential (with clear delegation of responsibilities where required) to adequately appreciate the system wide nature of robustness and its implications.

- The importance of lifecycle continuity in understanding the design concept of a structure, its implications and the role of different elements (members and connections) with regard to safety and performance cannot be overstated.

- A continuous process of updating of the knowledge about the structure during its lifecycle in response to new available information, possible warning signs in the structure or changes in codes and standards and the use of such knowledge in revising risk mitigation may be seen as generally desirable and essential in some contexts.

- A complete appreciation of risk and behaviour of the overall structure is necessary particularly for a clear and transparent communication of risks to stakeholders. The absence of such communication is crucial in the context of risk perception which may pose adverse societal consequences for failure events associated with the structure.

The manifestation of the design related situations described in Section 4.2.6 that require attention in the context of robustness is in the form of possible damages and failures in structures and/or their components leading to consequences. In this framework, damages or failures to components and sub-systems in structures are understood as states of the respective components and sub-systems which seriously impair their functionality in the structure. System failure refers to the loss of the functionality of the overall structure.
Using the insights gained from the experiences of past failures in this setting, the development of the failures and the consequences associated with structures can be considered to evolve over the different stages as shown in Figure 4.3.

**Figure 4.3 Generation and representation of failures and consequences.**

### 4.2.7.1 Build-up towards primary failures

The situations listed in Section 4.2.6 with regard to the baseline design for structures are seen as triggering (or initiating) events that lead to changes in the characterisation of relevant factors (exposures, effect or measures) for structures, thereby possibly rendering the baseline design envelope inadequate. The further evolution of these situations can be considered as a form of build-up towards potential primary failures in structures or as events or gateways for scenarios that call into question the robustness of structures.

### 4.2.7.2 Primary failures

In the absence of any suitable measures in the baseline design, the build-up events may lead to damages and/or failures in components or parts of the structure that are deemed to be most vulnerable in response to the build-up events. In the context of structural robustness, such failures may be understood as primary or initial failures. In this respect, an indicator based classification of elements with respect to initial failures achieved through a joint consideration of
the influences and relevant exposures, effects and measures in the design as well as the nature, significance and role of the elements with respect to the design concept of the structure is useful – this is discussed in Section 4.3.1.

4.2.7.3 Follow-up failures

The occurrences of primary failures impose extraordinary conditions on the structure in the baseline design, possibly precipitating build-up towards further follow-up failures. As for primary failures, the corresponding changes in the characterisation of relevant factors (exposures, effect or measures) for structures with regard to the baseline design envelope may be described in a similar manner, with the changes now significantly influenced by the primary failures and the build-up towards follow-up failures, together with the set of relevant influences for the structure.

With regard to structural robustness, the principal considerations of concern are the behaviour of the (modified) structural system after primary failures and the evolving load transfer and redistribution processes. These include considerations pertaining to:

- direction and rate of failure progression
- characterisation of structural system behaviour as a series/parallel/mixed system
- ability to mobilise different load paths and mechanisms at system and component level
- load redistribution path and mechanism
- rate of load redistribution
- possibility of common-cause or correlated failures
- occurrence of possible follow-up exposures and effects

As before, an indicator based classification of elements now with respect to follow-up failures and taking into account the impact of the primary failures
achieved through a joint consideration of the influences and relevant exposures, effects and measures in the design as well as the nature, significance and role of the elements with respect to the design concept of the structure is useful – this is discussed in Section 4.3.1.

Further, a categorisation for the levels of follow-up failures (following the occurrence of primary failures) can be devised which facilitates the understanding and planning of suitable failure mitigation measures:

- no damage or failure of structural components
- damage without implications on safety and functionality of structural components
- failure of structural components on auxiliary/secondary load paths
- failure of structural components on main/primary load paths
- structural system failure

4.2.7.4 System failure

Following from the above, system failure can then be defined as a threshold or critical level accumulated or reached during the follow-up failures. The threshold can be related to system functionality and failure of the entire structure.

4.2.7.5 Consequences

The occurrences of exposures followed by the possible evolution of the damages and failures in structures is associated with consequences at every stage. Consequences can generally be expressed in the form of fatalities/loss of lives and injuries, economic losses (e.g. losses incurred due to damages and failures), damages to qualities of the environment as well as social, political and other wider impacts (JCSS, 2008). In code-based structural design, the consideration of consequences forms the cornerstone for the specification of safety requirements in the standard safety format. This is done, for instance,
through the reliability differentiation approach advocated in the Eurocodes with the specification of target reliability index values for different limit states corresponding to different consequence classes.

<table>
<thead>
<tr>
<th>Consequence Class</th>
<th>Description</th>
<th>Examples of buildings and civil engineering works</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC3</td>
<td>High consequence for loss of human life, or very great economic, social or environmental consequences</td>
<td>Grandstands, public buildings where consequences of failure are high (e.g. a concert hall)</td>
</tr>
<tr>
<td>CC2</td>
<td>Medium consequence for loss of human life, considerable economic, social or environmental consequences</td>
<td>Residential and office buildings, public buildings where consequences of failure are medium (e.g. an office building)</td>
</tr>
<tr>
<td>CC1</td>
<td>Low consequence for loss of human life, and small or negligible economic, social or environmental consequences</td>
<td>Agricultural buildings where people do not normally enter (e.g. storage buildings), greenhouses</td>
</tr>
</tbody>
</table>

*Table 4.6 Categorisation of consequences classes in the Eurocodes (Source: BSI, 2002).*

Table 4.6 lists the consequence classes used in the Eurocodes (BSI, 2002) for this purpose. The categorisation here is based on the importance of the structure (or structural member) in terms of the consequences of its failure which is derived primarily from the use of the structure. The importance of consequence classes can also be seen in their use for the identification of recommended strategies and prescriptive rules for ensuring an acceptable level of robustness in structures (see Section 2.4).

As discussed in Section 3.2.2, direct consequences can be considered to be associated with the loss of functionality and performance of structural components – these can be related to the build-up towards primary failures, primary failures and follow-up failures stages in the representation as shown in Figure 4.3. Indirect consequences evolve from the combined impact of constituent failures and are connected with the loss of functionality of the overall structure together with the perception of such failure and other wider follow-up impacts – these are directly associated with the follow-up failures and system failure stages. The characterisation of consequences into direct and indirect forms is important in the context of risk assessment of structures and facilitates a risk-based quantification of robustness (see Section 2.6.1). Such differentiation is crucially dependent on the definition and clear identification and
demarcation of the boundaries of the structure or system and its components.

Table 4.7 provides a characterisation of the different types of consequences that can be considered under these forms. An overview of the quantification and modelling of these consequence types can be found in Imam and Chryssanthopoulos (2011) and Janssens et al. (2011).

<table>
<thead>
<tr>
<th>Type of Consequences</th>
<th>Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Loss of life</td>
</tr>
<tr>
<td></td>
<td>• Injuries</td>
</tr>
<tr>
<td></td>
<td>• Impact on dependents (psychological effects and lost income)</td>
</tr>
<tr>
<td>Economic</td>
<td>Structure specific</td>
</tr>
<tr>
<td></td>
<td>• Replacement, repair or reconstruction costs of structure or components</td>
</tr>
<tr>
<td></td>
<td>• Loss of equipment and assets</td>
</tr>
<tr>
<td></td>
<td>• Clean-up costs</td>
</tr>
<tr>
<td></td>
<td>• Rescue costs</td>
</tr>
<tr>
<td></td>
<td>• Loss of functionality and economic returns</td>
</tr>
<tr>
<td></td>
<td>• Temporary relocation</td>
</tr>
<tr>
<td></td>
<td>• Loss of reputation</td>
</tr>
<tr>
<td></td>
<td>• Disruption and delay costs</td>
</tr>
<tr>
<td>Beyond structure</td>
<td>• Losses from damages and failures of surrounding structures</td>
</tr>
<tr>
<td></td>
<td>• Disruption and delay costs</td>
</tr>
<tr>
<td></td>
<td>• Losses due to impact on regional (and wider) economy</td>
</tr>
<tr>
<td>Environmental</td>
<td>• Greenhouse gas emissions</td>
</tr>
<tr>
<td></td>
<td>• Release of toxic matter and pollutants during failures and debris flow</td>
</tr>
<tr>
<td></td>
<td>• Damage to ecosystem</td>
</tr>
<tr>
<td>Other</td>
<td>• Losses associated with culture and heritage</td>
</tr>
<tr>
<td></td>
<td>• Changes in engineering, industry and other professional practices and regulations</td>
</tr>
<tr>
<td></td>
<td>• Wider social and political impacts</td>
</tr>
</tbody>
</table>

Table 4.7 Characterisation of consequences.

The distinction of consequences into direct and indirect forms depends on the particular nature, context and scale of the risk assessment. As an example, a building is considered as the system for the purpose of risk assessment. The occurrence of exposures (such as permanent actions, environmental actions, impact, etc.) in different components of the structure may lead to possible damages and failures of these components and affect their functionality – these can be associated with direct consequences in the form of repair costs and possible disruption costs. Further, different combinations of such component
failures and their interactions may lead to failure or collapse of the structure – this can be associated with indirect consequences composed of fatalities and injuries, reconstruction costs and loss of building functionality. The risk assessment can also be performed at a different scale by considering a part of the structure (for instance, the composite flooring system) as the system and accordingly identifying the direct (associated with the failures of decking or tiles in the flooring system) and indirect (arising from the failure of the flooring system) consequences.

4.2.8 Strategies and provisions to ensure robustness

4.2.8.1 Introduction

As discussed in Sections 4.2.6 and 4.2.7, the implications arising from the baseline design according to the standard safety format and the ensuing potential damages, failures and consequences create the basic need for the consideration and provision of robustness in structural design. Accordingly, the development of a set of strategies to ensure robustness in the form of planning, design and execution of suitable provisions is essential in response to such demands placed on the design of the structure. In this respect, relevant guidance principles and considerations are first laid down in Section 4.2.8.2. A systematic categorisation and organisation of the different implementation level provisions to ensure robustness is then covered in Section 4.2.8.3. These serve as the basis for the identification, establishment and specification of the appropriate strategies and provisions to ensure robustness for a structure in consonance with the set of considerations derived from the influences, exposures, effects and design measures in the baseline design – this is described in Section 4.3.2.

4.2.8.2 Guidance principles and considerations

The important principles and considerations that need to be borne in mind during the development of strategies and provisions to ensure robustness in structures include:
• **Need for a holistic approach** – An integrated assessment and determination of the set of strategies to ensure robustness is necessary in order to systematically cater to the different stages in the evolution of damages, failures and consequences in structures with due consideration of the relevant factors associated with the influences, exposures, effects and design measures in the baseline design for the structure.

• **Lifecycle considerations and continuity** – It is also essential to consider the development of robustness strategies in the context of the lifecycle of the structure. This may be considered with regard to the phase in the lifecycle of the structure in which the strategies are applied and the effectiveness of these strategies over the (remaining) lifetime of the structure and the impact of the emergence of new knowledge and information with time that is relevant for the structure. The adherence to continuity and transfer of responsibilities and knowledge over the planning-design-execution-use-operations-maintenance lifecycle of the structure therefore assumes paramount importance in the context of its sustainable lifecycle performance.

• **Achieving a balance** – As discussed in Section 2.2, a fine balance is essential between use, safety, performance and economy in structural design. This is also true in the case of robustness strategies with considerations of cost on the one hand and the achieved robustness on the other. The guiding principle here is provided by the basic understanding of robustness which recognises that the identified strategies need to cater to situations and demands violating the ‘disproportionate cause-consequence’ criteria rather than the entire domain of all possible situations. Other situations involving decisions on balance and trade-offs include the consideration of possible restrictions in the design concept, conflicts with requirements arising from other performance criteria and even from considerations which impose competing requirements with regard to robustness.

