SEISMIC DESIGN, ASSESSMENT AND RETROFITTING OF CONCRETE BUILDINGS

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Seismic Design, Assessment and Retrofitting of Concrete Buildings

Based on EN-Eurocode8

by

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Springer

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To Tonia and Nikos

Preface

The goal of the book is to present and explain the state of the art of design or retrofitting concrete buildings for earthquake resistance. To serve this goal, it also covers behaviour of concrete members under cyclic loading and seismic response of concrete buildings, as well as their modelling. Its main focus is the European Design Standard EN1998 – Eurocode 8: Design of structures for earthquake resistance, and in particular its Parts 1 and 3, dealing with seismic design of new buildings and with assessment and retrofitting of existing ones, respectively.

The book is addressed to practitioners of seismic design, assessment and retrofitting, to graduate and advanced undergraduate students in structural earthquake engineering and to researchers with interests in the field of earthquake resistant concrete structures. Certain familiarity of the reader with design of structural concrete and with structural analysis – including seismic analysis and structural dynamics – is presumed.

The book has been written in the course of my teaching activity for the MSc Degree in Earthquake Engineering and Engineering Seismology (MEEES), granted jointly by the Universities of Pavia and Patras and the J. Fourier University of Grenoble in the framework of the Erasmus Mundus programme of the European Commission. It has drawn from my involvement in the development of Eurocode 8 as a European Design Standard, and of its Parts 1 and 3 in particular. It has also drawn from my research at the University of Patras during the past 25 years and in particular from the joint work with my former doctoral students Dionysis E. Biskinis, Antonis J. Kosmopoulos and Telemachos B. Panagiotakos and my current colleague Stathis N. Bousias – as evident from the referencing throughout the book. I would also like to express my gratitude and appreciation to Eduardo C. Carvalho and Amr S. Elnashai for their very meticulous review and their comments for the book.

Patras, Greece Michael N. Fardis

From the Reviews of the Book

The book is devoted to the seismic design of new buildings as well as to the assessment and retrofit of existing buildings, covering essentially the contents of Parts 1 and 3 of Eurocode 8. It must be stressed that its contents which refers to Assessment and Retrofit is a very important support tool to the application of Part 3 of Eurocode 8 which deals with Assessment and Retrofitting of Buildings and which in itself is a quite innovative document.

The book is organised in six chapters dealing sequentially with: the General Principles of Seismic Design; the Conceptual Design of Concrete Buildings for Earthquake Resistance; the Behaviour of Concrete Members under Cyclic Loading; the Analysis and Modelling for Seismic Design; the Detailing and Dimensioning and finally the Seismic Assessment and Retrofitting.

Summing up, the book is extremely valuable and represents a much updated state of the art in seismic design of concrete structures not only in Europe but also in other parts of the world. It is very carefully written with the clear intent to cover all aspects of seismic design and not leaving behind any aspect relevant for such. It shall be very useful and an authoritative source for the understanding and application of Eurocode 8 at several different levels, from the ordinary practitioner to the knowledgeable researcher passing by the software developer.

The book reflects the very solid knowledge of the author in earthquake engineering and his leading role in the recent developments of Eurocode 8, as well as the extreme care that was devoted to its planning and writing. No doubt, it shall become a reference in the field.

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The book starts with a Preamble that highlights a most important aspect of design, which is its interaction with construction, and emphasises the safety aspect of a well-designed structure that is difficult to build. The introductory notes set the scene for the subsequent detailed treatment of issues of seismic design of RC structures, a feature that is lacking in most design-oriented books in the earthquake engineering field. This leads naturally to Chapter 1, where the general principles of seismic design of RC structures are presented in a rational framework, which demonstrates the author's experience in conceptual and practical seismic design alike. Issues of single and multiple performance levels and their relationship with seismic hazard levels are succinctly explained. Covering both US and European practice, with emphasis on the latter, the author explains capacity design and the criteria used to establish a hierarchical dissipative and non-dissipative sequence of events. Capacity design is also applied in this chapter to typical systems, as well as to the flexure-shear problem.

Chapter 2 addresses conceptual design, guiding the reader through the steps postulated by the author for the selection of layout and preliminary sizing. The critical role of conceptual design in facilitating final and detailed design and reducing the number of iterations required is emphasised. A detailed treatment of regularity is given and examples are provided to demonstrate the adverse effects of irregularity on performance. Redundancy, continuity and mass minimisation are other features discussed in this chapter, with examples and practical guidance. The chapter concludes with examples of poorly conceived buildings that have been damaged in recent European earthquakes.

A most detailed and exhaustive treatment of the behaviour of RC members and connections is given in Chapter 3, with a wealth of behaviour-oriented expressions for deformation and strength. Examples from the literature are quoted and put into context to provide the reader with a comprehensive set of models for deformation and strength of members subjected to multi-axial stresses. This chapter is rather unique amongst recent seismic design books and on its own is worth reading carefully.

