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New Trends
in
Seismic Design of Structures

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Preface

During the last decades, engineers have developed sophisticated methods and computational techniques for a better description and understanding of the dynamic behavior of structural systems. With the exploitation of the most critical technical development of the 20th century, the computer, this particular field of Mechanics has steadily emerged as a discipline initiating revolutionary changes to their theoretical treatment as well as to the engineering practice through innovative design methodologies. These dramatic changes had a profound impact on all fields of Structural Dynamics such as: earthquake engineering, offshore engineering, bridge aerodynamics, vibro-acoustics, soil-structure and fluid-structure interaction, wind-induced vibrations, man-made motions, multi-body dynamics, structural control, etc.

In addition to these dramatic changes that have taken place, engineers always strive to design efficient structural systems which must be as light and economic as possible, yet strong enough to withstand all possible dynamic loads arising during its life-cycle without catastrophic failure, or absorb the induced dynamic energy of different levels of intensity in a controlled and predictable fashion. This effort, which is inherent in human nature, necessitates the use of refined computational techniques and reliable numerical simulation approaches for a more accurate prediction of the nonlinear system behavior up to failure under extreme dynamic loading conditions considering all types of uncertainties that influence structural response.

The design of engineering structures under dynamic loading is an extremely computational intensive task since, in order to assess the structural performance for different hazard levels, is required the accurate and reliable prediction of the non-linear dynamic response. Furthermore, in order to account for the shortage of data on the actual geometry, the properties of the materials, the numerical simulation as well as the intensity and characteristics of the dynamic loading, reliability analyses and design procedures considering both aleatory and epistemic uncertainties should be considered. If, in addition to system uncertainties, structural optimization is also implemented for obtaining not only a safe and feasible but also the most economic design, then the relative complexity and computational cost increase dramatically. The computational effort required for solving different types of Structural Dynamics problems increases dramatically starting from the linear dynamic time history analysis to the most demanding, but very essential in reaching a safe and economic design, reliability combined with robust design optimization with nonlinear system considering uncertainties. Even with today's decline in the cost of computational resources and the increasing availability of powerful computers, the cost of design of complex large-scale engineering systems and structures can be exorbitant.

The realization of such demanding designs could only be achieved by a reduction of orders of magnitude on the required computational effort. Such a reduction can be achieved by a synergy of the following actions: using cost-efficient and accurate-enough reduced numerical models for the simulation of the actual response of the physical problem; implementing efficient solution algorithms for handling the resulting nonlinear dynamic equations; applying reliable and efficient optimization algorithm for improving the design; quantifying the influence of system uncertainties. Therefore, accomplishing an economic and safe design requires the implementation of optimization algorithms for achieving the best possible design, and stochastic processes to account for the statistical uncertainties of dynamic loading as well as of structural and material parameters.

Nevertheless, despite all the aforementioned computational advances, until recently the provisions of seismic design codes for buildings were based on experience and were periodically revised after disastrous earthquakes. As a result, most of the current seismic design norms define a single design earthquake that is used for assessing the structural performance against earthquake hazard. Moreover, they accept many simplifying assumptions regarding the behavior of the structures under seismic actions. However, recent earthquakes caused severe damages and forced the engineering community to question the effectiveness of the existing seismic design codes. Given that the primary goal of contemporary seismic design is the protection of human life in connection to the restriction of repairing cost, it is evident that additional performance targets and earthquake intensities should be considered to assess structural performance for multiple hazard levels.

Most of the current seismic design codes belong to the category of prescriptive design procedures (or limit-state design procedures), where if a number of checks, most frequently expressed in terms of forces, are satisfied then the structure is considered safe since it fulfills the safety criterion against collapse. A typical limit-state based design can be viewed as one (i.e., ultimate strength) or two limit-state approach (i.e., serviceability and ultimate strength). Existing seismic design procedures are based on the principal that a structure will avoid collapse if it is designed to absorb and dissipate the kinetic energy that is induced in it during a seismic excitation. Most of the modern seismic norms express the ability of the structure to absorb energy through inelastic deformation using a reduction or behavior factor that depends on the material and the construction type of the structure.