• **Benchmark level of robustness and enhancements** – The process of development of strategies to provide robustness should preferably facilitate the identification of a benchmark level of robustness for a given structure
and its design and demonstrate a corresponding degree of compliance. If necessary, further enhancements in robustness levels or some form of value addition for the structure may be prescribed. This also helps in the establishment of trade-off relationships between cost on the one hand and robustness and lifecycle system performance on the other.

- **Quality control of robustness strategies** – It has been seen in Sections 4.2.6 and 4.2.7 that human errors and quality control issues associated with the baseline design contribute to the need for consideration and provision of structural robustness. The importance of quality control and monitoring for the planning, design, implementation and lifecycle maintenance associated with measures to ensure robustness therefore cannot be overemphasised.

### 4.2.8.3 Categorisation and organisation of robustness provisions

As discussed in Section 3.3.2, the set of robustness provisions for a structure aims to account for most indirect risks arising during its lifecycle. In the language of risk, a robust structure is then identified as one in which the prevailing indirect risks do not contribute significantly to the total risk associated with the structure, provided the associated direct risks are deemed to be acceptable and adequately covered by the standard safety format. The indirect risks principally result from the implications arising from the baseline design according to the standard safety format and the ensuing potential damages, failures and consequences. A hierarchical system of generic categorisation is developed to facilitate the identification of suitable strategies to provide and ensure robustness through the control of the indirect risks.

**Focus domain of risk control**

At the first or basic level of categorisation shown in Table 4.8, the generic categories are identified with respect to the focus domain of risk control and correspond to the different stages in the evolution of damages, failures and consequences described in Section 4.2.7.
State of failures and consequences | Focus domain of risk control for robustness strategies
---|---
Build-up towards primary failures | Event and hazard control
Primary failures | Localised failure control
Follow-up failures | System failure control
System failure | Consequences control

Table 4.8 Fields of categorisation for basic categorisation of robustness strategies.

In a quantitative sense, each generic category in this level of categorisation corresponds to the following quantities contributing to the indirect risks for a structure:

- probability of occurrence of events beyond the baseline design envelope having the potential to cause damages, failures or consequences in the structure – event and hazard control.
- probability of occurrence of primary failures given the occurrence of events precipitating build-up towards primary failures – localised failure control.
- probability of occurrence of follow-up failures and system failure given the occurrence of primary failures – system failure control.
- consequences arising from system failure and loss of system functionality – consequences control.

**Approach to risk treatment**

The next level of categorisation of strategies is based on their engineering approach to risk treatment. Here four generic categories – resistance, avoidance, protection and sacrifice taken from Menzies (2006) are used. This can be considered partly analogous to the risk reduction approaches – deny, detect, deter and devalue, used by the US Department of Homeland Security in connection with risk mitigation measures in building design (FEMA, 2005).

**Resistance** – This approach is based on the implementation of measures to adequately resist the effects of an unaccounted, unforeseen or accidental event. These include the provision of improved local resistance of selected
critical components in a structure, multiple independent load paths to ensure redundancy and measures such as the provision of ties that aim to reduce system failure.

**Avoidance** – The avoidance approach aims at the avoidance of extreme actions and their ensuing consequences through the adoption of measures such as quality management to minimise the occurrence of errors and ensure efficient design, detailing and execution, preventive replacement of components to ensure sufficient reliability throughout the intended design life and release mechanisms for energy dissipation.

**Protection** – The basis of the protection approach lies in the use of measures that modify a structure, its components or its ambient environment so that risks from events to which the structure is exposed to are reduced. These include, for instance, the placement of protective barriers and shields to protect a structure from impact and the use of protective coatings and membranes.

**Sacrifice** – The sacrifice approach involves the sacrifice of the structure or a part of it in order to reduce the probability of the failure of the whole structure or the ensuing consequences. Examples of this approach include the provision of sacrificial venting components to reduce the effect of explosions.

**Other fields of categorisation**

The two levels of categorisation may be seen to provide a generally adequate basis for the identification and establishment of suitable and optimal provisions for robustness in structures. Where relevant, the following three subsequent levels of categorisation may be considered:

**Nature of risk control** – Two generic categories are identified namely, direct and indirect. Direct measures can be seen as ‘active’ measures that confront unforeseen or accidental actions in order to minimise damage to the structure and ensure adequate resistance. On the other hand, indirect or ‘passive’ measures aim at implicit risk reduction through preventive or protective means.

**Relationship with event** – Here the classification of robustness provisions is carried out on the basis of whether they are event specific or independent.
Applicability in lifecycle of structure – The provisions are grouped as per the phase in the lifecycle of the structure in which they are relevant and applicable – these include the planning and design, execution, operation and maintenance phases.

Table 4.9 provides a listing of selected robustness provisions categorised into the relevant generic categories corresponding to the focus domain of risk control and the approach to risk treatment. The provisions listed have been obtained from different sources in literature including BSI (2006), Knoll and Vogel (2009), IStructE (2010), Starossek (2009) and Cormie et al. (2009). A viable and rational platform for the establishment of optimal provisions for robustness in structures is made available through this generic categorisation. The determination of the optimal set of robustness provisions for a structure is described in Section 4.3.

<table>
<thead>
<tr>
<th>Focus domain of risk reduction</th>
<th>Approach to risk treatment</th>
<th>Provisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure and hazard control</td>
<td>Avoidance</td>
<td>quality management to minimise the occurrence of errors and ensure efficient design, execution and maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>monitoring, quality control, correction and prevention</td>
</tr>
<tr>
<td></td>
<td></td>
<td>use of fire detection systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>due consideration of the (physical) location and layout of the structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>preventive maintenance and repair</td>
</tr>
<tr>
<td></td>
<td></td>
<td>use of alarm systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>control of access</td>
</tr>
<tr>
<td></td>
<td></td>
<td>controls for hazardous materials (event specific)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>minimised presence of fuel loads (event specific)</td>
</tr>
<tr>
<td>Protection</td>
<td></td>
<td>use of surveillance systems</td>
</tr>
<tr>
<td></td>
<td></td>
<td>use of stand-off distances, barriers, shields</td>
</tr>
</tbody>
</table>
### Development of a modified code format approach for the assessment of robustness of structures

<table>
<thead>
<tr>
<th>Focus domain of risk reduction</th>
<th>Approach to risk treatment</th>
<th>Provisions</th>
</tr>
</thead>
</table>
| Localised failure control     | Avoidance                 | • quality management to minimise the occurrence of errors and ensure efficient design, execution and maintenance  
                                 |                           | • monitoring, quality control, correction and prevention  
                                 |                           | • preventive replacement of components to ensure sufficient reliability throughout the intended design life  
                                 |                           | • use of mechanical devices such as tuned mass dampers to avoid extreme vibrations |
|                               | Protection                | • protective coatings and membranes against deterioration |
|                               | Resistance                | • use of key element design approach and improved local resistance  
                                 |                           | • use of (secondary) mechanisms such as catenary action  
                                 |                           | • provision of localised tying  
                                 |                           | • provision of robust connection behaviour  
                                 |                           | • use of strain hardening  
                                 |                           | • provision of (over) strength  
                                 |                           | • provision of stiffness  
                                 |                           | • use of post-buckling resistance |
| System failure control        | Avoidance                 | • quality management to minimise the occurrence of errors and ensure efficient design, execution and maintenance  
                                 |                           | • monitoring, quality control, correction and prevention  
                                 |                           | • provision of warning systems  
                                 |                           | • release mechanism for energy dissipation |
|                               | Protection                | • protection (shielding) of ‘critical’ components / parts of a structure  
                                 |                           | • use of segmentation / compartmentalisation  
                                 |                           | • design of ‘fuse’ elements (specified capacity) |
|                               | Resistance                | • provision of tying and structural continuity  
                                 |                           | • consideration of ductility in connections  
                                 |                           | • provision of multiple independent load paths  
                                 |                           | • provision of redundancy |
|                               | Sacrifice                 | • design to enable failure in ‘desirable’ modes – consideration of brittle failures  
                                 |                           | • mobilisation of energy absorption mechanisms  
                                 |                           | • provision of sacrificial venting components to reduce the effect of explosions |
Development of a modified code format approach for the assessment of robustness of structures

<table>
<thead>
<tr>
<th>Focus domain of risk reduction</th>
<th>Approach to risk treatment</th>
<th>Provisions</th>
</tr>
</thead>
</table>
| System failure consequences control | Avoidance | • provision of effective escape and evacuation routes  
| | | • provision of emergency management and warning systems |
| | Protection | • use of segmentation / compartmentalisation |
| | Resistance | • use of sprinkler systems  
| | | • provision of post-damage (cracking) ductility |

Table 4.9 Categorisation of robustness provisions.

4.3 Development of a guidance platform for structural design to achieve optimal and adequate robustness

4.3.1 Establishment of indicator based classification

The implications arising from the baseline design according to the standard safety format that require the consideration of robustness in structural design can arise in numerous possible ways. A scheme of indicator based classification is therefore advocated to provide guidance on the likely occurrences of deviations from the baseline design and the emergence of other situations beyond the baseline design envelope. The considerations are derived from the earlier established categorisation for influences, exposures and effects in the design and their possible linkages and interrelationships. Some illustrative fields and examples are provided below.

- Use related (widely spaced columns, cladded elements)
- Environment related (elements exposed to deterioration, exterior or publicly accessed columns)
- Material related (elements that exhibit brittle or insufficiently ductile behaviour)
- Time (attainment of deterioration thresholds in elements with time)
- Design process related
Development of a modified code format approach for the assessment of robustness of structures

- Exposure (aspects related to variability, load build-up, duration and location; elements whose failure can trigger wider failures)
- Effect and design measures (aspects related to path of load transfer, load utilisation, load cases and combinations; elements on the primary load paths, significant transfer elements, long span elements)
- Maintenance process related (elements with limited accessibility for inspections and maintenance)

Using this scheme, an identification of indicators in the structure judged to be significant is established with respect to the different stages in the evolution of failures and consequences in structures. This can be seen as a risk screening and prioritisation exercise for the development of significant scenarios of relevance with regard to structural robustness. This process of classification therefore facilitates the identification of credible situations for which suitable robustness strategies may then be formulated.

### 4.3.2 Identification of feasible robustness strategies

The deviations from the baseline design and the emergence of other situations beyond the baseline design envelope outlined in Section 4.2.6 principally encompass the domain of robustness considerations for a structure. Such deviations and situations set in motion the different stages associated with the evolution of damages, failures and consequences in structures in the (total or partial) implementation or absence of suitable counter-strategies. As seen in Section 4.2.8.3, strategies can, in principle, be provided to control the risks arising from each of these stages.

Depending on the degree of risk control achieved through the implementation of the robustness provisions, the deviations from the baseline design and the emergence of other situations beyond the baseline design envelope are seen to undergo changes during the different stages associated with the damages, failures and consequences for the structures, with the changes being reflective of the evolution of these stages. Accordingly, robustness strategies are identified in terms of generic categories pertaining to the focus domain of risk
control and approach to risk treatment and presented in Tables 4.10 to 4.12 together with some indicative provisions. Each table respectively corresponds to situations arising from the build-up towards primary failures, primary failures and follow-up failures. In accordance with the proposed risk-informed approach, a clear distinction is made between the standard safety format and the set of robustness provisions with regard to responsibilities for control of risks.