Another exhaustive treatment of modelling for design and assessment is given in Chapter 4, which also includes aspects of input motion. Elastic and inelastic analyses are addressed in detail, and examples and guidance on their applicability or otherwise are provided. Exceptionally insightful comments and guidance are given with regard to the intricate issue of modeling infill walls in frames. Three detailed examples are given in the closing part of the chapter where the guidance given throughout the chapter is applied to a test bed 3D frame structure, thus giving credence to the guidance.

Detailing and dimensioning requirement of Eurocode 8 are addressed in Chapter 5. Two worked examples that will prove invaluable to readers and potential users of the Eurocode are also given. The worked examples not only address the cases dealt with, but give clues as to how to apply Eurocode 8, as seen by the researcher who guided its final stages of development and implementation, to a wider range of design situations.

The last main chapter in the book, Chapter 6, deals with retrofitting of RC structures using Eurocode 8, with very considerable amounts of backup material from the research literature. The rules described in the chapter are then applied to two case studies, which are continuation of the "analysis" case studies, thus providing a thread through the various chapters. This thread will be valuable to readers because it establishes a clear link between design and analysis for assessment of the design, as well as retrofitting.

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Preamble

The main activity of today's civil engineers is the production of structures. This activity has two phases:

– design, and
– construction – also termed "execution", as "construction" is also used for civil engineering works in general.

In the construction phase the civil engineer does not necessarily have the central role. In design, by contrast, his/her role is not just prime but almost exclusive.

With design being the 1st phase of the production process, many areas of the broader field of Earthquake Engineering ultimately serve design. For instance:

– a prime goal of Engineering Seismology and Geotechnical Earthquake Engineering is to determine the ground motion for the seismic design;
– a major role of Structural Dynamics – within the context of Earthquake Engineering – is the calculation of the response of the structure to a given seismic motion, either to verify that performance is satisfactory, or to provide the basis for the dimensioning of structural elements so that performance is indeed satisfactory.

There is strong interaction between design and construction of a structure. Design can be considered to govern production of a structure, as construction implements design drawings and specifications. However, design is influenced by, or depends on, construction as well. A structure is designed to be ultimately built; so the way it will be constructed should be a determining factor for its design. So, when designing the structure the engineer should have a clear and precise idea of how his/her design will be implemented with the human resources, equipment and materials available for that particular project. A design that seems excellent on paper but cannot be easily implemented with the available means and resources may in reality be poor or even unsafe, because bad implementation means poor quality. This point is very important for earthquake resistant concrete structures, as:

– Seismic performance depends heavily on the detailing of the reinforcement;
– In seismic regions a building's safety problem may remain hidden for long and show up only through its catastrophic consequences in the event of a strong earthquake. By contrast, in structures controlled by non-seismic actions, safety problems due to poor construction quality may become evident early on (e.g. upon striking off the formwork and falsework, or after all permanent loads are applied), before delivering the facility to the users.

The engineer should keep in mind that the earthquake will "see" the structure as it is built. The intentions of the designer, the assumptions made, the analysis methods used and the care exercised in its design, matter only to the extent they are indeed reflected in the as-built structure.

The seismic design process of a new concrete structure comprises four distinct phases:

(1) Conceptual design: the selection of the type and layout of the lateral-load-resisting system and of preliminary member sizes.
(2) Analysis: the calculation of the effects of the design actions, including the seismic one, in terms of internal forces and deformations in structural members.
(3) Detailed design: the verification of the adequacy of member dimensions and the dimensioning of the reinforcement on the basis of calculated action effects.
(4) Preparation of the end product of the design to be applied in the field: material specifications, construction drawings with detailing of the reinforcement, and any other information that may be necessary or helpful for the implementation of the design.

The design of the seismic retrofitting of an existing structure has the same four phases, but referring specifically to the retrofitting. In this case, however, we have two preliminary phases:

(–2) Collection of information on the history, geometry, reinforcement, materials, etc., of the as-built structure, as input for the subsequent phases.
(–1) Analysis and verification of the as-built structure, to confirm that retrofitting is indeed necessary and identify the deficiencies to be remedied.

The outcome of the design is just that of phase (4) and is often considered as the "design". The outcomes of phases (2) and (3) (and of (–2) and (–1) for existing structures) are just documentation of the "design". Stage (1) is the designer's personal business and is not documented anywhere.

Be it for a new building or for retrofitting an existing one, conceptual design is of utmost importance for the economy and the seismic performance of the structure. The choices and decisions made there are entirely based on the experience, judgment and ingenuity of the designer, even on his/her personal design philosophy and preferences. To some people design is just the conceptual design; all other phases being considered as "code checking".

