CHAPTER 1: INTRODUCTION

1.1 Seismic design of concrete buildings in the context of the Eurocodes

As early as 1975, the European Commission launched an action programme for the structural Eurocodes. The objective was to eliminate technical obstacles to trade and harmonise technical specifications in the European Economic Community. In 1989 the role of the Eurocodes was defined as European EN standards to be recognised by authorities of the Member States for the following purposes:

- As a means for enabling buildings and civil engineering works to comply with the Basic Requirements 1, 2 and 4 of the Construction Products Directive 89/106/EEC of 1989, on mechanical resistance and stability, safety in case of fire and safety in use (replaced in 2011 by the Construction Products Regulation EU/305/2011 (EU 2011), which also introduced Basic Requirement 7 on the sustainable use of natural resources).
- As a basis for specifying public construction and related engineering service contracts; this relates to Works Directive (EU Directive 2004/18) on contracts for public works, public supply and public service (covering procurement by public authorities of civil engineering and building works) and the Services Directive (EU Directive 2006/123) on services in the Internal Market – which covers public procurement of services.
- As a framework for drawing up harmonised technical specifications for construction products.

It is worth quoting from Regulation EU/305/2011 by the European Parliament and the EU Council (EU 2011), given the importance of such a legal instrument in the EU, the Basic Requirement for buildings and civil engineering works (called below "Construction works") which the Eurocodes are called to serve:

"Construction works as a whole and in their separate parts must be fit for their intended use, taking into account in particular the health and safety of persons involved throughout the life cycle of the works. Subject to normal maintenance, construction works must satisfy these basic requirements for construction works for an economically reasonable working life.

1. Mechanical resistance and stability

   Construction works must be designed and built in such a way that the loadings that are liable to act on them during their construction and use will not lead to any of the following:

   (a) collapse of the whole or part thereof;

   (b) major deformations to an inadmissible degree;

   (c) damage to other parts of the construction work or to fittings or installed equipment as a result of major deformation of the load-bearing construction;

   (d) damage by an event to an extent disproportionate to the original cause.

2. Safety in case of fire

   Construction works must be designed and built in such a way that in the event of an outbreak of fire:

   (a) the load-bearing capacity of the construction work can be assumed for a specific period of time;

   (b) the generation and spread of fire and smoke within the construction work are limited;

   (c) the spread of fire to neighbouring construction works is limited;

   (d) occupants can leave the construction work or be rescued by other means;

   (e) the safety of rescue teams is taken into consideration.

[…]

4. Safety and accessibility in use

Construction works must be designed and built in such a way that they do not present unacceptable risks of accidents or damage in service or in operation such as slipping, falling, collision, burns, electrocution, injury from explosion and burglaries. In particular, buildings must be designed and built taking into consideration accessibility and use for disabled persons.

[…]

7. Sustainable use of natural resources

Construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable and in particular ensure the following:

(a) reuse or recyclability of the construction works, their materials and parts after demolition;

(b) durability of the construction works;

(c) use of environmentally compatible raw and secondary materials in the construction works)".

The 58 EN Eurocode Parts were published between 2002 and 2006, to be adopted by the CEN members and to be fully implemented as the sole structural design standards by 2010. They are the recommended European codes for the structural design of civil engineering works and of their parts, to facilitate integration of the construction market (construction works and related engineering services) in the European Union and enhance the competitiveness of European designers, contractors, consultants and material and product manufacturers in civil engineering projects world-wide. To this end, all parts of the EN-Eurocodes are fully consistent and have been integrated in a user-friendly seamless whole, covering in a harmonised way practically all types of civil engineering works.

In 2003 the European Commission issued a “Recommendation on the implementation and use of Eurocodes for construction works and structural construction products” (EC 2003). According to it, EU Member States should adopt the Eurocodes as a suitable tool for the design of construction works and refer to them in their national provisions for structural construction products. The Eurocodes should be used as the basis for the technical specifications in the contracts for public works and the related engineering services, as well as in the water, energy, transport and telecommunications sector. Further, according to the “Recommendation”, it is up to a Member State to select the level of safety and protection (which may include serviceability and durability) offered by civil engineering works on its national territory. To allow Member States to exercise this authority and to accommodate geographical, climatic, geological (including seismo-tectonic) differences, without sacrificing the harmonisation of structural design codes at European level, “Nationally Determined Parameters” (NDPs) have been introduced in the Eurocodes (and have been adopted by the Commission in its Recommendation) as the means to provide the necessary flexibility in their application across and outside Europe. Therefore, the Eurocodes allow national choice in all key parameters or aspects that control safety, durability, serviceability and economy of civil engineering works designed and built to them. The same approach has been followed when consensus could not be reached for some aspects not related to safety, durability, serviceability or economy. The “Nationally Determined Parameters” in Eurocodes are:

– Symbols (e.g. safety factors, the mean return period of the design seismic action, etc.).
– Technical classes (e.g. ductility or importance classes).
– Procedures or methods (e.g. alternative models of calculation).