The establishment of credible situations through the indicator based classification described in Section 4.3.1 provides a clear and present basis to consider and provide for suitable strategies and provisions to ensure robustness. The generic deviations and situations beyond the baseline design envelope are then integrated with the indicator based classification for a structure to arrive at specific scenarios for the consideration and provision of robustness. For such scenarios, the generic categories for robustness strategies obtained from Tables 4.10 to 4.12 provide a useful indication and guidance for the specific identification and design of suitable provisions. Corresponding to these generic categories, the actual selection and design of robustness provisions and their aggregation depends on the domain of available and possibly favourable provisions in accordance with the design of the structure. Several feasible packages each consisting of different combinations of the robustness provisions for a structure may then be formulated with the corresponding risk reduction achieved being used as a measure of ranking and comparison. The use of pre-posterior decision analysis can be useful in this context (Faber and Maes, 2005b; Baker et al., 2008).
<table>
<thead>
<tr>
<th>Consideration</th>
<th>Extent of deviation</th>
<th>Possible cause(s)</th>
<th>Risks meant to be dealt with through</th>
<th>Risks actually dealt with through</th>
<th>Robustness strategies for event and hazard control indicated as generic categories for approach to risk treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>adequately dealt with or within the safety margin in the standard safety format</td>
<td>–</td>
<td>standard safety format</td>
<td>standard safety format</td>
<td>none required</td>
</tr>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control and monitoring) protection (event specific)</td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
<td></td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td>circumstances beyond reasonable consideration</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>to be considered in the next stage of evolution of damages, failures and consequences</td>
<td></td>
</tr>
</tbody>
</table>
Generic deviations from baseline design according to standard safety format
Stage: build-up towards primary failures

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Extent of deviation</th>
<th>Possible cause(s)</th>
<th>Risks meant to be dealt with through</th>
<th>Risks actually dealt with through</th>
<th>Robustness strategies for event and hazard control indicated as generic categories for approach to risk treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>ignored</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, monitoring and corrective actions) protection (event specific)</td>
</tr>
<tr>
<td>ignored</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
<td></td>
</tr>
<tr>
<td>ignored</td>
<td>circumstances beyond reasonable consideration</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>to be considered in the next stage of evolution of damages, failures and consequences</td>
<td></td>
</tr>
<tr>
<td>not anticipated / unforeseen / unforeseeable exposure, effect or measure</td>
<td>not applicable</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, correction) protection (event specific)</td>
</tr>
<tr>
<td>not applicable</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
<td></td>
</tr>
<tr>
<td>not applicable</td>
<td>circumstances beyond reasonable consideration</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>to be considered in the next stage of evolution of damages, failures and consequences</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.10 Indication of robustness strategies for control of build-up towards primary failures.
Development of a modified code format approach for the assessment of robustness of structures

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Extent of deviation</th>
<th>Possible cause(s)</th>
<th>Risks meant to be dealt with through</th>
<th>Risks actually dealt with through</th>
<th>Robustness strategies for localised failure control indicated as generic categories for approach to risk treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>adequately dealt with or within the safety margin in the standard safety format</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>standard safety format</td>
<td>none required</td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td></td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, preventive replacement)</td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td></td>
<td>circumstances beyond reasonable consideration (e.g. brought about by build-up towards primary failures)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td></td>
<td>resistance (key element, over-strength, stiffness, secondary mechanisms)</td>
<td>set of robustness provisions</td>
<td>protection</td>
<td></td>
</tr>
</tbody>
</table>
### Generic deviations from baseline design according to standard safety format

**Stage:** primary failures

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Extent of deviation</th>
<th>Possible cause(s)</th>
<th>Risks meant to be dealt with through</th>
<th>Risks actually dealt with through</th>
<th>Robustness strategies for localised failure control indicated as generic categories for approach to risk treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>anticipated /foreseen exposure, effect or measure</td>
<td>ignored</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, preventive replacement)</td>
</tr>
<tr>
<td>ignored</td>
<td>ignored</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
</tr>
<tr>
<td>ignored</td>
<td>ignored</td>
<td>circumstances beyond reasonable consideration (e.g. brought about by build-up towards primary failures)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>resistance (secondary/alternate mechanisms) protection</td>
</tr>
<tr>
<td>not anticipated/unforeseen/unforeseeable exposure, effect or measure</td>
<td>not applicable</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, preventive replacement)</td>
</tr>
<tr>
<td>not applicable</td>
<td>not applicable</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
</tr>
<tr>
<td>not applicable</td>
<td>not applicable</td>
<td>circumstances beyond reasonable consideration (e.g. brought about by build-up towards primary failures)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>resistance (secondary/alternate mechanisms) protection</td>
</tr>
</tbody>
</table>

*Table 4.11 Indication of robustness strategies for control of primary failures.*
<table>
<thead>
<tr>
<th>Consideration</th>
<th>Extent of deviation</th>
<th>Possible cause(s)</th>
<th>Risks meant to be dealt with through</th>
<th>Risks actually dealt with through</th>
<th>Robustness strategies for system failure control indicated as generic categories for approach to risk treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>adequately dealt with or within the safety margin in the standard safety format</td>
<td>—</td>
<td>standard safety format</td>
<td>standard safety format</td>
<td>none required</td>
</tr>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, preventive replacement, release mechanisms)</td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
<td></td>
</tr>
<tr>
<td>inadequate beyond the safety margin of the standard safety format</td>
<td>circumstances beyond reasonable consideration (e.g. brought about by primary failures)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>resistance (redundancy and multiple independent load paths, tying, ductility) protection (segmentation, depending on load level) sacrifice (failure of desired modes, venting components)</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.12 Indication of robustness strategies for control of system failures.

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Extent of deviation</th>
<th>Possible cause(s)</th>
<th>Risks meant to be dealt with through</th>
<th>Risks actually dealt with through</th>
<th>Robustness strategies for system failure control indicated as generic categories for approach to risk treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>anticipated / foreseen exposure, effect or measure</td>
<td>ignored</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, preventive replacement)</td>
</tr>
<tr>
<td></td>
<td>ignored</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
</tr>
<tr>
<td></td>
<td>ignored</td>
<td>circumstances beyond reasonable consideration (e.g. brought about by primary failures)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>resistance (redundancy and multiple independent load paths, tying, ductility) protection (segmentation, depending on load level) sacrifice (failure of desired modes, venting components)</td>
</tr>
<tr>
<td>not anticipated / unforeseen / unforeseeable exposure, effect or measure</td>
<td>not applicable</td>
<td>human (and other) errors</td>
<td>standard safety format</td>
<td>set of robustness provisions</td>
<td>avoidance (quality control, preventive replacement)</td>
</tr>
<tr>
<td></td>
<td>not applicable</td>
<td>lack of knowledge (prevailing best practice and state of the art)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>avoidance (lifecycle monitoring and updating)</td>
</tr>
<tr>
<td></td>
<td>not applicable</td>
<td>circumstances beyond reasonable consideration (e.g. brought about by primary failures)</td>
<td>set of robustness provisions</td>
<td>set of robustness provisions</td>
<td>resistance (redundancy and multiple independent load paths, tying, ductility) protection (segmentation, depending on load level) sacrifice (failure of desired modes, venting components)</td>
</tr>
</tbody>
</table>
4.3.3 Optimisation and determination of optimal strategies for robustness

The ideal culmination of a structural design process can be in the form of a holistic optimisation exercise that judiciously caters to the identified risks arising from the design. From the perspective of engineering decision making for societal development, such optimisation aims to achieve a sustainable balance between resources on the one hand and requirements related to safety and performance on the other. Bayesian decision theory provides a strong theoretical basis for the establishment of principles for optimal risk-based decision engineering making; its implementation in practice may be possible with due recognition and consideration of the practical challenges arising from its use. Such challenges include the proper representation of uncertainties, the use of societal risk perception in decision making, consistency in use across application domains and the consideration and importance accorded to sustainability (Faber & Maes, 2008).

The primary considerations for an optimisation process can be derived from relevant events and consequences associated with structures. These are concerned with life safety, safety pertaining to the structure and qualities of the environment and also economic implications in the form of losses or benefits associated with the use of the structure. Relevant acceptance criteria for investments into safety then need to be established which can take the shape of suitable constraints in the optimisation. An overall lifecycle optimization of the total risks associated with structures with due constraints for life safety and other requirements can be considered as a complete framework for engineering decision making.

4.3.3.1 Risk acceptance for life safety

Suitable risk acceptance criteria for life safety can be established using the marginal life saving cost principle which can be implemented through the use of the Life Quality Index (LQI). The LQI fundamentally aims to model the preferences of a society through a social-economic-demographic indicator and is represented by a relationship between the Gross Domestic Product (GDP)
per capita \( g \), the life expectancy at birth \( e \) and the proportion of life spent for earning a living \( w \). Details regarding the LQI principle and approach can be found in Nathwani et al. (2009) and Nathwani et al. (1997). A simple form of expressing the LQI is:

\[
L = g^q e
\]

(4.1)

Here the parameter \( q \) is a measure of the trade-off between wealth or consumption and leisure time and can be assessed as:

\[
q = \frac{1}{\beta} \frac{w}{1-w}
\]

(4.2)

In Equation 4.2, \( \beta \) accounts for the fact that only a certain part of the GDP is based on work or labour and the other part realised through investments and other activities.

An acceptance criterion in the form of a threshold for investments into life safety can then be established using the consideration that any such investment into life risk mitigation shall lead to an increase in the value of the LQI. By setting the full derivative of the LQI as zero, this is obtained as (Faber, 2010):

\[
dL = \frac{\partial L}{\partial g} dg + \frac{\partial L}{\partial e} de \geq 0
\]

(4.3)

\[
\frac{dg}{g} + \frac{1}{q} \frac{de}{e} \geq 0
\]

(4.4)

\[
-dg \geq \frac{g}{q} \frac{de}{e} = \frac{g}{q} C dm
\]

(4.5)

The underlying understanding behind this societal acceptance criterion for life safety is that investments into the risk mitigation measures associated with life safety need to be carried out till the corresponding marginal risk mitigation exceeds the marginal costs of risk mitigation. Investments into life safety below the threshold in Equation 4.5 are therefore not acceptable based on this criterion – this threshold is also referred as the Societal Willingness to Pay.
(SWTP) into life saving measures. For engineering decision making problems, the marginal mortality reduction (or the expected number of lives saved) $dm$ is generally specified. This reduction in mortality or the expected number of lives saved is transformed into a corresponding increase in life expectancy through a demographic constant $C_x$ that can be estimated from population life tables (Rackwitz, 2006).

The life safety investment threshold may also be expressed in economic terms, if so required in the optimisation. Such representation accounts for the possible loss of lives through the use of the Societal Value of a Statistical Life (SVSL) expressed as:

$$SVSL = \frac{g}{q}E$$ \hspace{1cm} (4.6)

Here $E$ is the age averaged discounted life expectancy (Rackwitz, 2006).

When seen in the context of a societal decision making framework, the use of the LQI provides a rational basis for the assessment of decisions (involving risk mitigation options) concerning investments into life safety with due consideration of their compliance with societal preferences.

### 4.3.3.2 Safety and reliability requirements for structures

Safety and reliability requirements are handled in code-based structural design through the specification of target reliabilities for identified limit states in structures (BSI, 2002) which are currently used to ensure safety of structural components with respect to identified component failure modes. In order to ensure robustness in structures, safety requirements may need to be specified at the level of the overall structure. Such requirements need to take into account the consequences associated with life safety, economic losses and damages to the qualities of the environment in structures (see Section 4.2.7.5). The conceptual basis for such requirements may be drawn from the target reliability index values obtained from the Probabilistic Model Code of the Joint Committee on Structural Safety (JCSS, 2001a). These values given in Table 4.13 are for a
Development of a modified code format approach for the assessment of robustness of structures

reference period of one year and specified as a function of consequences of failure and the relative cost or the efficiency of design provisions concerning safety. The classification with respect to the relative cost of safety measures can be understood in a manner somewhat analogous to the LQI risk acceptance criteria discussed in Section 4.3.3.1. Investments concerning safety need to be undertaken as long as there are suitable efficient measures available in line with relevant best practices; this, in turn, determines the achievable reliability level for the structure together with the corresponding consequences of failure.