During all design phases the engineer should use not just the scientific/technical tools at his/her disposal, but also judgment and experience, to produce a design that – to the best of his or her knowledge – cost-effectively fulfils the performance requirements. Experience is very important for the successful design of earthquake-resistant buildings. It provides ideas from previous, possibly similar, projects and helps avoiding poor choices, pitfalls or even design errors. Experience is also valuable to understand the "idiosyncrasy" of an existing building which is assessed for possible retrofitting.

The technology for earthquake resistance evolved essentially after 1970. Since then, scientific knowledge and technology in earthquake engineering and seismic design codes alike have seen a very rapid, and still ongoing, development. As a result, structures designed and constructed according to present generation codes enjoy a much higher safety level against earthquakes than older ones. The higher level of seismic safety comes at a higher cost (albeit less than proportional to the added safety). Moreover, the ultimate criterion for the success or not of current seismic codes and technology will be the performance of structures built with them in the event of an earthquake. Note that, owing to the short history of exposure of concrete construction to earthquakes (shorter than the time intervals between strong earthquakes, even in highly seismic regions) and the continuous evolution of seismic design codes during that history, we still lack sufficient feedback from the actual performance of concrete buildings. Finally, the short-term future will see further advances, as our knowledge and technology for earthquake resistance is in a state of continuous development. So, although we presently believe that our current know-how is satisfactory and produces safe structures, most likely in the medium-term seismic design will be quite different. Developments are expected mainly towards further rationalisation of seismic design, to achieve the same or better performance at lower cost. Empirical and prescriptive approaches will certainly give way to procedures based on more solid and rational grounds. The main vehicle for the transfer of such progress to engineering practice will be codes and standards for earthquake resistant design, notably those of the countries or regions most advanced in earthquake engineering (in alphabetical order, of the EU, Japan and the US). Practitioners of seismic design should follow the developments in codes and be prepared for changes to come. For those active in seismic assessment and retrofitting of existing buildings as well, certain knowledge of past codes and practice will help them identify and remedy their problems and deficiencies.

Chapter 2 of the book is devoted to conceptual design of new building structures for earthquake resistance. Chapter 1 provides an overview of the performance requirements for new building structures, of the philosophy of current seismic design codes for new earthquake-resistant buildings and of the main instruments for its implementation. Chapter 3 covers the behaviour under cyclic loading of the constituent materials and of concrete members of the type common in buildings, as well as the quantification of this behaviour. That chapter provides the background for Chapters 5 and 6. Chapter 4 is devoted to analysis and modelling issues, with emphasis on the analysis approaches commonly used within the context of codified seismic design or assessment (phase (2) of the design process). Chapter 5 deals with dimensioning and detailing of new building structures for earthquake resistance and gives the background of some of the rules in Eurocode 8 on the basis of the material of Chapters 1 and 3. Chapter 6, on assessment and upgrading of the seismic performance of existing buildings, builds on Chapters 3 and 4, as well as on the general performance requirements set out in Chapter 1.

To a certain extent the book develops with reference to the European Standards for seismic design, assessment and retrofitting of buildings, Parts 1 and 3 of Eurocode 8. Some parts of Chapter 1 and 4 include references to Eurocode 8, but also to US seismic design standards. Chapters 5 and 6 are linked with Eurocode 8 – Chapter 5 very closely, but Chapter 6 less so.

In December 2004, Part 1 of Eurocode 8 (CEN 2004a) was published by the European Committee for Standardisation to become the first in history European Standard for seismic design of new buildings, complementary to the other EN-Eurocodes. It was followed in June 2005 by Part 3 of Eurocode 8 (CEN 2005a), for seismic assessment and retrofitting of existing buildings. The 31 member countries in CEN have since then published these European Standards as their own National Standards, together with their National Annexes. These Annexes state the national choices for the so-called "Nationally Determined Parameters", devised to provide the flexibility required for the application of Eurocode 8 in a whole continent with diverse engineering traditions and seismicity. Until March 2010 national design standards will be used in parallel with Eurocode 8, but by March 2010 national design standards that conflict in any aspect with any EN-Eurocode should be withdrawn.

In the USA seismic design of buildings follows a building design code that covers also non-structural aspects (architectural, mechanical, electrical, building equipment, etc.). Seismic design provisions for new buildings were traditionally developed either by the Building Seismic Safety Council (BSSC) and published as "NEHRP Recommended Provisions for the Development of Seismic Regulations for Buildings and Other Structures" (BSSC 2003), or by the Structural Engineers Association of California (SEAOC) and published as "SEAOC Recommended Lateral Force Requirements" (SEAOC 1999). With some time-lag the NEHRP provisions have traditionally been reflected in (but not fully adopted by) the "National Building Code", the "Standard Building Code" and more recently the "International Building Code" (ICC 2006). The SEAOC requirements have been in general reflected in the "Uniform Building Code", the last version of which was issued in 1997 (ICBO 1997). Local Authorities (States, counties, cities) formally adopt one of the three model codes after adaptation to local traditions/conditions. Recent years have seen a convergence of the seismic design provisions in the NEHRP and SEAOC documents, extending also to the main material codes referred to, or used as source documents by them, such as the ACI 318 code (ACI 2008), prepared by the American Concrete Institute. Moreover, in 1997 the "International Code Council" was formed and issued in 2000 the "International Building Code". Since then, the updated code (ICC 2006) is gradually adopted throughout the US.