Alternative classes and procedures/methods considered as NDPs are identified and described in detail in the normative text of the Eurocode. For NDP-symbols, the Eurocode may give a range of acceptable values and will normally recommend in a non-normative note a value for the symbol. It may also recommend a class or a procedure/method among the alternatives identified and described in the Eurocode text as NDPs.

National choice regarding the NDPs is exercised through the National Annex, which is published by each Member State as an integral part of the national version of the EN-Eurocode. According to the

Commission's "Recommendation", Member States should adopt for the NDPs the choices recommended in the notes of the Eurocode, so that the maximum feasible harmonisation across the EU is achieved (diverging only when geographical, climatic, geological differences or different levels of protection make it necessary). National Annexes may also contain country-specific data (seismic zoning maps, spectral shapes for the various types of soil profiles foreseen in Eurocode 8, etc.), which constitute also NDPs. A decision to adopt nationally or not an informative Annex of the Eurocode may also be made there. If the National Annex does not exercise national choice for some NDPs, the choice will be the responsibility of the designer, taking into account the conditions of the project and other national provisions.

A National Annex may also provide supplementary information, non-contradictory to any of the rules of the Eurocode. This may include references to other national documents, to assist the user in the application of the EN. What is not allowed is to modify through the National Annex any Eurocode provisions or replace them with other – e.g. national – rules. Although not encouraged, such deviations from the Eurocode are allowed in national regulations other than the National Annex. However, when use is made of national regulations allowing deviation from certain Eurocode rules, the design cannot be called "design according to the Eurocodes", as by definition this term means compliance with all EN Eurocode provisions, including the national choices for the NDPs.

A National Annex is not required for a Eurocode part, if that part is not relevant to the Member State concerned. This is the case for Eurocode 8 in countries of very low seismicity.

The approved Eurocodes were given to the National Standardisation Bodies in English, French and German. Member States have adopted one of these three official versions, or have translated them into their national language, or have adopted the translation by another Member State. This national version is supreme in the country over those in any other language (including the original three-language version). Member States have also published the National Annexes, including the national choice for the NDPs, after calibrating them so that, for the target safety level, structures designed according to the national version of the Eurocodes do not cost significantly more than those designed according to National Standards applicable hitherto.

Member States are expected to make known to the Commission the national choices for the NDPs. The impact of differences in the national choices upon the end product of the design (the works or their parts), as far as the actual level of protection and the economy provided is concerned, will be assessed jointly by the Member States and the Commission. According to the European Commission's "Recommendation", on the basis of the conclusion of such an evaluation the Commission may ask Member States to change their choice, so that divergence within the internal market is reduced.

National Standards competing or conflicting with any EN Eurocode part have been withdrawn and the Eurocodes have become the exclusive standards for structural design in the European Union.

In the set of 10 Eurocodes, two cover the basis of structural design and the loadings ("actions"), one covers geotechnical and foundation design and five cover aspects specific to concrete, steel, composite (steel-concrete), timber, masonry or aluminum construction. Instead of distributing seismic design aspects to the Eurocodes on loadings, materials or geotechnical design, all aspects of seismic design are covered in Eurocode 8: "EN1998: Design of Structures for Earthquake Resistance". This is for the convenience of countries with very low seismicity, as it gives them the option not to apply Eurocode 8 at all.