<table>
<thead>
<tr>
<th>Consequences of failure</th>
<th>Minor consequences</th>
<th>Moderate consequences</th>
<th>Large consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>$\beta = 3.1 \ (p_F \approx 10^{-3})$</td>
<td>$\beta = 3.3 \ (p_F \approx 5 \times 10^{-4})$</td>
<td>$\beta = 3.7 \ (p_F \approx 10^{-4})$</td>
</tr>
<tr>
<td>Normal</td>
<td>$\beta = 3.7 \ (p_F \approx 10^{-4})$</td>
<td>$\beta = 4.2 \ (p_F \approx 10^{-5})$</td>
<td>$\beta = 4.4 \ (p_F \approx 5 \times 10^{-6})$</td>
</tr>
<tr>
<td>Small</td>
<td>$\beta = 4.2 \ (p_F \approx 10^{-5})$</td>
<td>$\beta = 4.4 \ (p_F \approx 5 \times 10^{-6})$</td>
<td>$\beta = 4.7 \ (p_F \approx 10^{-6})$</td>
</tr>
</tbody>
</table>

*Table 4.13 Target reliability index ($\beta$) and probability of failure ($p_F$) values for safety, corresponding to a reference period of one year (Source: JCSS, 2001a).*

The underlying philosophy behind the reliability requirements given in Table 4.13 addresses failure modes in structures in general which can include component as well as system failure modes without differentiation. With this understanding, design situations with regard to member failure modes in a structure can be considered to correspond to the reliability requirements associated with minor consequences of failure. Then, the design situations corresponding to system failures given the occurrences of member failures can be related to the reliability requirements for failure modes with large consequences.

This provides a useful first basis for the establishment of suitable safety requirements that aim to address robustness in structures. Two important issues however need to be addressed. The first issue concerns the identification of relevant design situations for consideration of system failures. In contrast to the readily available standardised library of limit states in code-based design for structural components, difficulties presently exist in the formulation of relevant system limit states in structures that can then be used to adequately characterise overall structural safety through verification with
Development of a modified code format approach for the assessment of robustness of structures

respect to the target reliability index values. Secondly, as mentioned in JCSS (2001a), failures due to human errors and lack of knowledge are not covered in the specification of target safety values given in Table 4.13. As discussed in Sections 4.2.6 and 4.2.7, these considerations can be seen to exert a significant degree of influence on the robustness of structures. Addressing these concerns, the framework described in this thesis provides a clear approach for the determination of credible design situations that require attention from a robustness perspective and may also be eventually used for the calibration of target safety values for robustness (see Section 4.3.3.5).

4.3.3.3 Lifecycle optimisation

The determination of optimal design parameters for a structure is then carried out in an optimisation process through the consideration of all relevant costs and benefits associated with the structure and the maximisation of the total expected net benefits over its lifecycle. The optimisation function \( W \) that needs to be maximised can be expressed in a simple form (with possible constraints on safety) as:

\[
W = B(z) - (C_i(z) + C_m(z) + C_c(z))
\]  

(4.7)

The cost components include the initial construction costs \((C_i)\), the lifecycle inspection and maintenance costs \((C_m)\) and the expected consequence costs \((C_c)\) associated with fatalities/loss of lives and injuries, economic losses and damages to qualities of the environment. Benefits \((B)\) arising from the use of structure are also taken into account. As discussed in Section 4.3.3.1, life safety consequences can be considered in the form of constraints in the optimisation or in the form of equivalent consequence costs. Further, requirements in the form of target safety values for structures as discussed in Section 4.3.3.2 may also be applied as constraints in the optimisation. Appropriate discounting needs to be considered in the optimisation; an interest rate reflecting the economic growth in society is recommended for use for all benefits and costs associated with engineering decision making (Paté-Cornell, 1984).
4.3.3.4 Identification of optimal robustness strategies

For practical implementation purposes, the issue of optimisation needs to be considered in the domain of code-based structural design. For this purpose, the complete risk model as described in Section 3.1 is again considered. As illustrated in Figure 3.4, the code standard safety format and the set of robustness provisions each correspond to a certain proportion of the risk information considered in the ideal complete risk model for a structure and cater to the corresponding domain of risks. The code standard safety format can be considered to be already optimised in line with prevailing best practice design. The remaining issue at hand is therefore the optimisation of the set of robustness provisions.

The basic considerations for this optimization involve:

- the lifecycle costs associated with the different alternatives for robustness strategies and provisions, and
- the trade-offs involving investments into reduction of risks achieved through the implementation of the robustness strategies.

These trade-offs may be based on the marginal criteria for risk reduction which stipulates that risk reduction needs to be undertaken till the marginal cost of additional risk reduction equals the corresponding marginal benefit in terms of reduced risks. As discussed in Section 4.3.3.1, suitable investments into the reduction of life safety risks may be determined using the Life Quality Index criterion (Nathwani et al., 1997) concerning marginal life safety investments. The optimisation therefore provides a clear and rational basis for the allocation of resources towards ensuring robustness in structures as well as decision support for their prioritisation.

4.3.3.5 Calibration

Past work on code calibration (Faber and Sørensen, 2003; JCSS, 2003; Sørensen et al., 1994; Ellingwood et al., 1982; Ravindra & Galambos, 1978) has mostly focused on structural member design, though the underlying approach philosophies may have the potential for use in a structure wide
context. A specific form of calibration at the structural system level can be seen in Ghosn and Frangopol (2007) through the specification of system factors used for girder superstructures in bridge design and evaluation.

Calibration in the context of code-based structural design is identified at two levels – calibration of target reliabilities and calibration of partial safety factors (Sørensen et al., 1994). The calibration of target reliabilities at the level of overall structures can be seen to be particularly relevant in the context of robustness. The values from the Probabilistic Model Code of the Joint Committee on Structural Safety (JCSS, 2001a) given in Table 4.13 provide a first basis for the establishment of such target system safety levels. The key challenges in the calibration of target safety levels for system safety involve the establishment of systematic approaches to identify representative design situations for evaluation and target verification and the provision of a more visible and explicit association of robustness provisions for these design situations. The developed approach described in this thesis effectively addresses both these issues. It can therefore provide useful answers for calibration through its application for different principal classes of structures, designs and materials in a formal decision optimisation framework (see Section 4.3.3.3) with constraints on life safety formulated based on the LQI approach (see Section 4.3.3.1). Such applications will provide the information necessary for the comparison of robustness levels corresponding to different sets of design circumstances and corresponding provisions and ultimately lead to the calibration and establishment of robustness benchmarks and safety requirements for structures.

4.3.4 Determination of suitable use of the approach – classification of structures

The determination of the general approach and the strategies to be adopted to ensure robustness in structures can be guided by the use of classification systems found in structural design codes and standards. Such classification systems are in the form of the consequence classes in the Eurocodes (BSI, 2002; BSI 2006) or the occupancy categories in the American standards (DoD, 2009). The parameters of classification include the type, dimensions, use and
occupancy associated with the structures. Using the Eurocode consequence class categorisation (BSI, 2006) as a basis, the general approach to be adopted to ensure robustness in structures can be established in the following manner:

**Structures in consequence class 1** – These can be considered to be structures of low importance with minor consequences in case of failure for which generally no specific consideration of robustness may be necessary.

**Structures in consequence classes 2a and 2b** – The use of the approach described in this chapter may be seen to be most for structures belonging to these intermediate categories. This is facilitated through a visible process for the consideration and identification of situations and scenarios that need to be addressed through the provision of robustness in structures followed by the recommendation of generic strategies for robustness which can be detailed depending on the specific circumstances and conditions associated with each structure.

**Structures in consequence class 3** – These are structures of great importance for which a detailed scenario-based systematic risk assessment is required. For such structures, the developed approach described in this chapter provides a strong basis for the identification, screening and consideration of scenarios and strategies for further detailed treatment.
Chapter 5

Illustration of the proposed approach

5.1 Problem description

An illustration of the approach described in Chapter 4 for the assessment and provision of robustness in structures is provided in this chapter. A 10-storeyed steel framed commercial building partly adapted from Way (2011) is considered. The front and side elevations of the structure are shown in Figure 5.1. The overall dimensions of the building on plan are 36 m by 36 m and the height of each storey is 4 m.

Figure 5.1 Illustration of the front and the side elevations of the considered structure.
5.2 Baseline design

The column elements of the structure are laid out on a 6 m by 9 m grid spacing. The primary beam elements have a span of 6 m whereas the secondary beam elements have a span of 9 m. The floor slab elements are made of reinforced concrete with a thickness of 150 mm. The loading for each storey is considered to comprise a permanent action component of 3 kN/m$^2$ and a variable action component of 6 kN/m$^2$.

The baseline design for this structure according to the code standard safety format is carried out in accordance with the Eurocodes (BSI, 2002; BSI, 2005). The design situations thus considered correspond to the combination of actions for persistent or transient design situations as defined in BSI (2002). Suitable sizes of the beam and column elements are taken from design tables in SCI (2009). The sizes of the primary and secondary beam elements are obtained as 406 x 178 x 54 UB and 356 x 171 x 51 UB both using steel of grade S355. The column sizes obtained for the structure are given in Table 5.1.

<table>
<thead>
<tr>
<th>Level</th>
<th>Perimeter column (grade S355)</th>
<th>Interior column (grade S355)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground-1</td>
<td>356 x 406 x 235 UC</td>
<td>356 x 406 x 287 UC</td>
</tr>
<tr>
<td>1-2</td>
<td>356 x 406 x 235 UC</td>
<td>356 x 406 x 287 UC</td>
</tr>
<tr>
<td>2-3</td>
<td>356 x 368 x 177 UC</td>
<td>356 x 368 x 202 UC</td>
</tr>
<tr>
<td>3-4</td>
<td>356 x 368 x 177 UC</td>
<td>356 x 368 x 202 UC</td>
</tr>
<tr>
<td>4-5</td>
<td>356 x 368 x 153 UC</td>
<td>356 x 368 x 177 UC</td>
</tr>
<tr>
<td>5-6</td>
<td>356 x 368 x 153 UC</td>
<td>356 x 368 x 177 UC</td>
</tr>
<tr>
<td>6-7</td>
<td>356 x 368 x 153 UC</td>
<td>356 x 368 x 153 UC</td>
</tr>
<tr>
<td>7-8</td>
<td>356 x 368 x 153 UC</td>
<td>356 x 368 x 153 UC</td>
</tr>
<tr>
<td>8-9</td>
<td>356 x 368 x 129 UC</td>
<td>356 x 368 x 129 UC</td>
</tr>
<tr>
<td>9-Roof</td>
<td>356 x 368 x 129 UC</td>
<td>356 x 368 x 129 UC</td>
</tr>
</tbody>
</table>

Table 5.1 Design column sizes.