Contents

Chapter 1
General Principles for the Design of Concrete Buildings for Earthquake Resistance

Chapter 1 presents the requirements posed by modern seismic codes and standards for the protection of life and property in new building designs and highlights the means provided for their fulfilment. The requirements and design rules provided in the European Standard for the seismic design of new buildings – EN 1998-1:2004, termed also Part 1 of Eurocode 8 – are given certain emphasis and compared to their US counterparts. These Eurocode 8 rules are elaborated further in Chapter 5 in the context of the process for the detailed design of new concrete buildings for earthquake resistance.

Chapter 1 gives also an overview of a new thinking towards more comprehensive coverage of the seismic performance needs of owners and occupants over the lifetime of the building. This thinking is currently penetrating newly emerging codes and standards for the seismic evaluation and upgrading of existing substandard buildings, including EN 1998-3:2005 (also known as Part 3 of Eurocode 8). The requirements and rules provided in this latter European Standard for the seismic assessment and retrofitting of existing buildings are further elaborated in Chapter 6.

1.1 Seismic Performance Requirements for Concrete Buildings

1.1.1 The Current Situation: Emphasis on Life Safety

Traditionally, introduction and enforcement of structural design codes and standards has been the responsibility of competent Authorities, with public safety as the overriding consideration. Accordingly, traditional seismic design codes or standards for buildings aim at protecting human life by preventing local or global collapse under a single level of earthquake. The no-(local-)collapse requirement normally refers to a rare seismic action, termed "design seismic action". In most present codes the "design seismic action" for ordinary structures is conventionally chosen as the one having a 10% probability to be exceeded in a conventional working life of 50 years, or 0.2% in a single year. This corresponds to a mean return period of 475 years for the "design seismic action".

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Within a single-tier design framework, enhanced safety of facilities that are essential or have large occupancy is normally achieved by modifying the hazard level (the mean return period) of the "design seismic action". The seismic action is multiplied times an "importance factor", γ_{I}. By definition, $\gamma_{\mathrm{I}} = 1.0$ for structures of ordinary importance (buildings of "Importance Class" II in Eurocode 8). For buildings whose collapse may have unusually large social or economic consequences (large occupancy buildings, such as schools or public assembly halls, etc.) or for facilities housing institutions of cultural importance (e.g., museums), Eurocode 8 recommends a value $\gamma_{\mathrm{I}} = 1.2$ (buildings of "Importance Class" III in Eurocode 8). It recommends $\gamma_{\mathrm{I}} = 1.4$ for buildings which are essential for civil protection during the immediate post-earthquake period: hospitals, fire or police stations, power plants, etc. (categorised as "Importance Class" IV). For buildings of minor importance for public safety (i.e., belonging in "Importance Class" I, comprising agricultural and similar buildings) Eurocode 8 recommends a value $\gamma_{\mathrm{I}} = 0.8$.

1.1.2 Performance-Based Requirements

Already in the 1960s the international earthquake engineering community was fully aware of the property loss that may be caused by frequent seismic events and their other economic consequences. Recognising that it is not feasible to avoid any damage under very strong earthquakes, the Structural Engineers Association of California (SEAOC) adopted in its 1968 recommendations the following requirements for seismic design:

"Structures should, in general, be able to:

- Resist a minor level of earthquake ground motion without damage.
- Resist a moderate level of earthquake ground motion without structural damage, but possibly experience some nonstructural damage.
- Resist a major level of earthquake ground motion having an intensity equal to the strongest either experienced or forecast for the building site, without collapse, but possibly with some structural as well as nonstructural damage."

Major earthquakes that hit developed countries in the second half of the 1980s and the first half of the 1990s caused relatively few casualties but very large damage to property and economic losses. In response to this, "Performance-based earthquake engineering" emerged in the SEAOC Vision 2000 document and developed into the single most important idea of recent years for seismic design or retrofitting of buildings (SEAOC 1995).

"Performance-based engineering" focuses on the ends, notably on the ability of the engineered facility to fulfil its intended purpose, taking into account the consequences of its failure to meet it. Conventional structural design codes, by contrast, are process-oriented, emphasising the means, namely the prescriptive, easy to apply, but often opaque rules that disguise the pursuit of satisfactory performance. These rules have been developed over time as a convenient means to provide safe-sided, yet economical solutions for common combinations of building layout, dimensions and materials. They leave limited room for the designer to exercise judgement and creativity and do not provide a rational basis for innovative designs that benefit from recent advances in technology and structural materials.