The concept of performance-based design (PBD) was introduced a few decades ago, for designing structures subjected to seismic loading conditions. In PBD more accurate and time-consuming analysis procedures are employed, to estimate non-linear structural response. The progress that takes place in the area of computational mechanics, as well as in computer technology, continuously expands the capabilities and the applicability of PBD procedures. ATC-40 and FEMA-273 were the first guidelines for performance-based seismic rehabilitation of existing buildings in USA, while in the Vision 2000 report these ideas were extended to the design process of new buildings. The main objective of this kind of design procedures is to achieve more predictable and reliable levels of safety and operability against natural hazards. According to PBD procedures, the structures should be able to resist earthquakes in a quantifiable manner and to present specific target performance levels of possible damages. PBD procedures are multi-level design approaches, in which various levels of structural performance are simultaneously considered. PBD design criteria try to define certain levels of structural performance for various levels of seismic hazard.

Taking all the aforementioned aspects into account, the aim of this edited book is to present state-of-the-art contributions in the area of seismic design of structures. In this context, the book topics include simulation issues for the accurate prediction of the seismic response of structures, computationally efficient numerical treatment of the resulting dynamic problems, design optimization procedures, performance-based design, life-cycle cost design principles, treatment of uncertainties in earthquake engineering, repair and retrofit of structures, engineering seismology, geotechnical earthquake engineering, soil-structure interaction, and various other important advancements in seismic analysis and design as briefly described in the sequence.

In the first chapter by I. Takewaki fundamental properties on earthquake input energy to single and connected building structures are presented. Stable characteristics of earthquake input energy to elastic structures with and without passive dampers are examined via time and frequency domain methods. The advantages of both approaches are discussed and as a representative example, two buildings connected by viscous dampers are examined. It is shown that total input seismic energy of the overall system, including both buildings and connecting dampers, is approximately constant regardless of connecting dampers capabilities for energy absorption. Therefore, if the energy in the connecting dampers increases, the input energies to the buildings can be effectively reduced. This finding can be very advantageous for the seismic design of connected structures.

As illustrated in the work of J.E. Hurtado, there is still great need for the development and application of efficient stochastic methods for incorporating various unavoidable uncertainties in practical seismic design with reasonable accuracy and computational effort. For this purpose, the two main optimum structural design options considering uncertainties, namely, robust design optimization (RDO) and reliability-based design optimization (RBDO), are presented. In addition, advanced stochastic analysis methods based on Monte Carlo simulation (MCS) are used to obtain accurate probability estimates. The example of a base-isolated building verifies that the presented methodology requires only a small number of MCS runs to achieve excellent accuracy.

The impact of spatial variability of earthquake ground motion and its implications for the dynamic response of extended structures is given by A.G. Sextos. More specifically, the objective of this chapter is to investigate and quantify the degree of detrimental influence, if any, of the aforementioned phenomenon by applying a comprehensive methodology that simultaneously considers spatial variability, site effects and soil-structure interaction to the analysis of long bridges and other extended structures such as ancient city walls. Moreover, a review of current seismic provisions is made and recent developments regarding the available methods for generating spatially variable earthquake ground motion scenarios are given. The chapter concludes with practical recommendations that can be readily used in the seismic design process of elongated engineering structures.

The creation of seismologically-consistent stochastic response spectra is the topic of the contribution of S. Sgobba, G.C. Marano, P.J. Stafford and R. Greco. Under this perspective, an effective method is proposed for developing stochastic response spectra and predicting the earthquake signal generated at a site on the basis of random vibration theory. This approach evaluates the maximum structural response, namely the response spectrum, without requiring the use of repeated time history analyses, but directly obtaining the peak response of a single degree of freedom system subject to a stochastic process which represents a given earthquake. For this purpose, a non-stationary stochastic model for the ground motion is developed and relations between stochastic model and seismological parameters are formulated. The method is capable of predicting the amplitudes of peak responses which are useful to assess potential seismic damages.

The probabilistic assessment of the seismic performance of steel buildings designed according to contemporary norms is presented by C.A. Bermúdez, J.E. Hurtado, L.G. Pujades, A.H. Barbat and J.R. González-Drigo. The motivation of this study is to assess whether steel buildings designed and constructed according to contemporary load and resistance factor design (LRFD) specifications, reasonably meet the probabilistic requirements on structural member safety. This is achieved by applying non-linear dynamic analyses and Monte Carlo simulations covering a wide range of combinations of random variables that affect the demand and strength of the examined steel buildings to determine the probability of exceedance of limit states and to assess safety levels of structural members. The results show that uncertainties may lead to significant failure probabilities, especially for moment-resisting steel frames which, thus, require increased safety margins. In contrast, braced steel frame have a much better behaviour and fulfil seismic safety requirements.