5.3 Assessment and development of robustness strategies and provisions

5.3.1 Identification of indicators and robustness strategies

The identification of the relevant indicators for the structure is then carried out based on the procedure described in Section 4.3.1. Table 5.2 gives the indicators deemed to be important in the consideration and provision for
robustness in the structure. The indicators are organised based on the categorised exposures (Section 4.2.3.2), effects (Section 4.2.3.3) and influences (Section 4.2.3.4). For each consideration (influence/exposure/effect/design measure), the associated indicators and their relevant descriptors and characterisation are identified. Following this, the suitable strategies for robustness are identified from Tables 4.10 to 4.12 in terms of their generic categories corresponding to the focus domain of risk control and the approach to risk treatment.
### Illustration of the proposed approach

<table>
<thead>
<tr>
<th>Considerations (Influence / exposure / effect / design measure)</th>
<th>Associated indicators</th>
<th>Robustness strategies</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Category/field</strong></td>
<td><strong>Sub-category/field</strong></td>
<td><strong>Identification</strong></td>
<td><strong>Focus domain of risk control</strong></td>
</tr>
<tr>
<td><strong>Use</strong></td>
<td>Activities, time of use and occupancy profile</td>
<td>Rescue and evacuation routes</td>
<td>Consequences control</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Climate</td>
<td>Deterioration beyond expected considerations</td>
<td>Exposed elements</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Vicinity to highway and susceptibility to impact</td>
<td>Ground floor exterior columns</td>
<td>Event and hazard control</td>
</tr>
<tr>
<td><strong>Spatial characteristics</strong></td>
<td>Form and configuration – structural layout and arrangement</td>
<td>Publicly accessed columns</td>
<td>Ground floor exterior columns</td>
</tr>
<tr>
<td><strong>Other characteristics – façade</strong></td>
<td>Façade glazing</td>
<td>Building areas in the vicinity of building façade</td>
<td>Consequences control</td>
</tr>
<tr>
<td><strong>Time related characteristics</strong></td>
<td>Period in which the design and execution has been carried out</td>
<td>Lack of knowledge</td>
<td>General</td>
</tr>
<tr>
<td><strong>Technical and economic service life of components</strong></td>
<td>Deviations from expected technical service life</td>
<td>Localised failure control</td>
<td>Avoidance (periodic inspection and replacement)</td>
</tr>
<tr>
<td>Considerations (Influence / exposure / effect / design measure)</td>
<td>Associated indicators</td>
<td>Robustness strategies</td>
<td>Reference</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>------------------------</td>
<td>-----------------------</td>
<td>-----------</td>
</tr>
<tr>
<td><strong>Basic Category/field</strong></td>
<td><strong>Sub-category/field</strong></td>
<td><strong>Identification</strong></td>
<td><strong>Description/Location</strong></td>
</tr>
<tr>
<td>Material aspects</td>
<td>Material production</td>
<td>Correlations and possibility of common cause failures</td>
<td>Localised failure control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>System failure control</td>
</tr>
<tr>
<td>Material behaviour</td>
<td>Insufficiently ductile behaviour in members and connections</td>
<td>Localised failure control</td>
<td>Avoidance (periodic inspection and replacement) Protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>System failure control</td>
</tr>
<tr>
<td>Design process related</td>
<td>Consideration of effects and design measures – load utilisation</td>
<td>High load utilisation</td>
<td>Columns at storeys just before change of section dimensions</td>
</tr>
<tr>
<td>Maintenance process related</td>
<td>Inspections and maintenance</td>
<td>Elements with limited accessibility for inspections and maintenance</td>
<td>Localised failure control</td>
</tr>
<tr>
<td>All lifecycle processes and activities related</td>
<td>Design, execution, use and maintenance</td>
<td>Human (and other) errors</td>
<td>General</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lack of knowledge (prevailing best practice)</td>
<td>General</td>
</tr>
</tbody>
</table>

Table 5.2 Considerations and indicators used in the assessment and provision of robustness and corresponding robustness strategies for the structure.
5.3.2 Selection of robustness provisions

The identification of the generic robustness strategies provides an indication of the possible approaches that exist to deal with the identified indicators. The next step involves the selection of suitable implementation provisions to ensure robustness and the formulation of different possible sets or packages of robustness provisions for the structure. To facilitate this process, a further categorisation of provisions is established based on their nature of risk control into direct provisions which are based on a ‘resistance’ approach and indirect provisions which are protective and preventive in nature. Accordingly, a suitable combination of direct and indirect robustness provisions for the structure derived based on Table 5.2 are given in Table 5.3. As mentioned in Section 4.3.3.4, the choice of an optimal set or package of robustness provisions can then be based on the considerations of their lifecycle cost and their degree of risk reduction.

<table>
<thead>
<tr>
<th>Indicator reference</th>
<th>Robustness provisions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct provisions</strong></td>
<td></td>
</tr>
<tr>
<td>3b, 4b</td>
<td>Improved local resistance of ground floor exterior columns</td>
</tr>
<tr>
<td></td>
<td>In the absence of any structure specific information, the existing design is checked for compliance with the key element design approach in accordance with BSI (2006) using the recommended design value of 34 kN/m².</td>
</tr>
<tr>
<td>8b, 9b, 10</td>
<td>Provision of explicit tying and multiple load paths through catenary action in the structural frame and action of bracing system to take care of possible:</td>
</tr>
<tr>
<td></td>
<td>• common cause failures</td>
</tr>
<tr>
<td></td>
<td>• cases of insufficiently ductile behaviour</td>
</tr>
<tr>
<td></td>
<td>• failures of critical elements (such as columns with high load utilisation) whose failure can lead to wider failures in the structure</td>
</tr>
</tbody>
</table>

The provision of horizontal and vertical ties is carried out in accordance with BSI (2006). Using Equations (A.1) and (A.2) of BSI (2006), the required horizontal tie resistances for the internal and perimeter beams in the primary direction are obtained as 260 kN and 130 kN respectively. Similarly, the required horizontal tie resistances for the internal and perimeter beams in the secondary direction are obtained as 130 kN and 65 kN respectively. The vertical tie resistance is obtained using guidance from Clause A.6(2) of BSI (2006) applied together with Equation 6.10b of BSI (2002) as 690 kN for the internal columns and 345 kN for the external columns.
<table>
<thead>
<tr>
<th>Indicator reference</th>
<th>Robustness provisions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Indirect provisions</strong></td>
<td></td>
</tr>
</tbody>
</table>
| 1 | Provision of effective escape and evacuation routes  
Provision of emergency management and warning systems |
| 2 | Lifecycle inspections to monitor deterioration of exposed elements |
| 3a, 4a | Provision of barriers around building perimeter in the form of bollards and chain-link fencing |
| 5 | Suitable material consideration and design of glazing with the use of laminated glass |
| 7 | Periodic inspection and replacement of components in accordance with their technical service life |
| 8a | Periodic inspection and preventive replacement of components exhibiting high degree of correlation with damage detected components for avoidance of possible common cause failures |
| 9a | Periodic inspection and replacement of components exhibiting insufficiently ductile material behaviour and monitoring to ensure adequate connection rotation capacities |
| 9b | Monitoring to ensure adequate connection rotation capacities, together with corresponding prescribed direct provisions above |
| 10 | Periodic inspection of critical elements (columns with high load utilisation), together with corresponding prescribed direct provisions above |
| 11 | Periodic preventive replacement of elements with limited accessibility for inspections and maintenance |
| 12 | Quality control, correction and preventive monitoring to account for human (and other) errors |
| 6, 13 | Lifecycle monitoring and updating to account for emergence of new knowledge and information with time and lack of knowledge at the time of design and execution |

*Table 5.3 Set of robustness provisions for the structure.*
5.4 Evaluation of lifecycle costs, risks and robustness of the structure

5.4.1 Estimation of lifecycle costs

The estimation of the lifecycle costs associated with the robustness provisions is carried out based on information obtained for Singapore from the schedule of unit rates for construction work published by the regulatory body for Singapore’s construction industry (BCA, 2011) and from interviews with Singapore construction industry sources, where necessary. This information is given in Table 5.4.

<table>
<thead>
<tr>
<th>Cost category</th>
<th>Costs (in Singapore Dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial costs (associated during design and execution stages)</td>
<td>578,900</td>
</tr>
<tr>
<td>Inspection, monitoring and associated repair costs (indicative; for each inspection)</td>
<td>360,300 – 387,150</td>
</tr>
<tr>
<td>Associated replacement costs (indicative; following each inspection)</td>
<td>202,650 – 222,950</td>
</tr>
</tbody>
</table>

*Table 5.4 Information for estimation of lifecycle costs for the robustness provisions.*

As seen in Table 5.4, a range of values is obtained for the costs associated with the stipulated inspection, monitoring and associated repair and replacement measures during the lifecycle of the structure, reflecting the underlying uncertainties, efficiencies and other considerations involved in their pricing. The inspection and the associated repair/replacement costs are relevant in the context of the local practice of performing structural inspections every 5 years for non-residential buildings which is mandated by statutory legislation (AGC, 1999). In order to be harmonious with these regulations, the inspection interval corresponding to the relevant robustness provisions is taken to be 5 years. A discount rate of 2.02% (Narasimhan and Chew, 2009) is used for the discounting of all future costs to their present values. The estimation of lifecycle costs for the robustness provisions is discussed in Section 5.4.3.
5.4.2 Methodology for the evaluation of risks and robustness

The design scenarios in the structure that warrant attention from a robustness perspective can arise in numerous possible ways and can be principally derived based on the identified indicators in the structure (see Section 5.3.1). For the purposes of illustration, the analysis reported in this section focuses on the evaluation of the risks and the robustness of the structure following the occurrence of an extraordinary exposure event and the ensuing failure of identified elements in the structure. This evaluation of robustness is based on the system safety of the remaining undamaged structure and can therefore be seen to be conditional on the specified exposure and damage events. The occurrence of such an extraordinary exposure event followed by failure or loss of structural elements triggers a structural response which is typically dynamic in nature and involves nonlinearities associated with geometry and material behaviour as discussed in Section 4.2.3.4. The analysis performed here does not directly consider these effects and can be seen as a simple approximation of the problem in order to obtain a first estimate of the safety of the undamaged structure.

The following parameters and considerations are taken up in the analysis.

i) Location of occurrence of extraordinary exposure and damage events

The scenarios considered for analysis involve the assessment of the residual safety of the structure following the occurrence of an extraordinary exposure event (such as explosion or impact) and the resulting damage to identified column elements in the structure. Two damage scenarios are considered – one involving the damage to a corner column on the ground storey and the second the damage to a perimeter (not situated at the building corners) column on the ground storey, both occurring on the front elevation. Such scenarios are commonly considered in robustness and associated disproportionate collapse analyses (Vlassis et al., 2008). These damage scenarios are shown in Figure 5.2 and are considered to be applied independently. Damage here refers to the failure or exceedance of prescribed design limit states associated with bending and axial load effects for the concerned column element and the failure of the immediately supported beam, slab and bracing elements.
ii) **Efficiency of lifecycle inspection, monitoring and associated repair and replacement**

The importance of lifecycle inspection and associated repair and replacement measures for targeted areas and properties associated with the structure can be clearly seen in the set of robustness provisions given in Table 5.3. The efficiency of such measures (hereinafter also referred to as lifecycle robustness measures) is hence a crucial factor in order to ensure adequate robustness of the structure. The efficiency associated with these measures can be related to aspects with regard to their quality as well as the scope of coverage of involved works – an efficiency of 100% corresponds to complete compliance with the stipulated provisions. In order to evaluate the effectiveness of the implementation of these measures, the following two-step approach is used:

a) It is assumed the degree of compliance and efficiency of the stipulated inspection, maintenance and associated repair/replacement measures in

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*Figure 5.2 Location of damage scenarios considered independently: a) damage to corner column and b) damage to a perimeter column.*
addressing the robustness requirements associated with the structure is represented by their corresponding lifecycle costs through a linear relationship. Based on the information from the interviews conducted to obtain the cost information, it is established that the range of costs obtained for the inspection, monitoring and associated repair and replacement measures correspond to an efficiency ranging between 70% and 90%. Accordingly, five values for the efficiency of the lifecycle robustness measures – 70%, 75%, 80%, 85% and 90% are considered for analysis.

b) The effect of the efficiency of the measures is considered in the form of a multiplication factor on the resistance of the elements identified based on Table 5.2 and for which the inspections, monitoring and necessary repair/replacement are performed. This is broadly based on the approach suggested in Vrouwenvelder and Leira (2011). The multiplication factor is modelled as a truncated Normal distributed random variable with a mean value of one and a coefficient of variation equal to $0.25(1-e)$, where $e$ is the efficiency associated with the robustness measures. Such modelling can be seen as a first approximation contextual to this example and may be updated following a Bayesian approach depending upon the availability of relevant information in the future.

For each scenario, estimates of the system reliability of the structure and hence the system probability of failure are obtained using the $\beta$-unzipping method (Thoft-Christensen and Murotsu, 1986). A risk-based measure of robustness (Baker et al., 2008) as defined in Section 2.6.1 is then used to obtain an estimate of the robustness of the structure. Since specific exposure and damage events are considered, the measure of robustness in such cases is computed conditional on the specified exposure and damage events.
Using Equation 2.3 as the basis, the conditional index of robustness is then obtained as:

$$I_{ROB|D,E} = \frac{R_{DIR}}{R_{DIR} + R_{IND}} = \frac{C_{DIR}}{C_{DIR} + P(F|D,E)C_{IND}}$$  \hspace{1cm} (5.1)

where:

- $I_{ROB|D,E}$ is the index of robustness conditional on the occurrence of specified exposure event(s) followed by specified damage event(s),
- $R_{DIR}$ and $R_{IND}$ are the direct risks and indirect risks (defined in Section 2.6.1) respectively,
- $C_{DIR}$ and $C_{IND}$ are the associated direct consequences and indirect consequences (defined in Section 2.6.1) respectively, and
- $P(F|D,E)$ is the probability of system failure conditional on the specified exposure and damage events.