Seismic design of concrete buildings is covered in EN1998-1 "General rules, seismic actions, rules for buildings", called also (including throughout this book) Part 1 of Eurocode 8. However, this part of Eurocode 8 is not sufficient for the seismic design of concrete buildings. So, it is meant to be applied as part of a package, which includes all Eurocodes needed for the package to be self-sufficient, namely:

- EN1990: “Basis of structural design”,
- EN1991-1-1: “Actions on structures – General actions – Densities, Self weight and Imposed loads for buildings”,
- EN1991-1-2: “Actions on structures – General actions – Actions on structures exposed to fire”,
- EN1991-1-3: “Actions on structures – General actions – Snow loads”,
- EN1991-1-4: “Actions on structures – General actions – Wind actions”,
- EN1991-1-5: “Actions on structures – General actions – Thermal actions”
- EN1991-1-6: “Actions on structures – General actions – Actions during execution”,
- EN1991-1-7: “Actions on structures – General actions – Accidental actions”,
- EN1992-1-1: “Design of concrete structures – General – General rules and rules for buildings”,
- EN1992-1-2: “Design of concrete structures – General – Structural fire design”,
- EN1997-1: “Geotechnical design – General rules”,
- EN1997-2: “Geotechnical design – Ground investigation and testing”,
- EN1998-1 “General rules, seismic actions, rules for buildings”
- EN1998-3 “Assessment and retrofitting of buildings”
- EN1998-5 “Foundations, retaining structures, geotechnical aspects”

Besides Part 1 of Eurocode 8 (CEN 2004a), four other Eurocodes from the package are important for the seismic design of concrete buildings: EN1992-1-1 (CEN 2004b), EN 1997-1 (CEN 2003), EN1998-5 (CEN 2004c) and EN1998-3 (CEN 2005a), called in this book Eurocode 2, Eurocode 7, and Parts 5 or 3 of Eurocode 8, respectively.

1.2 Seismic design of concrete buildings in this book

This work is addressed to graduate or advanced undergraduate students, researchers and academics interested in the seismic response, behaviour or design of concrete buildings, seismic design professionals, software developers and other users of Eurocode 8, even code writers. Familiarity and experience of the reader in structural dynamics, earthquake engineering or seismic design are not presumed: although the book does not go in depth in each one of these topics, it is self-sufficient in this respect. However, certain background in structural analysis and in design of concrete structures and foundations, be it without reference to seismic loading, is necessary. Familiarity with the notation which has become standard internationally and is currently used in Europe is also desirable.

In order to define from the outset the target to which design according to Chapters 2 to 7 aims, the book starts off in this very Chapter with the dual requirements of Eurocode 8 for the performance of buildings of any type of material (namely protection of life in a rare earthquake, protection of property in a more frequent one), and the way they are implemented. It continues with a general overview of the physics and the mechanics of earthquakes and of their typical effects on concrete buildings and their foundations, as well as on other geotechnical works. Pictures and descriptions of typical damage help the reader to understand and appreciate the specific objectives of Eurocode 8 and the means it uses to achieve them.

After presenting the fundamentals of structural dynamics, with emphasis on dynamic loading due to seismic ground motions, Chapter 3 gives a fairly detailed and complete description of the methods adopted in Eurocode 8 for the linear or nonlinear analysis of buildings under seismic loading, alongside the appropriate modeling. The fundamental concept of the reduction of elastic forces by a factor which derives from the deformation capacity of the structure and links linear analysis with nonlinear response ("behaviour factor" in Eurocode 8) is introduced. Three short analysis examples of simple structures illustrate the basic points of the Chapter.

Chapter 4 covers the principles of sound conceptual seismic design of concrete buildings, emphasising its importance and the challenges it poses. It presents the available system choices for the superstructure and the foundation, their advantages and disadvantages, along with ways to profit the most from the former and minimise the impact of the latter. It then proceeds with the fundamentals of capacity design, which is the main means available to the designer according to Eurocode 8 in order to control the inelastic seismic response of the building. Note that, although New Zealand was where the concept of capacity design originated and was first introduced into seismic design codes, it is in Eurocode 8 that it has found its widest scope of application and, indeed, in its most pure and rigorous form, with very little empirical additions or interventions. The specifics of practical application are described in Chapter 5. Chapter 4 closes with the choices offered by Eurocode 8 for trading deformation capacity and ductility for strength, alongside the values prescribed for the "behaviour factor" under the various possible circumstances. A good number of short examples illustrate various aspects of conceptual design, as well as the use of the "behaviour factor" to reduce seismic design loads.

Chapters 5 and 6 cover all aspects of detailed design of the superstructure of concrete buildings and their foundation. Although they deal primarily with the base case, leaving aside special applications or cases, they go into significant depth, presenting everything a designer may need for the complete seismic design of a concrete building. Numerous short examples are given, with transparent hand-calculations.

