CEB

Seismic Design of Concrete Structures

Comité Euro-International du Béton (CEB)

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Prepared by
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THE CEB MODEL CODE FOR THE SEISMIC DESIGN OF CONCRETE STRUCTURES

PREFACE

When Prof. Paolo E. Pinto, Rome, the Chairman of CEB General Task Group on Seismic Design, was so kind as to invite me to preface this volume, I recalled once again the particular Italian contributions towards the realization of this long-term CEB project: the chairmanship, the calibration examples and the financing of this publication. For all this, CEB feels indebted to our italian colleagues- although they may feel somehow guilty for earthquakes being still produced all over the world by the giant Enceladus buried underneath the italian Mount Etna.

Synthesis of research results into practical documents being the vocation of CEB, its activities could not be limited to normal situations only. Design versus accidental actions (fire, impact and earthquake) is also covered by more recent CEB endeavours. More specifically regarding seismic design, three preliminary editions of the present document (CEB Bulletins n. 133, 149 and 160) during the last five years, indicate the continuous efforts of CEB in this field since the inspiring initiative of Prof. Julio Ferry Borges (1979).

This document has now reached its maturity: it has been repeatedly checked, it has been proved to be operative by several worked-out examples and, to a large extent, it is performance oriented; thus, the CEB General Assembly (Prague, 1983) after some final amendments, has granted to this document the status of a "Model Code".

It is hoped that the CEB Seismic Model Code, a product of long international collaboration, having also partly contributed to the drafting of the Eurocode EC 8, will further serve the professional community of Structural Engineering world-wide.

Athens, April 1985

Prof. Theodosios P. Tassios
President of CEB

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Applied Technology Council (U.S.A.)
New Zealand National Society for Earthquake Engineering (N.Z.)
Standard Association of New Zealand (N.Z.)

whose code documents and background material have been of greatest assistance in drafting of this Code.

The "Associazione Italiana Cemento Armato e Precompresso" (AICAP) contributed to this project from the start, with the organization of the AICAP-CEB Symposium: "Structural Concrete under Seismic Actions" held in Rome, 1979, whose success greatly facilitated the accomplishment of the initiative. Financial and organizational contribution has also been provided by AICAP for the three preceding drafts of this document.

The "Associazione Italiana Tecnico-Economica del Cemento" (AITEC) has provided technical assistance and partial funding for the editing of the present volume.

REFERENCES

Ref. 1 - CEB-FIP Model Code for Concrete Structures, 3rd Edition, 1978

Ref. 2 - Applied Technology Council "Tentative Provisions for the Development of Seismic Regulations for Buildings" Publ. ATC 3-06, June 1978.

INTRODUCTION

The last twenty years or so will be probably looked back at as the "golden age" of Seismic Engineering.

The stride towards theoretical solutions to basic problems of this multidisciplinary branch of Engineering has been especially impressive during the first half of this period, with the second half witnessing an equally impressive growth of worldwide exchange of research results and professional practice.

Consolidation of the discipline, mutual knowledge and joint research projects within the specialists, has led quite naturally to the idea of harmonizing seismic design provisions on an international scale. Not an easy task however, especially between countries possessing ancient "aseismic" cultures of their own; a seismic code is in fact an integrated part of a comprehensive building code, this latter reflecting particular situations of technical and economical nature, as well as different approaches to the fundamental aspects of structural safety, of the level of social protection, etc.

The idea of a Seismic Model Code had been in the mind of C.E.B. from sometime, when Prof. Julio Ferry Borges decided in 1979 to implement the project. By virtue of his personal prestige and of the established liasons of C.E.B. with major international associations he was able to gather a forum of specialists covering all the different sources of knowledge and design practices.

Many of these colleagues did not only generously share with the group the wealth of their experience, but they contributed also hard to merge opinions and habits sometimes a bit distant into a consistent document based on the conceptual framework that C.E.B. has developed over the years.

For this first success of an international harmonization in the seismic field both the group and the C.E.B. deserve praise; as for the document itself, its present state leaves ground for confidence that its obvious future evolution will be a rather slow and gradual process.