Direct consequences are considered to be associated with the repair, replacement and disruption costs arising from the damage of the column and supported elements as specified in the damage scenarios and are taken to be 1% of the total reconstruction costs of the structure. The indirect consequences are determined based on the estimates provided in a study on the failure of the World Trade Center towers in the USA (Faber et al., 2004); in this study, the total consequences associated with the failure of the structures are estimated to be between 7.6 to 19.7 times the reconstruction costs of the structures. Using the lower bound of this estimate, the ratio of the indirect consequences to direct consequences for this example is estimated to be 759.

### 5.4.3 Results and analysis

For the two damage scenarios and the different values of the efficiency of the lifecycle robustness measures, the estimated lifecycle costs, the system reliability index (and system probability of failure) and the index of robustness are given in Table 5.5. Here, the primary system safety criteria is assumed to be...
established in terms of the system reliability of the undamaged structure; other forms of evaluation of the system safety may include the consideration and extent of local damage, for instance, in the form of code-specified admissible limits (BSI, 2006).

<table>
<thead>
<tr>
<th>Efficiency of lifecycle robustness measures (in %)</th>
<th>Lifecycle costs (in Singapore Dollars)</th>
<th>Evaluation of robustness (scenario specific)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Damage to corner column</td>
</tr>
<tr>
<td></td>
<td></td>
<td>System reliability index (Probability of system failure)</td>
</tr>
<tr>
<td>70</td>
<td>3,753,585.73</td>
<td>3.74 (9.2 x 10^{-5})</td>
</tr>
<tr>
<td>75</td>
<td>3,786,896.95</td>
<td>3.95 (3.9 x 10^{-5})</td>
</tr>
<tr>
<td>80</td>
<td>3,820,208.17</td>
<td>4.51 (3.2 x 10^{-6})</td>
</tr>
<tr>
<td>85</td>
<td>3,853,519.38</td>
<td>4.54 (2.8 x 10^{-6})</td>
</tr>
<tr>
<td>90</td>
<td>3,886,830.60</td>
<td>4.58 (2.3 x 10^{-6})</td>
</tr>
</tbody>
</table>

Table 5.5 Results from the evaluation of lifecycle costs, residual safety and robustness of the structure.

With respect to the considered damage scenarios, it is consistently seen that the cases arising from the damage to the corner column have a relatively lower system reliability and index of robustness values compared to the cases initiated from the damage to the perimeter column. As shown in Figure 5.3, this difference is seen to reduce with an increase in the efficiency of the lifecycle robustness measures, with a negligible difference obtained for the maximum efficiency (90%) case – this indicates the possible insensitivity of the system to the different triggering events. The observed difference can be due to the relatively geometrically favourable configuration for load redistribution after damage that emerges in the latter case where the damaged column element is located in the centre of the structural frame as opposed to the former case where the damaged column element is located in one end of the frame. Further, the scenarios involving the damage of the corner column may involve the possible absence of axial restraint provided by the undamaged structure due to bidirectional cantilever beam action.
Considering the target safety values in Table 4.13 and based on the discussion in Section 4.3.3.2, a target reliability index value of 4.4 (which is the target value corresponding to large consequences of failure and normal relative costs of safety measures) may be considered to be a preliminary benchmark system safety level for the structure. A comparison of the values in Table 5.5 against this benchmark value shows that a preliminary acceptable robustness level for the structure requires the implementation of the lifecycle robustness measures with efficiency levels of at least 80% or above.

Figure 5.3 Variation of residual system reliability index with efficiency of lifecycle robustness measures.
A further evaluation of the optimal effectiveness of the robustness measures can be carried according to the marginal risk reduction principle discussed in Section 4.3.3.4. The variation in reduction achieved in the indirect risks due to the implementation of the robustness provisions is determined with reference to the baseline design. Figure 5.4 shows the variation of the achieved indirect risk reduction with the lifecycle costs corresponding to the different values of the efficiency of the lifecycle robustness measures. Based on the above stipulated target safety criteria, the acceptable alternatives are those corresponding to efficiency levels of 80% and higher. From these acceptable options, the optimal alternative is associated with lifecycle costs of 3,820,208.17 Singapore Dollars and an efficiency level of 80% for the lifecycle robustness measures. Beyond this alternative, the cost of achieving risk reduction is higher than the corresponding benefits achieved from the risk reduction. This optimal and acceptable alternative may be seen to correspond to a benchmark level of robustness for the structure, with the higher lifecycle cost alternatives providing further enhancements in robustness levels.
5.5 Discussion

The example discussed in this chapter demonstrates the use of a simple workable approach that can be integrated with code-based structural design for the clear determination of situations requiring attention from a robustness perspective and the identification of strategies and approaches to deal with such situations. From the prescribed set of robustness provisions for this example (see Table 5.3), it is clear that targeted monitoring and maintenance of identified areas and properties associated with the structure with regard to identified situations relevant for robustness play a crucial role in ensuring robustness throughout the lifecycle of the structure. Such focus on the use of indirect or preventive/protective measures and the degree of reliance on lifecycle maintenance to ensure robustness can hence form one possible basis for the selection of optimal robustness provisions for structures. The scenario-specific nature of such analyses however needs to be borne in mind while interpreting the obtained results. Further improvements in the application of this framework may therefore involve the identification and use of representative sets of scenarios for robustness verification in different classes of structures.

The Eurocode approach to robustness for this example first involves the classification of the building as a class 2b (upper risk group) structure (BSI, 2006). Principally, there are three alternative approaches available:

i) Provision of horizontal and vertical ties

ii) Notional (member) removal

iii) Key element design

The notional (member) removal approach is seen to be inadequate in this case as the area of collapse exceeds the specified limit of admissible local damage in the structure. This leaves the tying and the key element approaches for which the implementation rules for the first and the third approaches are laid out in a prescriptive fashion. The insufficiency of tying measures in ensuring robustness in different situations has been brought out in literature (Izzuddin et al., 2008; Byfield and Paramasivam, 2007). These approaches may be essential elements in ensuring robustness in the structure; however the engineering thought
process in the development of the situations that warrant the need for such provisions is not detailed in the code approach.

The developed approach can be seen as a guidance platform that provides for a more interactive process in the consideration of situations and scenarios that need to be addressed through the provision of robustness in structures. The approach in its simple form as outlined in the example in this chapter may be seen to be most suitable for the intermediate class of structures which lie between structures of low importance with minor consequences in case of failure (for which generally no specific consideration of robustness may be necessary) and structures of major importance (for which a detailed scenario-based risk assessment is required). Further refinement of the analysis and the comparison of different sets of robustness provisions can be carried out through the future application of this approach for different principal classes of structures, designs and materials and the establishment of relevant robustness benchmarks. Such analyses can also be seen to eventually contribute to the calibration of target safety values for overall structures.
Illustration of the proposed approach
Chapter 6

Conclusions and outlook

6.1 Conclusions

The built environment plays an important role in shaping societal development and progress. The ever growing complexity of the interrelationship between the built environment and society with regard to use, safety, performance and economy calls for a new paradigm in engineering decision making – a paradigm setting focus on system lifecycle performance together with eventual consideration of sustainability. In this setting, the due consideration of structural robustness has assumed paramount significance in the fulfilment of expected system performance in structures.

Robustness of structures has been one of the areas at the forefront of research in structural engineering, particularly in the last decade. Achieving ‘adequate robustness’ is today recognized as an integral part of best practice structural system design; however, in present code based design and assessment procedures this is neither spelt out in specific nor in explicit detail. Also there is no agreement on what constitutes adequate or acceptable robustness for a structure placed in a given environment. This situation prevails, mainly because of the lack of a systematic and integrated engineering understanding of all the requirements and considerations necessary to ensure adequate safety in structures and the implications arising from structural design practice that have a bearing on the integrity of the overall structure. At a conceptual level, pure risk-based design offers viable solutions to address the above issues; this however comes at the cost of significant rigour and detail, thereby making it unwieldy for use in common structural design practice.
6.1.1 Major contributions

This thesis has examined the issue of robustness of structures from a fundamental perspective as well as from a practical viewpoint. At a theoretical level, a risk-informed approach is developed that integrates the essential ingredients from a holistic risk and lifecycle performance understanding of structures together with code-based structural design. Under the aegis of this approach, a differentiated architecture to ensure adequate robustness in structures is proposed as the viable design basis for a future format for structural design codes and standards which comprises:

- a well-defined and separated code standard safety format that accounts for most component related (direct) risks in structures, and
- a set of clearly stated principles and application rules to ensure appropriate robustness that account for most structure/system related (indirect) risks.

A framework that facilitates a comprehensive consideration of factors that influence the robustness of structures from a lifecycle performance perspective is developed. The framework is organised using a system of generic categorisation and mapping for the different factors associated with robustness in structures. A generic treatment of the implications arising from code-based structural design that impinge upon the robustness of structures and their ensuing evolution in the form of failures and consequences in structures is provided. This establishes a strong foundation and identifies the principal needs that necessitate the development of suitable strategies to ensure robustness in structures. Towards this end, a risk-oriented organisation and categorisation of robustness provisions is developed; this also forms the basis for the establishment of a systematic and differentiated mapping of the consideration and treatment of robustness in European standards.

At a practical implementation level, a guidance platform based on the developed risk-informed approach is established which channels engineering design thinking towards i) a logical and systematic consideration of situations and scenarios that necessitate the consideration of robustness in structures and ii) the planning of suitable strategies and provisions to ensure adequate robustness. The use of the guidance platform is illustrated through a design example which typifies its use for improved decision making in the assessment
and management of structural robustness in different situations and circumstances.

A scenario-based risk analysis is generally recommended in structural design codes to be carried out on a case-by-case basis for important or exceptional structures (for example those belonging to the Eurocode consequence class 3). The level of detail and rigour involved in meaningful analyses of such nature makes it practically impossible in practice to perform such assessments for the more common classes of structures. The use of the guidance platform in its principal form is recommended to be particularly suitable for such intermediate class of structures (for example those classified as belonging to classes 2a and 2b in the Eurocodes). The provision of targeted monitoring and maintenance of the structure with regard to identified situations relevant for robustness that arise during its lifecycle are seen to play a crucial role in ensuring robustness throughout its lifetime. Through the use of the system of generic categorisation and mapping, the developed guidance platform aims to represent the systematic risk analyses in a simplified and standardised manner in order to make it practically relevant and computationally manageable for such classes of structures. Its use can also provide a strong basis for the identification, screening and consideration of scenarios and strategies for further detailed treatment in the case of exceptional structures.

The robustness of structures can be seen to depend on a vast array of factors and considerations which include the exposures and their effects occurring on the structures during their lifetime, the evolving structural performance, the ensuing consequences and the effectiveness of strategies for the management of safety and integrity in structures. The developed approach provides a structured and flexible manner to systematically and more importantly visibly account for such factors and considerations in the process of provision of robustness in structures. A greater appreciation and systematic understanding of the risks accounted for in the design and the lifecycle of structures through the code standard safety format and the set of robustness provisions is therefore ascertained through the use of the developed approach.

This thesis aims to supplement and enrich existing code based structural design practices through a risk-informed approach for the better understanding and
handling of risks in the context of robustness and lifecycle system performance, both at a pre-normative level and at an implementation level. This will ultimately improve the efficiency of structural design seen from a lifecycle perspective and ensure rational treatment of structural safety and integrity, particularly imparting greater visibility and purposeful direction to the consideration of robustness in structures.