The book culminates in the design of a real-life building, complete with analysis using the two main methods per Eurocode 8, capacity design across the board and sample detailed design calculations for all types of elements:

- design of beams (and deep foundation beams) at the ULS (Ultimate Limit State) in flexure and SLS (Serviceability Limit State) design for crack and stress control under service loads;
- check of columns for second-order effects under the factored gravity loads ("persistent and transient design situation" in EN1990) and dimensioning of their vertical reinforcement for the ULS in

flexure with axial force;

- capacity design of beams and columns in shear, with ULS design of their shear reinforcement, including detailing for confinement;
- dimensioning of the vertical reinforcement of walls for the ULS in flexure with axial force and of their horizontal reinforcement for capacity-design shears, with detailing for ductility;
- capacity design of footings at the ULS in flexure, shear or punching shear, with capacity-design verification of the bearing capacity of the soil.

Outcomes are illustrated through diagrams of internal forces from the two types of analysis, full construction drawings of the framing and detailing, and representative examples of all sorts of design/dimensioning calculations.

1.3 Seismic performance requirements for buildings in Eurocode 8

1.3.1 Life safety under a rare earthquake. The "design seismic action" and the "seismic design situation"

The main concern in Eurocode 8 for buildings subjected to earthquake is safety of the public – occupants and users of the facility. Eurocode 8 pursues safety of life under a specific earthquake, called "design seismic action", whose choice is left to the National Authorities, as a Nationally Determined Parameter (NDP). The "design seismic action" should be a rare event, with low probability of being exceeded during the conventional design life of the building. For "ordinary" buildings, Eurocode 8 recommends setting this probability to 10% in 50 years. This is equivalent to a mean return period of 475 years for earthquakes at least as strong as the "design seismic action". The performance requirement is then to avoid failure ("collapse") of structural members or components under this "design seismic action".

Member integrity under the "design seismic action" is verified as for all other types of design loadings: it is ensured that members possess a design resistance at the Ultimate Limit State (ULS), R_d, which exceeds the "action effect" (internal force or combinations thereof), E_d, produced by the "design seismic action", acting together with the long-term loadings expected to act when this seismic action occurs:

$$R_d \geq E_d \tag{1.1}$$

These long-term loadings are the arbitrary-point-in-time loads, or, in Eurocode terminology, the "quasi-permanent combination" of actions, $\sum_j G_{k,j} + \sum_i \psi_{2,i} Q_{k,i}$, i.e., the loads acting essentially all the time. The Eurocode 1990 "Basis of Structural Design" (CEN 2002) defines the quasi-permanent value of the other actions as:

- the nominal value (subscript: k) of permanent loads, $G_{k,j,}$ (where index *j* reflects the possibility of having several types of permanent loads: dead loads, earth or water pressure, etc.), and
- the expected value of variable actions, such as the imposed (i.e., live) gravity loads or snow at an arbitrary-point-in-time ("quasi-permanent value"); if $Q_{k,i}$ is the nominal value (i.e., the characteristic, hence the subscript k) of variable action *i*, its "quasi-permanent value" is taken as $\psi_{2,i}Q_{k,i}$.

  The values of $\psi_{2,i}$ are given in normative Annex A1 of Eurocode 1990 as a Nationally Determined Parameter (NDP), with recommended values as follows:

  – $\psi_{2,i}$ = 0.3 on live loads in residential or office buildings and traffic loads from vehicles of 30 to 160 kN;

  – $\psi_{2,i}$ = 0.6 on live loads in areas of public gathering or shopping, or on traffic loads from vehicles less than 30 kN;

  – $\psi_{2,i}$ = 0.8 on live loads in storage areas;

  – $\psi_{2,i}$ = 0 for live loads on roofs;

- $\psi_{2,i}$ = 0 for snow on the roof at altitudes less than 1000 m above sea level in all CEN countries except Iceland, Norway, Sweden and Finland, or $\psi_{2,i}$ = 0.2 everywhere in these four countries and at altitudes over 1000 m above sea level everywhere else;
- $\psi_{2,i}$ = 0 for wind or temperature.

The combination of the "design seismic action" and the "quasi-permanent combination" of actions, $\sum_j G_{k,j} + \sum_i \psi_{2,i} Q_{k,i}$, is called in the Eurocodes "seismic design situation". In common language, it is the design earthquake and the concurrent actions.