Rome, April 1985

Prof. Paolo E. Pinto
C.E.B. Task Group "Seismic Design"

1. SCOPE AND FIELD OF APPLICATION

This Code sets down minimum design requirements to be met when dealing with seismic situations, that is, situations in which the earthquake action is considered as a critical action in conjunction with other permanent or variable actions.

The present Code applies to reinforced and prestressed concrete buildings for ordinary uses, having structural resisting systems belonging to one of the three types as defined below:

— *Frame System* A system in which both vertical loads and lateral forces are resisted by space frames.

— *Wall System* A system in which both vertical loads and lateral forces are resisted by vertical structural walls, either single or coupled. A coupled wall is composed by two or more simple walls, connected in a regular pattern by adequately reinforced ductile beams ("coupling beams").

— *Dual System* A system in which support for the vertical loads is essentially provided by a space frame. Resistance to lateral action is contributed in part by the frame system in part by structural walls, isolated or coupled.

Other structural systems, not included in the above classification (ex., inverted pendulum structures, flat slab systems, etc.) can be designed, subject to a documented proof that they satisfy all the requirements of this Code with at least the same amount of reliability.

Buildings having special characteristics, as for example the elements of lifeline systems or buildings involving high induced risk (e.g., chemical or nuclear facilities) are outside the scope of this document.

2. REQUIREMENTS

2.1 STRUCTURAL SAFETY

It is required that the entire structure and all of its elements, including the main structural system designed to resist the total seismic action, as well as any secondary connected system not possessing a seismic resistance of its own, retain with adequate reliability their integrity and a residual capacity after the seismic action has ceased.

2.2 SERVICEABILITY

It is required that the building as a whole, including structural and non structural elements, be protected with adequate reliability against the occurrence of damages and limitations of use as a consequence of the seismic action.

C 2.2

Minimum expected losses expressed in monetary terms and including initial cost plus expected cost due to loss of function, repair or replacement works for structural and non structural elements such as cladding, partitions, installations, etc., are the main concern of this requirement.

— In ordinary buildings (residential, schools, etc.) the damage measure can be approximately related to the value of interstory drift.

— For other categories of buildings (ex. hospitals, industrial plants, etc.), where unserviceability can be caused by equipment failure, different parameters are relevant to damage measure: absolute or relative displacements between parts of the structure or between adjacent structures, absolute accelerations, etc.

The admissible values of the relevant deformation parameters depend on the type of non structural elements and equipments installed, and on their connections, as well as on the functional/economical consequences of their failure.

Apart from damage control, limitation of the deformations serves the parallel purposes of:

- avoiding excessive deformability of the structure, which could lead to premature failure due to instability effects

- ensuring adequate protection to the building occupants.

3. DESIGN CRITERIA

C 3.1

The combination of measures to be adopted in order to fulfil the general requirements of safety and serviceability are summarized in Table 3.1 and Table 3.2.

DESIGN CRITERIA: I

Limit-states verification	
Safety	*Serviceability*
— *Stability* — *Control of collapse mechanism* — *Ultimate resistance of critical regions* — *Ductility*	— *Ultimate resistance of critical regions* — *Ductility* — *Limit deformations*

Table 3.1

DESIGN CRITERIA: II

Other measures	
Global ductility	*Quality assurance*
— *Quality of materials* — *Detailing*	*(see last paragraph of C 3.1)*

Table 3.2

Stability verifications include: *rigid body equilibrium (sliding and overturning), and foundation stability.*

Foundation systems have to be designed so as to allow for the intended energy-dissipation mechanism of the superstructure without impairment of their gravity load carrying capacity. To achieve this aim, in case of direct foundations (mats, footings, etc.) the bearing areas shall be dimensioned such that the soil strains will remain essentially elastic, i.e., without appreciable residual deformations.

In case of pile foundations, the piles shall be able to sustain with adequate reliability against failure the forces transmitted by the superstructure, and to adapt in a ductile way to the curvatures resulting from the dynamic deformations of the upper soil layers.

3.1 DEFINITIONS

Design criteria comprise the set of operations to be performed in order to satisfy the general requirements set forth in Ch. 2. These operations include:

— consideration of the relevant limit-states of structural behavior, and checking of these limit-states by means of analytical procedures based on appropriate models and values of actions and resistances.

— detailing of structural elements according to the provisions contained in this Code.