"Performance-based earthquake engineering" in particular tries to maximise the utility from the use of a facility by minimising its expected total cost, including the short-term cost of the work and the expected value of the loss in future earthquakes (in terms of casualties, cost of repair or replacement, loss of use, etc.). One would like to take into account all possible future seismic events with their annual probability and carry out a convolution with the corresponding consequences during the design working life of the facility. However, this is not practical. Therefore, at present "performance-based earthquake engineering" advocates just replacing the traditional single-tier design against collapse and its prescriptive rules, with a transparent multi-tier seismic design, meeting more than one discrete "performance levels", each one under a different seismic event, identified through its annual probability of exceedance and termed "seismic hazard level". Pairing off all "performance levels" considered for a particular case with the associated "seismic hazard levels" is termed, in performance-based earthquake engineering, "performance objective".

Each "performance level" is normally identified with a physical condition of the facility, well-described together with its possible consequences: likely casualties, injuries and property loss, continued functionality, cost and feasibility of repair, expected length of disruption of use, cost of relocation of occupants, etc. Commonly four "performance levels" are identified:

(i) "Operational"
(ii) "Immediate occupancy"
(iii) "Life-safety" and
(iv) "Near collapse".

The definition of these "performance levels" is roughly as follows:

"Operational": The facility has suffered practically no structural or non-structural damage and can continue serving the original intention of its design with little disruption of use for repairs. Continuous operation is supported either by undamaged lifelines or by back-up systems. Any repair that is necessary can take place in future without disruption of occupancy or use.

"Immediate occupancy": The facility can return to full use, as soon as utility systems are back in operation and cleanup is complete. The structure itself is very lightly damaged: some yielding of reinforcement may have taken place and concrete cracking may be visible, but there are no residual drifts or other permanent structural deformations. The risk to life is negligible. The structure retains fully its pre-earthquake strength and stiffness. Its ability to withstand future earthquakes, including aftershocks, is not diminished. Non-structural components and systems may have minor damage (e.g. distributed cracking in infill walls) that can be easily and economically repaired at a later stage.

"Life-safety": The structure, or any parts of it, do not collapse, retaining integrity and residual load capacity after the earthquake. The structure is significantly damaged and may have moderate permanent drifts, but retains its full vertical load-bearing capacity and sufficient residual lateral strength and stiffness to protect life even during strong aftershocks. Non-structural components are damaged, but do not block evacuation routes or cause life-threatening injuries by falling. Sometimes reparability is economically questionable and demolition may be preferable.

"Near collapse": The structure is heavily damaged, at the verge of collapse of several gravity load-carrying elements in a storey, or even of total collapse. It may have large permanent drifts and retains little residual strength and stiffness against lateral loads, but its vertical elements can still carry the (quasi-)permanent gravity loads. Most non-structural elements (e.g. infill walls) have collapsed. There is substantial, but not full, life safety, as falling hazards may cause life-threatening injury. The building is unsafe for use, as it may collapse in a strong aftershock. Repair may not be technically feasible and certainly is not economically sensible.

Sometimes, reference is made to two more performance levels: "Damage onset", as a performance level before "Operational" associated with absolutely no structural or non-structural damage; and "Reparable", as a performance level between "Immediate occupancy" and "Life-safety", associated with structural or non-structural damage that is not only technically, but also economically, reparable.

Different performance criteria are also defined for the verification of structural or non-structural elements under the various performance levels. Criteria for structural or non-structural damage are normally expressed in terms of deformation limits. For example, performance level (i) ("Operational") may be identified with "yielding" of structural members, while performance level (iv) ("Near collapse") is often associated with near exhaustion of member "ultimate" deformation, signalling loss of lateral load capacity. Damage limitation criteria for non-structural cladding or partitions that follow the deformations of the structural frame are normally expressed in terms of interstorey drift limits. For equipment mounted or supported on the structure, limits relevant to damage may be expressed in terms of response accelerations at the support points of the equipment.

The discrete hazard levels normally paired off with the four main performance levels listed under (i)–(iv) above for the design of ordinary (i.e., standard occupancy) new buildings, are:

1. a "frequent" earthquake, expected to take place during the conventional working life of the building, having therefore a mean return period much shorter than 50 years (e.g., around 25 years);
2. an "occasional" earthquake, not expected during the conventional working life of the building, with a mean return period between 75 and 200 years;
3. a "rare" earthquake, with a mean return period of about 500 years; and
4. a "very rare" or "maximum considered" earthquake, with quoted values of the mean return period in the order of 1000–2500 years.

According to this idea, the "performance objective" for structures of ordinary importance is to meet performance level (i) under hazard level (1), (ii) under (2), etc.

If higher performance is desired, or for critical facilities, an "enhanced objective" may be selected – e.g. performance level (ii), or even (iii), under hazard level (1), etc.