6.1.2 Limitations
This thesis has examined the issue of robustness from a purely structural lifecycle performance perspective. In one way, this may be considered as looking at the problem in isolation, particularly when it creates situations of conflicting demands with other disciplines in structures – a simple example involves the conflict between structural integrity for which tying requirements are mandated and acoustic isolation for which tying is detrimental. Some degree of harmonisation with overall integrity and facility management of structures involving different disciplines is therefore required; this requires a clear understanding of the arising implications and issues for robustness and possible realignments and reconciliations in strategies and provisions.

6.2 Outlook
6.2.1 Further research and development
Several directions for further research and development of the work presented in this thesis can be identified. The first aspect is concerned with the development of target values for robustness for use in code-based structural design; in simple terms these can be seen similar to the recommended target reliability index values used in structural component design. Towards this end, future applications of the developed approach for the robustness assessment of different principal classes of structures, designs and materials will help in the calibration and the establishment of benchmark levels of robustness for different applications. Information from such applications will also contribute to the development of comparative databases on the performance and safety metrics of different structures and their classes. As systems thinking gradually takes
Conclusions and outlook

centre stage in engineering design, the demonstration and assurance of a certain basic level of structural system safety becomes important together with system efficiency. The establishment of robustness benchmarks can therefore be seen as an important step towards a robustly reliable quantification of safety of structural systems.

A second direction of further research involves the eventual development of possibly more meaningful provisions (in place of present prescriptive rules covering, for instance, the requirements of tying and key element design) to ensure robustness in structures and provide a viable basis for the consistent ranking of different design alternatives. This work can be seen to get a significant impetus with the establishment of benchmarks for robustness in structures.

Thirdly, the issue of sustainability which poses increasingly greater challenges for societal infrastructure development provides interesting collaborative avenues for further research concerning robustness. The influence of considerations which present themselves in the form of sustainable use of materials, design configurations and use patterns on the robustness of structures and the potential tradeoffs needs to be examined. It can be said that the developed risk-informed approach and the guidance platform provide a conceptually consistent basis for such considerations and design evaluations.

6.2.2 Revision of structural design code formats
The developed approach in this thesis can be seen to establish a clear pre-normative foundation and a viable structure for the development of revised structural design code formats which are characterised by a systematic, visible and explicit consideration of structural lifecycle performance with regard to robustness in the structural design, execution and maintenance processes for structures. This provides significant support and paves the way for further developments towards establishing an improved design basis for structures that provides for a seamless incorporation of robustness considerations into structural design procedures that will eventually be useful in daily engineering practice. Such normative developments will also have significant ripple effects.
Conclusions and outlook

on the rational and direct consideration of system safety and robustness issues in structural engineering academic curriculums.


Faber, M.H. (2009) On the assessment and improvement of robustness of structures. Discussion note to the Joint Committee on Structural Safety.


Conference of COST Action TU0601 (pp. 189-204). Prague: Czech Technical University in Prague.


Schubert, M., & Faber, M.H. (2007). Robustness of Infrastructures Subject to Rare Events, In J. Kanda, T. Takada, & H. Furuta (Eds.) Proceedings of


Appendix A

Categorisation of robustness related provisions in European standards
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<table>
<thead>
<tr>
<th>CLAUSE</th>
<th>TEXT</th>
<th>APPROACH TO RISK TREATMENT</th>
<th>NATURE OF RISK CONTROL</th>
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<th>DOMAIN OF RISK REDUCTION</th>
<th>APPLICABILITY IN LIFECYCLE OF STRUCTURE</th>
</tr>
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<tbody>
<tr>
<td>EN 1990 : 2002</td>
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</tr>
<tr>
<td>2.1 (4) P</td>
<td>A structure shall be designed and executed in such a way that it will not be damaged by events such as: – explosion, – impact, and – the consequences of human errors, to an extent disproportionate to the original cause.</td>
<td>1 – avoidance</td>
<td>1, 4 – indirect</td>
<td>1, 2, 3, 4, 5 – independent</td>
<td>1 – exposure</td>
<td>1, 2, 3, 4 – planning and design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – protection</td>
<td>2, 3, 5 – direct</td>
<td>1 - specific</td>
<td>2, 3 – local damage</td>
<td>1.5 – design and execution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2, 3, 4, 5 – resistance</td>
<td></td>
<td></td>
<td>3, 5 – system failure</td>
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<td></td>
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<td>4 – consequences</td>
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<tr>
<td>2.1 (5) P</td>
<td>Potential damage shall be avoided or limited by appropriate choice of one or more of the following: 1– avoiding, eliminating or reducing the hazards to which the structure can be subjected; 2– selecting a structural form which has low sensitivity to the hazards considered; 3– selecting a structural form and design that can survive adequately the accidental removal of an individual member or a limited part of the structure, or the occurrence of acceptable localised damage ; 4– avoiding as far as possible structural systems that can collapse without warning ; 5– tying the structural members together.</td>
<td>1 – avoidance</td>
<td>1, 4 – indirect</td>
<td>1, 2, 3, 4, 5 – independent</td>
<td>1 – exposure</td>
<td>1, 2, 3, 4 – planning and design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 – protection</td>
<td>2, 3, 5 – direct</td>
<td>1 - specific</td>
<td>2, 3 – local damage</td>
<td>1.5 – design and execution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2, 3, 4, 5 – resistance</td>
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<td></td>
<td>3, 5 – system failure</td>
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<td>4 – consequences</td>
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<tr>
<td>2.2 (2) and (3)</td>
<td>Different levels of reliability may be adopted inter alia : – for structural resistance ; – for serviceability. The choice of the levels of reliability for a particular</td>
<td>1, 2, 3, 4 – resistance</td>
<td></td>
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</table>

Note: Permission to reproduce the below extracts from British Standards is granted by BSI. British Standards can be obtained in PDF or hard copy formats from the BSI online shop: www.bsigroup.com/Shop or by contacting BSI Customer Services for hardcopies only: Tel: +44 (0)20 8996 9001, Email: cservices@bsigroup.com.
Structure should take account of the relevant factors, including:
1– the possible cause and/or mode of attaining a limit state;
2– the possible consequences of failure in terms of risk to life, injury, potential economical losses;
3– public aversion to failure;
4– the expense and procedures necessary to reduce the risk of failure.

2.2 (5) The levels of reliability relating to structural resistance and serviceability can be achieved by suitable combinations of:
a) preventative and protective measures (e.g. implementation of safety barriers, active and passive protective measures against fire, protection against risks of corrosion such as painting or cathodic protection);
b) measures relating to design calculations:
   – representative values of actions;
   – the choice of partial factors;
c) measures relating to quality management;
d) measures aimed to reduce errors in design and execution of the structure, and gross human errors;
e) other measures relating to the following other design matters:
   – the basic requirements;
   – the degree of robustness (structural integrity);
   – durability, including the choice of the design working life;
   – the extent and quality of preliminary investigations of

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<tr>
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<td>a – protection b – resistance c,d,f,g – avoidance</td>
<td>a,b – indirect a,c,d,e,f,g – independent a - specific</td>
<td>b,c,d,e,f,g – local damage e,f,g – system failure c,d – all</td>
<td>a,b,c,d,e – planning and design a,c,d,f – execution g – operation and maintenance</td>
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### Categorisation of robustness related provisions in European standards

<table>
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<tr>
<th>CLAUSE</th>
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<tr>
<td>2.4 (1) and (2)</td>
<td>The structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended, having due regard to its environment and the anticipated level of maintenance. In order to achieve an adequately durable structure, the following should be taken into account: – the intended or foreseeable use of the structure; – the required design criteria; – the expected environmental conditions; – the composition, properties and performance of the materials and products; – the properties of the soil; – the choice of the structural system; – the shape of members and the structural detailing; – the quality of workmanship, and the level of control; – the particular protective measures; – the intended maintenance during the design working life.</td>
</tr>
<tr>
<td>EN 1991-1-7 : 2006</td>
<td>A localised failure due to accidental actions may be acceptable, provided it will not endanger the stability of</td>
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### CATEGORIZATION

<table>
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<tr>
<th>APPROACH TO RISK TREATMENT</th>
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<tr>
<td>resistance avoidance protection</td>
<td>direct indirect</td>
<td>independent specific</td>
<td>local damage consequences</td>
<td>planning and design execution operation and maintenance</td>
</tr>
<tr>
<td>avoidance</td>
<td>indirect</td>
<td>independent</td>
<td>system failure</td>
<td>planning and design</td>
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</tbody>
</table>
the whole structure and that the overall load-bearing capacity of the structure is maintained and allows necessary emergency measures to be taken. NOTE 1 For building structures such emergency measures may involve the safe evacuation of persons from the premises and its surroundings. NOTE 2 For bridge structures such emergency measures may involve the closure of the road or rail service within a specific limited period.

3.2 (3) Measures should be taken to mitigate the risk of accidental actions and these measures should include, as appropriate, one or more of the following strategies:

- a) preventing the action from occurring (e.g. in the case of bridges, by providing adequate clearances between the trafficked lanes and the structure) or reducing the probability and/or magnitude of the action to an acceptable level through the structural design process (e.g. in the case of buildings providing sacrificial venting components with a low mass and strength to reduce the effect of explosions);
- b) protecting the structure against the effects of an accidental action by reducing the effects of the action on the structure (e.g. by protective bollards or safety barriers);
- c) ensuring that the structure has sufficient robustness by adopting one or more of the following approaches: 1) by designing certain components of the structure upon which stability depends as key elements (see 1.5.10) to increase the likelihood of the structure’s

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<tr>
<td>3.2 (3)</td>
<td>Measures should be taken to mitigate the risk of accidental actions and these measures should include, as appropriate, one or more of the following strategies: a) preventing the action from occurring (e.g. in the case of bridges, by providing adequate clearances between the trafficked lanes and the structure) or reducing the probability and/or magnitude of the action to an acceptable level through the structural design process (e.g. in the case of buildings providing sacrificial venting components with a low mass and strength to reduce the effect of explosions); b) protecting the structure against the effects of an accidental action by reducing the effects of the action on the structure (e.g. by protective bollards or safety barriers); c) ensuring that the structure has sufficient robustness by adopting one or more of the following approaches: 1) by designing certain components of the structure upon which stability depends as key elements (see 1.5.10) to increase the likelihood of the structure’s</td>
<td>a – avoidance</td>
<td>a,b,c2 – indirect</td>
<td>c1,c2,c3 – independent</td>
<td>a – exposure</td>
<td>a,b,c1,c2,c3 – planning and design</td>
</tr>
<tr>
<td></td>
<td></td>
<td>a – sacrifice</td>
<td>a,b – execution</td>
<td>a,b - specific</td>
<td>a – execution</td>
<td>a,b – execution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b – protection</td>
<td>c1,c3 – direct</td>
<td>c1,c2,c3 – local damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c1,c2,c3 – resistance</td>
<td></td>
<td>c1,c2,c3 – system failure</td>
<td></td>
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<tr>
<td>CLAUSE</td>
<td>TEXT</td>
<td>APPROACH TO RISK TREATMENT</td>
<td>NATURE OF RISK CONTROL</td>
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<td>APPLICABILITY IN LIFECYCLE OF STRUCTURE</td>
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<tr>
<td>3.3 (2)</td>
<td>The mitigation should be reached by adopting one or more of the following approaches: a) designing key elements, on which the stability of the structure depends, to sustain the effects of a model of accidental action ( A_d ); b) designing the structure so that in the event of a localised failure (e.g. failure of a single member) the stability of the whole structure or of a significant part of it would not be endangered;</td>
<td>a,c – resistance</td>
<td>b,c – indirect</td>
<td>a,b,c – independent</td>
<td>a – local damage</td>
<td>a,b,c – planning and design</td>
</tr>
<tr>
<td></td>
<td>NOTE 1 The National Annex may define the model which may be a concentrated or a distributed load with a design value of ( A_d ). The recommended model for buildings is a uniformly distributed notional load applicable in any direction to the key element and any attached components (e.g. claddings, etc). The recommended value for the uniformly distributed load is 34 kN/m(^2) for building structures. An example of the application of ( A_d ) is given in A.8.</td>
<td>b – avoidance</td>
<td>a,c – direct</td>
<td></td>
<td>b,c – system failure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NOTE 2 The National Annex may state the acceptable limit of &quot;localised failure&quot;. The indicative limit for building structures is 100 m(^2) or 15 % of the floor area, whichever is less, on two adjacent floors caused by the removal of any supporting column, pier or wall. This is</td>
<td></td>
<td></td>
<td></td>
<td>c – consequences</td>
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</table>
likely to provide the structure with sufficient robustness regardless of whether an identified accidental action has been taken into account.

c) applying prescriptive design/detailing rules that provide acceptable robustness for the structure (e.g. three-dimensional tying for additional integrity, or a minimum level of ductility of structural members subject to impact).