The "seismic design situation" is the condition for which the local verifications of Eq. (1.1) are carried out; the "quasi-permanent combination" comprises the loads acting at the instant of the "design seismic action" on a limited part of the building and directly affect the local verification. These loads are always taken into account in E_d, regardless of whether they are locally favourable or unfavourable for the verification of Eq. (1.1). However, the inertia forces are considered to be produced not by the full mass corresponding to $\psi_{2,i}Q_{k,i}$, but by a fraction thereof. This is because it is considered unlikely to have 100% of the “quasi-permanent value” of variable action *i*, $\psi_{2,i}Q_{k,i}$, applied throughout the building. Moreover, some masses due to live loads may be non-rigidly connected to the structure and can vibrate out of phase to their support, or with smaller amplitude.

The fraction of $\psi_{2,i}Q_{k,i}$ considered to produce inertia forces through its mass is a NDP. Its recommended value is 0.5, for all storeys (except the roof) of residential or office use, or those used for public gathering (except shopping), provided that these storeys are considered as independently occupied. In storeys of these uses which are considered to have correlated occupancies, the recommended fraction is 0.8. There is no reduction of the masses corresponding to $\psi_{2,i}Q_{k,i}$ for uses other than the above, or on roofs.

The 10% probability of exceedance in 50 years, or the mean return period of 475 years are recommended in Eurocode 8 for the "design seismic action" of "ordinary" buildings. To offer better protection of life to facilities with large occupancy and reduce damage to facilities critical for the post-disaster period (e.g. hospitals, power stations etc.), the "design seismic action" is multiplied by an “importance factor” γ_I. By definition, for buildings of ordinary importance $\gamma_I = 1.0$; for facilities other than "ordinary", the importance factor γ_I is a NDP, with recommended values as in Table 1.1.

Table 1.1 Importance classes and factors for buildings in Eurocode 8

Importance Class and type of facility	γ_I
I: Not occupied by people; temporary or auxiliary buildings	0.8
II: Ordinary	1.0
III: High consequences (large occupancy, congregation areas, etc), cultural facilities	1.2
IV: Critical, essential for civil protection (hospitals, fire stations, power plants, etc)	1.4

1.3.2 Limitation of damage in occasional earthquakes

In addition to life safety under the "design seismic action", Eurocode 8 aims at protecting property, by minimizing structural and non-structural damage in occasional, more frequent, earthquakes. A specific occasional earthquake, called “serviceability seismic action” or “damage limitation seismic action”, is selected for that purpose by national authorities, as NDP. The recommendation in Eurocode 8 is to choose an earthquake with 10% probability of being exceeded in 10 years, which corresponds to a mean return period of 95 years. Specifically for buildings, Eurocode 8 introduces the ratio of the “serviceability seismic action” to the “design seismic action”, v, and considers it a NDP. For buildings of ordinary or lower importance (“Importance Classes” I and II in Table 1.1) it recommends $v = 0.5$; for importance above ordinary (“Importance Classes” III and IV) a value of 0.4 is recommended for v. This gives in the end about the same level of property protection to Importance Classes II and III; property protection is 15-20% lower for "Importance Class" I and 15% higher for Class IV, compared to Classes II and III.

After the occurrence of the “serviceability seismic action”, the structure itself is meant to be free of permanent deformations, not to need any repair and to retain its full strength and stiffness. Non-structural elements, notably partition walls, may have suffered some damage, which should be easily and economically repairable later.

The verification required per Eurocode 8 for buildings is carried out in terms of the interstorey drift ratio (i.e., the relative horizontal displacement of the mass centres of two successive floors due to the “serviceability seismic action”, Δu, divided by the storey height, h_{st}). For a partition wall, this is an average shear strain in the plane of a wall panel. If the partitions are in contact or attached to the structure and follow its deformations, the limits to be met by this average shear strain are:

- $\Delta u/h_{st} \leq 0.5\%$, for brittle partitions; (1.2a)
- $\Delta u/h_{st} \leq 0.75\%$, for ductile partitions (uncommon in practice) (1.2b)

For buildings without partitions, or with partitions not attached to the structure in a way that imposes on them horizontal relative deformations, the limit for the interstorey drift ratio is:

- $\Delta u/h_{st} \leq 1\%$. (1.2c)

Eq. (1.2c) refers to the structure itself and aims to protect its members from large excursions in the inelastic range under the “serviceability seismic action”.

If the structure is a frame, Eqs. (1.2) may govern the size of the cross sections of its members.