— adopting quality assurance procedures both in the design and construction processes.

The principles laid down in the CEB-FIP Model Code (Ref. 1), Vol. I, establish that the degree of safety and serviceability of a given design be measured in terms of "operational" failure probabilities, to be checked against their respective "target" values.

To ensure uniformity, "operational" probabilities must be evaluated with reference to precisely defined models of actions, structural response, and materials and members resistance: these models are given in the present text.

A level I, partial safety factors format, is used in this Code to meet the safety and serviceability requirements: the numerical values of the safety elements have been calibrated with reference to the particular structures and for the analytical algorithms allowed by this Code.

Collapse mechanism: *The provisions of this Code have been developed on the choice that structures should resist earthquake actions by means of a stable, non linear, energy-dissipating mechanism of response. This aim will be achieved by following the dimensioning rules of the various elements given in Ch. 4.*

Resistance and ductility: *Critical regions (i.e. where most of the energy dissipation is expected) must be provided by an appropriate balance of these properties, both of them contributing to safety and serviceability. Specific analytical provisions, which take into account the influence of accumulative damage and degrading of mechanical properties, are given in Ch's 4 and 5.*

Limit deformations: *The amplitude of the structure's deformation under the design forces shall be limited, in accordance with Cl. 4.4.6.4, for the reasons illustrated in C. 2.2.*

Global ductility: *Use of appropriate materials (Ch. 4.1), as well as of experimentally validated detailing arrangements (Ch. 5) contribute to ductile behavior at least as significantly as the available analytical procedures.*

Quality assurance *aspects of special relevance are:*

— check of the correspondence between the structural model adopted for the analysis and the actual structure, considering all the elements, either structural or not, which could alter the intended behavior;

— check of good workmanship in the detailing, especially in those areas indicated as critical by the designer (extremities of columns and beams, base zones of walls, lintels, etc.).

C 3.2

Examples of Class I buildings include: essential rescue facilities such as hospitals, fire and police stations, electricity stations, etc.; buildings with likely large number of occupants, such as schools, audience or spectacle halls, etc.

The importance factor I is an additional safety factor, used here to increase the design actions, which is explicitly recognized in Ref. 1 (Vol. 1, Ch. 10.1), to account for different consequences of failure.

The partial factor I, although primarily relevant to the safety with respect to collapse, has also influence on the serviceability condition. Actually, an increase of the design strength of the structure leads to a smaller ductility demand under the entire range of possible earthquake intensities, and this in turn reduces the expected amount of damage.

For certain types of buildings, however, functional requirements may be more critical for the design than the safety requirements, and the former are not necessarily properly accounted for by the factor I.

In those cases, specific serviceability limit-states must be introduced, and adequate reliability with respect their exceedance shall be ensured.

3.2 RELIABILITY DIFFERENTIATION

Target reliabilities shall be established on the basis of the consequences of failure, considering both aspects of safety and serviceability.

Consequences of failure, in which monetary and non monetary losses are included, depend principally on the use given to buildings, on their contents, and on the importance of their functions.

At least two different reliability levels shall be recognized for the structures covered by this Code; where necessary, however, a more articulate subdivision will be adopted.

In case two levels are deemed as adequate, the structures may be classified as follows:

Class I: buildings that are required to remain functional and to suffer reduced damages after a strong seismic attack.

Class II: buildings not included in the above Class.

The different reliability levels proper to each Class shall be obtained by amplifying the design action with a factor I, called 'importance factor'.

In addition or in alternative of the use of the factor I, checking of specific limit-states relevant to damage or loss of function can be required for certain types of buildings.

C 3.3

In the context of seismic structural response the term: "ductility", either referred to an element or to a structural system, is used as abbreviative for: "ability to dissipate significant amount of energy through inelastic behavior under large amplitude cyclic deformations, without substantial reduction of strength".

3.3 DUCTILITY LEVELS

The structural systems covered by this Code can be designed to possess different 'ductility' levels, according to the following classification:

— *Ductility Level 1* (DL I) - this level is defined as that proper to structures proportioned in accordance to Ref. 1, Vol. II, with the few additional requirements on detailing

The presently available knowledge would permit, on the basis of the characteristics of the component materials, steel and concrete, of the sectional dimensions, of the amount and detailing of the reinforcement, of the relative proportioning of structural subassemblages, to evaluate the order of magnitude of the "ductility" that an entire structural system of the types classified in Ch. 1 could develop during a strong earthquake.