(1) Adoption of the following recommended strategies should provide a building with an acceptable level of robustness to sustain localised failure without a disproportionate level of collapse.

a) For buildings in Consequences Class 1:
Provided a building has been designed and constructed in accordance with the rules given in EN 1990 to EN 1999 for satisfying stability in normal use, no further specific consideration is necessary with regard to accidental actions from unidentified causes.

b) For buildings in Consequences Class 2a (Lower Group):
In addition to the recommended strategies for Consequences Class 1, the provision of effective horizontal ties, or effective anchorage of suspended floors to walls, as defined in A.5.1 and A.5.2 respectively for framed and load-bearing wall construction should be provided.

NOTE 1 Details of effective anchorage may be given in the National Annex.
c) For buildings in Consequences Class 2b (Upper Group):
In addition to the recommended strategies for Consequences Class 1, the provision of:
– horizontal ties, as defined in A.5.1 and A.5.2 respectively for framed and load-bearing wall construction (see 1.5.11), together with vertical ties, as defined in A.6, in all supporting columns and walls should be provided, or alternatively,
– the building should be checked to ensure that upon the notional removal of each supporting column and each beam supporting a column, or any nominal section of load-bearing wall as defined in A.7 (one at a time in each storey of the building) the building remains stable and that any local damage does not exceed a certain limit.
Where the notional removal of such columns and sections of walls would result in an extent of damage in excess of the agreed limit, or other such limit specified, then such elements should be designed as a "key element" (see A.8).
In the case of buildings of load-bearing wall construction, the notional removal of a section of wall, one at a time, is likely to be the most practical strategy to adopt.

For buildings in Consequences Class 3:
A systematic risk assessment of the building should be undertaken taking into account both foreseeable and unforeseeable hazards.
## Categorisation of robustness related provisions in European standards

<table>
<thead>
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<tr>
<td><strong>EN 1992-1-1 : 2004</strong></td>
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</tr>
<tr>
<td>3.2.4 (1)P</td>
<td>The reinforcement shall have adequate ductility as defined by the ratio of tensile strength to the yield stress, ((f_t/f_y)<em>{\text{k}}), and the elongation at maximum force, (\varepsilon</em>{\text{uk}}).</td>
</tr>
<tr>
<td><strong>APPROACH TO RISK TREATMENT</strong></td>
<td>Resistance</td>
</tr>
<tr>
<td><strong>NATURE OF RISK CONTROL</strong></td>
<td>Indirect</td>
</tr>
<tr>
<td><strong>RELATION WITH EVENT</strong></td>
<td>Independent</td>
</tr>
<tr>
<td><strong>DOMAIN OF RISK REDUCTION</strong></td>
<td>Consequences</td>
</tr>
<tr>
<td><strong>APPLICABILITY IN LIFECYCLE OF STRUCTURE</strong></td>
<td>Planning and design execution</td>
</tr>
<tr>
<td>4.1</td>
<td>(1)P A durable structure shall meet the requirements of serviceability, strength and stability throughout its design working life, without significant loss of utility or excessive unforeseen maintenance (for general requirements see also EN 1990). (2)P The required protection of the structure shall be established by considering its intended use, design working life (see EN 1990), maintenance programme and actions. (3)P The possible significance of direct and indirect actions, environmental conditions (4.2) and consequential effects shall be considered. Note: Examples include deformations due to creep and shrinkage (see 2.3.2). (4) Corrosion protection of steel reinforcement depends on density, quality and thickness of concrete cover (see 4.4) and cracking (see 7.3). The cover density and quality is achieved by controlling the maximum water/cement ratio and minimum cement content (see EN 206-1) and may be related to a minimum strength class of concrete.</td>
</tr>
<tr>
<td><strong>APPROACH TO RISK TREATMENT</strong></td>
<td>Resistance</td>
</tr>
<tr>
<td><strong>NATURE OF RISK CONTROL</strong></td>
<td>Direct</td>
</tr>
<tr>
<td><strong>RELATION WITH EVENT</strong></td>
<td>Indirect</td>
</tr>
<tr>
<td><strong>DOMAIN OF RISK REDUCTION</strong></td>
<td>Specific</td>
</tr>
<tr>
<td><strong>APPLICABILITY IN LIFECYCLE OF STRUCTURE</strong></td>
<td>Local damage consequences</td>
</tr>
<tr>
<td>4.3</td>
<td>(1)P In order to achieve the required design working life of the structure, adequate measures shall be taken to protect each structural element against the relevant environmental actions.</td>
</tr>
<tr>
<td><strong>APPROACH TO RISK TREATMENT</strong></td>
<td>Resistance</td>
</tr>
<tr>
<td><strong>NATURE OF RISK CONTROL</strong></td>
<td>Protection</td>
</tr>
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<td><strong>RELATION WITH EVENT</strong></td>
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<td>Planning and design execution operation and maintenance</td>
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<tr>
<td>CLAUSE</td>
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<tr>
<td>E.1</td>
<td>(1) The choice of adequately durable concrete for corrosion protection of reinforcement and protection of concrete attack, requires consideration of the composition of concrete. This may result in a higher compressive strength of the concrete than is required for structural design. The relationship between concrete strength classes and exposure classes (see Table 4.1) may be described by indicative strength classes.</td>
</tr>
<tr>
<td>9.1 (3)</td>
<td>Minimum areas of reinforcement are given in order to prevent a brittle failure, wide cracks and also to resist forces arising from restrained actions.</td>
</tr>
<tr>
<td>9.10.1</td>
<td>(1)P Structures which are not designed to withstand accidental actions shall have a suitable tying system, to prevent progressive collapse by providing alternative load paths after local damage. The following simple rules are deemed to satisfy this requirement. (2) The following ties should be provided: a) peripheral ties b) internal ties c) horizontal column or wall ties d) where required, vertical ties, particularly in panel buildings.</td>
</tr>
</tbody>
</table>

EN 1993-1-1 : 2005

3.2.2 Ductility requirements (1) For steels a minimum ductility is required that | resistance | indirect | independent | consequences | planning and design |


should be expressed in terms of limits for:
– the ratio \( f_u / f_y \) of the specified minimum ultimate tensile strength \( f_u \) to the specified minimum yield strength \( f_y \);
– the elongation at failure on a gauge length of 5,65 \( \sqrt{A_0} \) (where \( A_0 \) is the original cross-sectional area);
– the ultimate strain \( \varepsilon_u \), where \( \varepsilon_u \) corresponds to the ultimate strength \( f_u \).

NOTE The limiting values of the ratio \( f_u / f_y \), the elongation at failure and the ultimate strain \( \varepsilon_u \) may be defined in the National Annex. The following values are recommended:
– \( f_u / f_y \geq 1.10 \);
– elongation at failure not less than 15%;
– \( \varepsilon_u \geq 15\varepsilon_y \), where \( \varepsilon_y \) is the yield strain \( (\varepsilon_y = f_y / E) \).

(2) Steel conforming with one of the steel grades listed in Table 3.1 should be accepted as satisfying these requirements.

4
(2) The means of executing the protective treatment undertaken off-site and on-site shall be in accordance with EN 1090.

(3) Parts susceptible to corrosion, mechanical wear or fatigue should be designed such that inspection, maintenance and reconstruction can be carried out satisfactorily and access is available for in-service inspection and maintenance.

(5) For elements that cannot be inspected an appropriate corrosion allowance shall be included.

<table>
<thead>
<tr>
<th>CLAUSE</th>
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<th>APPROACH TO RISK TREATMENT</th>
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<th>RELATION WITH EVENT</th>
<th>DOMAIN OF RISK REDUCTION</th>
<th>APPLICABILITY IN LIFECYCLE OF STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>(2)</td>
<td>avoidance protection</td>
<td>indirect</td>
<td>specific</td>
<td>local damage consequences</td>
<td>planning and design</td>
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</thead>
<tbody>
<tr>
<td>5.6.2</td>
<td>(1) The measures to protect a footbridge should be defined. NOTE Footbridges (piers and decks) are generally much more sensitive to collision forces than road bridges. Designing them for the same collision load may be unrealistic. The most effective way to take collision into account generally consists of protecting the footbridges: – by road restraint systems at appropriate distances before piers, – by a higher clearance than for neighbouring road or railway bridges over the same road in the absence of intermediate access to the road.</td>
<td>avoidance protection</td>
<td>indirect</td>
<td>specific</td>
<td>exposure local damage</td>
<td>planning and design execution</td>
</tr>
<tr>
<td>EN 1993-2 : 2006</td>
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<tr>
<td>2.1.3.4</td>
<td>(1) The design of the bridge should ensure that when the damage of a component due to accidental actions occurs, the remaining structure can sustain at least the accidental load combination with reasonable means. NOTE: The National Annex may define components that are subject to accidental design situations and also details for assessments. Examples of such components are hangers, cables, bearings. (2) The effects of corrosion or fatigue of components and material should be taken into account by appropriate detailing, see also EN 1993-1-9 and EN 1993-1-10.</td>
<td>resistance direct</td>
<td>independent local damage</td>
<td>planning and design execution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1.3.4</td>
<td>(4) For elements that cannot be inspected fatigue checks should be carried out (see EN 1993-1-9) and appropriate corrosion allowances should be provided.</td>
<td>avoidance indirect</td>
<td>independent local damage</td>
<td>planning and design</td>
<td></td>
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</tr>
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<tr>
<td>EN 1992-1-2 : 2004</td>
<td>2.1.1</td>
<td>(2)P Where compartmentation is required, the elements forming the boundaries of the fire compartment, including joints, shall be designed and constructed in such a way that they maintain their separating function during the relevant fire exposure. This shall ensure, where relevant, that: - integrity failure does not occur, see EN 1991-1-2 - insulation failure does not occur, see EN 1991-1 -2 - thermal radiation from the unexposed side is limited.</td>
<td>resistance</td>
<td>indirect</td>
<td>specific</td>
<td>system failure consequences</td>
</tr>
<tr>
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<td></td>
<td>(1)P For the standard fire exposure, members shall comply with criteria R, E and I as follows: - separating only: integrity (criterion E) and, when requested, insulation (criterion I) - load bearing only: mechanical resistance (criterion R) - separating and load bearing: criteria R, E and, when requested I</td>
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<td>(6) Components that cannot be designed with sufficient reliability to achieve the total design working life of the bridge should be replaceable. These may include: – stays, cables, hangers; – bearings; – expansion joints; – drainage devices; – guardrails, parapets; – asphalt layer and other surface protection; – wind shields; – noise barriers.</td>
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<td></td>
<td>execution</td>
</tr>
</tbody>
</table>
Clauses: 5.2

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<tr>
<td>5.2</td>
<td>(1) Requirements for separating function (Criterion E and I (see 2.1.2)) may be considered satisfied where the minimum thickness of walls or slabs is in accordance with Table 5.3. For joints reference should be made to 4.6.</td>
<td>resistance sacrifice</td>
<td>indirect</td>
<td>specific</td>
<td>system failure consequences</td>
<td>planning and design execution</td>
</tr>
</tbody>
</table>

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