Note that, depending on the slope of the seismic hazard curve, at any given site certain aspects of the design may be governed by the fulfilment of one performance level under the corresponding hazard level. The other performance levels will be met then automatically at the associated hazard levels. If this applies in general to all types of buildings at a given geographic location or region, then a four-tier performance-based seismic design may degenerate there into a fewer-tier (e.g., a two-tier) one.

Performance-based seismic design serves better the interests and objectives of owners, by allowing more rational decision-making, with explicit verification of performance levels related to property loss and operation of the facility under frequent or occasional earthquakes. It may also provide more flexibility in conceptual design, as collapse prevention under very rare events is explicitly verified, instead of indirectly designed against by explicit verification only at the "life safety" level and using capacity design as a safeguard against collapse under much stronger earthquakes (see Section 1.3). On the other hand, a full-fledged performance-based design process may be arduous and complex. Besides, there is a liability issue to be resolved: the designer is protected to a certain extent against liability claims or other charges for property loss, casualties, etc., in an unforeseeable future event, if he or she has strictly adhered to all rules of a current-generation prescriptive code, which is opaque about the intended performance objective. This may not be the case anymore in a performance-based design context, with explicit and transparent performance objectives which the owner or the courts may interpret as guaranteed. For all these reasons, there is still a long way to go before seismic design codes for new buildings adopt a full-fledged performance-based approach. Such an approach has been adopted, though, in guidelines and standards for the seismic assessment and retrofitting of existing buildings, as it is there that the inherent flexibility of the approach can best bear fruits to accommodate the specific interests, objectives and means of owners. Moreover, buildings not designed to modern-day seismic codes normally do not possess structural features serving as safeguards against collapse under very strong earthquakes (e.g., a layout and a hierarchy of strengths that prevent concentration of deformation demands in a small part of the structural system). Therefore, older buildings require explicit verification against such an outcome.

1.1.3 Performance-Based Seismic Design, Assessment or Retrofitting According to Eurocode 8

In Europe performance levels in seismic design, assessment or retrofitting are associated to, or identified with, Limit States of the structure. The Limit State concept appeared in Europe in the 1960s, to define states of unfitness of the structure for its intended purpose (CEB 1970, Rowe 1970). Limit States concerning the safety of people or of the structure are termed Ultimate Limit States. Those concerning the normal function and use of the structure, the comfort of its occupants, or damage to property (mainly to finishes and non-structural elements) are called Serviceability Limit States. Intermediate Limit States may also be considered (CEB 1988b). According to the Eurocode "Basis of Structural Design" (CEN 2002) the Limit States approach is the backbone of structural design for any type of action, including the seismic one.

Part 1 of Eurocode 8 (CEN 2004a) provides for a two-tier seismic design of new buildings, with the following explicit performance levels ("Limit States"):

1. No-(local-)collapse, which is considered as the Ultimate Limit State against which the structure should be designed according to the Eurocode "Basis of Structural Design" (CEN 2002). It entails protection of life under a rare seismic action, through prevention of collapse of any structural member and retention of structural integrity and residual load capacity after the event.
2. Damage limitation, which plays the role of the Serviceability Limit State against which the structure should be designed according to CEN (2002). The aim is mitigation of property loss in frequent earthquakes, through limitation of structural and non-structural damage. After such an earthquake structural elements are supposed to have no permanent deformation, retain their full strength and stiffness and need no repair. Non-structural elements may suffer some damage, which can be easily and economically repaired at a later time.

The no-(local-)collapse performance level is achieved by dimensioning and detailing structural elements for a combination of strength and ductility that provides a safety factor (in the order of 1.5–2) against substantial loss of lateral load resistance.

The damage limitation performance level is achieved by limiting the overall deformations (lateral displacements) of the building to levels acceptable for the integrity of all its parts (including non-structural ones). More specifically, interstorey drift ratios (defined as the difference between the mean lateral displacements of adjacent storeys divided by the interstorey height) are limited to the following values:

(i) 0.5%, if the storey has brittle non-structural elements attached to the structure (notably, ordinary masonry infills);
(ii) 0.75%, if the storey's non-structural elements are ductile; or
(iii) 1%; when there are no non-structural elements that follow the deformations of the structural system.

The two explicit performance levels – (local-)collapse prevention and damage limitation – are pursued under two different seismic actions. The seismic action under which (local) collapse should be prevented is the "design seismic action". The one for which damage limitation is pursued is called the "damage limitation seismic action". Within the Eurocode philosophy of national competence on issues of safety and economy, the hazard levels for these two seismic actions are left to national determination. For structures of ordinary importance, Part 1 of Eurocode 8 recommends:

1. a “design seismic action” having 10% probability of being exceeded in 50 years (a mean return period of 475 years); and
2. a “damage limitation seismic action” with 10% exceedance probability in 10 years (mean return period: 95 years).