For reasons of simplicity, however, the Code does not require any explicit evaluation of ductility: 3 levels of ductility are identified, and progressively more stringent provisions for proportioning and detailing are considered as effective means for obtaining structures having "improved" degrees of ductility.

Since the Model Code does not contemplate significant incursions into yielding state for reversed loading, ductility level I *is necessarily associated with relatively large design lateral forces, so that little inelastic response should occur even for large earthquakes. This makes ductility level I suitable for low rise (more generally, for structurally and economically unimportant) buildings, for which sophisticated design would be unjustified or difficult to impose.*

In the aim of the present provisions, DL II and DL III structures should be provided with a substantially equal level of reliability.

If this result were actually achieved, the choice between DL II and DL III would be basically dictated by the economic-technological condition proper to each Code user.

It is admitted however, that since DL III involves a closer control on the entire design process, it is likely to provide ampler cover to possible deviations of the characteristics of the seismic action from the way they have been idealized for design purposes.

DL III structures should then be preferred whenever large uncertainties exist (for ex. the possibility of near field events, local amplification effects of difficult evaluation, etc.).

For some special cases, a convenient solution could be to combine the use of DL II design forces with DL III detailing provisions.

contained in Ch. 5.

— *Ductility Level II* (DL II) - for this level specific aseismic provisions are to be adopted, enabling the structure to enter the inelastic range of response under repeated reversed loading, while avoiding premature brittle-type failures.

— *Ductility Level III* (DL III) - for this level special procedures for the evaluation of the design actions, and for the proportioning and detailing of the elements are to be adopted to ensure the development of selected stable mechanisms associated with large energy-dissipation capacities.

The greater ductility level conferred to a structure, the lower is the seismic action to be considered for the design, as quantified by the value of the 'behavior factor' K (Ch 4.1.3).

4. METHODS OF ASSESSMENT

4.1 BASIC DATA

4.1.1 MATERIAL CHARACTERISTICS

4.1.1.1 CONCRETE

— Normal or lightweight aggregate concrete grades shall satisfy the following minimum requirements:

Ductility level	Minimum grades	
DL II	C 20	LC 20
DL III	C 25	LC 25

Table 4.1

Lightweight aggregate concrete grades higher than LC 30 shall not be used in absence of special proof of their adequate ductility characteristics.

C 4.1.1.1

Concrete qualities higher than the minimum admitted for non-seismic situations are required to allow for a stable behavior under repeated large deformations.

4.1.1.2 STEEL

DL I and DL II Structures

Steel properties shall be in accordance with the requirements contained in Ref. 1, Ch. 3.

DL III Structures

The following additional requirements shall be satisfied:

a) It must be proven that the steel used possesses adequate ductility under repeated reversed deformations.

b) Steel grades higher than S400 shall not be used, unless it is demonstrated that the use of higher grades in special section arrangements does not affect unfavourably the ductility.

c) The actual yield stress shall not exceed its nominal value by more than 15%.

d) The ratio of the mean value of the ultimate strength to the actual yield stress shall not be less than 1,25 for S 220 and 1,15 for S 400.

e) Only high bond steel shall be used for flexural reinforcement, unless adequate provisions are taken to ensure bond and anchorage.

C 4.1.1.2

a) *This requirement may be considered as satisfied if the steel is able to sustain three symmetrical cycles of deformation up to strains of ± 4%, over a bar length not greater than 5ϕ.*

b) *Higher steel grades reduce the flexural ductility of the section: in the range between S 220 and S 400, a 50% increase in f_y may result roughly in a 50% decrease in ductility.*

c) *Uncontrolled steel overstrengths may unfavourably alter the intended dissipative mechanisms.*

d) *The requirement of a minimum amount of strain hardening aims at avoiding critical concentrations of strains at some sections, permitting thus the formation of larger zones where inelastic rotations can develop.*

e) *The bond strength of smooth bars deteriorates rapidly during cyclic loading, especially after yielding has set in.*