Although not explicit, an additional performance objective in buildings designed to provide earthquake resistance by dissipating energy is to prevent global collapse during a very strong and rare earthquake (performance level (iv) in Section 1.1.2 under hazard level (4)). This implicit performance objective is pursued via systematic and across-the-board application of capacity design, which imposes a hierarchy of strengths that permits full control of the inelastic response mechanism (see Section 1.3).

Following the example of the US standard for seismic rehabilitation (ASCE 2007) and its draft predecessors, Part 3 of Eurocode 8 for assessment and retrofitting of buildings (CEN 2005a) has fully adopted the “performance-based” approach. It provides for three different performance levels (termed Limit States):

1. “Damage Limitation” (DL), corresponding to “Immediate Occupancy”: The structure has no permanent drifts; its elements have no permanent deformations, retain fully their strength and stiffness and do not need repair. Members are verified to remain elastic.
2. “Significant Damage” (SD), corresponding to “Life safety” and to the (local-)collapse prevention performance level to which new buildings are designed according to Part 1 of Eurocode 8. The structure is significantly damaged, may have moderate permanent drifts, but retains some residual lateral strength and stiffness and its full vertical load-bearing capacity. Repair may be uneconomic. The verifications should provide a margin against member ultimate capacities.
3. “Near Collapse” (NC), similar to “Collapse prevention” in the US: The structure is heavily damaged, may have large permanent drifts, retains little residual lateral strength or stiffness, but vertical elements can still carry the gravity loads. In the verifications, a member may approach its ultimate force or deformation capacity.

The “Seismic Hazard” levels for which the three Limit States should be met are chosen either nationally through the National Annex to this part of Eurocode 8, or by the owner if the country leaves the choice open. The Eurocode itself gives no recommendation, but mentions that the performance objective recommended as suitable for ordinary new buildings is a 225 year earthquake (20% probability of exceedance in 50 years), a 475 year event (10% probability in 50 years), or a 2475 year one (2% probability of being exceeded in 50 years), for the DL, the SD or the NC "Limit State", respectively. Countries (or the owners, if the country lets the choice to them) have the authority to decide whether all three Limit States will be verified, or whether checking one or two of them at the corresponding seismic hazard level suffices.

1.1.4 Performance-Based Design Aspects of Current US Codes

In the NEHRP provisions (BSSC 2003) seismic design of new buildings is for a single level of ground motion, namely for two-thirds of the Maximum Considered Earthquake (MCE). This is the "design seismic action" in the US. The MCE is given by the USGS Seismic Hazard Maps from the USGS/BSSC 97 project (Frankel et al. 1996, 1997). These maps are also used by almost all recent nationally applicable US documents. They map the values of the 5%-damped elastic response spectral acceleration in the acceleration-controlled region, S_{as} (which is equal to 2.5 times the effective peak acceleration, *EPA*) and at a period of 1 s (S_{a1}, from which the velocity-controlled spectral region is derived). National and regional maps (at a scale of 1:500.000–1:5.000.000) are given for the MCE, which is defined for this purpose as 1.5 times the characteristic event produced by well known active faults every few hundred years. Where no major active faults can be identified, the values of S_{as} and S_{a1} with 2% probability of being exceeded in 50 years (i.e., with mean return period of 2500 years) is used. Factors are given for the conversion of the values of S_{as} and S_{a1} over firm rock to other types of ground.

For structures of ordinary importance the Life Safety performance level is required under the design seismic action of two-thirds of MCE. If this performance objective is fulfilled, it is deemed that collapse prevention is indirectly achieved under the 1.5-times stronger MCE and that immediate occupancy is expected under a frequent event with 50% probability of being exceeded in 50 years (mean return period of 72 years). Facilities which are essential for post-earthquake recovery or contain hazardous substances are designed for 1.5-times higher forces (through a 1.5-times smaller force reduction factor), implying Life Safety performance under the MCE. Such structures are claimed to indirectly achieve the Immediate Occupancy performance level under frequent earthquakes. Structures with increased public hazard, owing to large occupancy or limited ability of occupants to evacuate (medical or daycare facilities, schools, jails), are designed for 25% higher forces than ordinary ones and believed to fulfill intermediate performance objectives.

The performance objectives achieved by other than ordinary structures through the SEAOC '99 recommendations are less clear: they provide just for 25% increased design forces for essential or hazardous facilities.

Note that the importance of the structure is taken into account only in the performance under the single level of design action considered and does not affect the design seismic action. This is also evident from the fact that the importance factor does not enter in the calculation of storey drifts – calculated and checked under the design seismic action for life protection and not under a more frequent event for damage limitation.

1.2 Force-Based Seismic Design

1.2.1 Force-Based Design for Energy-Dissipation and Ductility

For the no-(local-)collapse requirement to be met for the "design seismic action" the structure does not need to remain elastic under this action. That would have required a lateral force resistance close to 50% of the building's weight. Although technically feasible, this is economically prohibitive. It is also completely unnecessary, as the earthquake is a dynamic action and imparts to the structure a certain total energy input and certain displacement and deformation demands, but not a demand to sustain specific forces. So, current codes for earthquake-resistant design allow structures to develop significant inelastic deformations under the design seismic action, provided that the integrity of individual members and of the structure as a whole is not impaired. The design approach for this is still based on forces, but its real aim is to impart to the structure capacity for energy dissipation and ductility.

Force-based seismic design is against physical reality. It is the deformation that causes a structural member to lose its lateral load resistance. It is lateral displacements (and not lateral forces) that cause structures to collapse under their own weight during the earthquake. However, force-based seismic design is well-established in current seismic design codes, because:

– structural engineers are familiar with force-based design for other types of actions (such as gravity and wind loads),
– static equilibrium for a set of prescribed external loads is a robust basis for the analysis, and
– tools for the direct verification of structures for seismic deformations are not considered yet as fully developed for practical application.

The last bullet point refers both to nonlinear analysis methods for the calculation of deformation demands and to the estimation of deformation capacities of structural members.

For all these reasons, it seems that in the foreseeable future force-based seismic design for energy dissipation and ductility will not disappear from design codes and practice.

Force-based seismic design for ductility is based on the inelastic response spectrum of a single-degree-of-freedom (SDOF) system with elastic-perfectly plastic force-displacement curve, F-δ, in monotonic loading. For a fixed value of viscous damping (the value $\zeta = 5\%$ is commonly adopted by convention), the inelastic spectrum relates:

– the period, T, of the SDOF system;
– the ratio $q = F_{\mathrm{el}}/F_{\mathrm{y}}$ of the peak force, F_{el}, that would had developed if the SDOF system were linear-elastic, to the yield force of the system, F_{y}, (q is called "behaviour factor" in Europe, while the term "force reduction factor" or "response modification factor" and the symbol R are used in the US for it) and

– the maximum displacement demand of the inelastic SDOF system, $\delta_{\max}$, expressed as a ratio to the yield displacement, δ_y (i.e. as the displacement ductility factor, $\mu_\delta = \delta_{\max}/\delta_y$).

Eurocode 8 has adopted the inelastic spectra proposed in (Vidic et al. 1994):

$$\mu_\delta = q, \qquad \text{if } T \geq T_C \tag{1.1}$$

$$\mu_\delta = 1 + (q-1)\frac{T_C}{T}, \quad q = 1 + (\mu_\delta - 1)\frac{T}{T_C} \quad \text{if } T < T_C \tag{1.2}$$

where T_C is the "transition" or "corner" period of the elastic spectrum between the constant spectral pseudo-acceleration and the constant spectral pseudovelocity ranges (see Fig. 1.1, for inelastic spectra normalised to peak ground acceleration of 1 g, with $T_C = 0.6\,\text{s}$).

The reduction in force response due to ductility bears certain similarities with the effect of higher viscous damping on an elastic SDOF system. The underlying mechanism is similar: energy dissipation; viscous in the case of the elastic SDOF, of hysteretic nature for the elastic-perfectly plastic one. Equation (1.1), applicable in the intermediate-to-long period range, expresses Newmark's well known "equal displacement rule", i.e. the empirical observation that in the constant spectral pseudo-velocity range the peak displacement response of the inelastic and of the elastic SDOF systems are approximately the same. The underlying physical reason is that inertia tends to keep the mass of a flexible SDOF system at the same absolute position while the ground moves underneath, no matter whether the spring of the system yields or not. Equation (1.2) suggests that a very high ductility is needed to appreciably reduce the peak force in a very stiff system (i.e., one with $T << T_C$): for the hysteretic energy dissipation to significantly reduce the force response, the system has to undergo large displacements, which, when divided by the low yield displacement, δ_y, of the very stiff system are translated to very high ductility demands.

The "behaviour factor" q (as well as the "force reduction" or "response modification" factor R) is applied as a global reduction factor of the internal forces that would

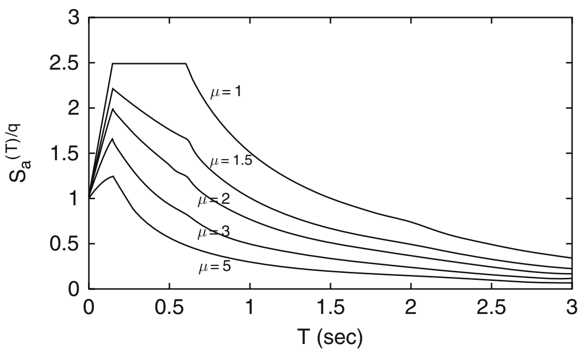

Fig. 1.1 Inelastic spectra from Eqs. (1.1) and (1.2) normalised to peak ground acceleration