Important techno-economic issues related to reliable and efficient seismic design of buildings are highlighted in the contribution by C.C. Mitropoulou, S.A. Krikos, A.D. Fotis, N.D. Lagaros and M. Papadrakakis. The main aim of this chapter is the assessment of the European seismic design codes and in particular EC8 and EAK2000 with respect to the recommended behaviour factor q using life-cycle-cost (LCC) analysis as an efficient assessment tool. LCC analysis, in conjunction with structural optimization, is proven to be a reliable procedure to assess the performance of reinforced concrete (RC) structures designed for different behaviour factors during their life time. It is concluded that a RC structure designed using the proposed performance-based approach can lead to economical designs with respect to the total cost compared to a code conforming design.

Performance-based seismic design of buildings using effective optimization schemes is the focus of the contribution by M. Fragiadakis. Both deterministic and probabilistic frameworks for the performance-based optimal seismic design of reinforced concrete and steel frames have been discussed. The implemented single and multi-objective formulations have been solved utilizing efficient evolutionary optimizers, while linear and non-linear, static and dynamic analysis methods have been used. All implementations presented are consistent with modern performance-based design concepts taking into account structural response at a number of limit-states, from serviceability to collapse prevention. The final designs always comply with the provisions of European design codes and offer significant cost reduction and improved control on the seismic demand and capacity.

Performance-based seismic design of light-frame wood buildings is discussed in the work of J.W. van de Lindt and S. Pei. Such structures are very commonly used for residential buildings in many countries worldwide. Performance-based design (PBD) and analysis for these structures has been an evolving research topic in the wood and seismic community. The current developments of PBD approaches for wood frames are summarized in this chapter, including displacement-based design and damage/loss-based design. The analysis method adopted in this study was the incremental dynamic analysis (IDA) in order to evaluate the maximum inter-story drifts of wood building under different seismic intensity levels. To improve their seismic loss estimation procedure for wood frame structures, the authors design the building for a target loss performance expectation by applying a simple trial-and-error type optimization procedure within the design process.

The performance-based optimization of hospital systems based on an efficient decision support scheme is presented by G.P. Cimellaro, A.M. Reinhorn and M. Bruneau. More specifically, the authors introduce an organizational model describing the optimum response of the hospital emergency department (ED) which is an important tool for engineers and decision-makers. The hybrid simulation/analytical model (the so-called “metamodel”) is able to estimate the hospital capacity and dynamic response in real time and incorporate the influence of the damage of structural and non-structural components on the organizational ones. The waiting time is the main parameter of response and it is used to evaluate disaster resilience of health care facilities. The metamodel has been designated to cover a large range of hospital configurations and takes into account hospital resources, in terms of staff and infrastructures, operational efficiency and possible existence of an emergency plan, maximum capacity and behaviour both in saturated and over capacitated conditions. The sensitivity of the model to different arrival rates, hospital configurations, and capacities as well as the technical and organizational policies applied during and prior the strike of the disaster has been investigated.

G. Muscolino and A. Palmeri propose an extended response spectrum method for the seismic analysis of light secondary substructures. The seismic survival of relatively light non-structural attachments may be important in practice similar to the earthquake resistance of the main structural system. In this chapter, aimed at overcoming some drawbacks of existing procedures, a new combination rule is formulated and numerically validated for the response spectrum analysis of light secondary substructures (LSSs), whose definition is hereby rigorously established. The main advantages of the proposed approach are: the eigenproperties involved in the computations are those of the decoupled substructures, assumed to be fixed to their own bases; the new combination coefficients incorporate the effects of frequency tuning and different damping in the two components; the elastic response spectrum for just a single value of the viscous damping ratio is required, and this spectrum can be selected as the reference one provided by the seismic code. Under this perspective, the results of numerical investigations carried out on representative systems have been presented and discussed.

C. Zeris aims at exploiting the impact of unreinforced masonry infills on the seismic response of existing non-conforming reinforced concrete buildings. Existing reinforced concrete buildings, also referred to as non-conforming ones, comprise the largest inventory of buildings that have been widely constructed in seismic regions all over the world over the last decades. As it is also evident from damages occurred in recent earthquakes, these structures are very vulnerable and there is great demand for their proper assessment and seismic mitigation. For this purpose, dynamic response and vulnerability assessment of typical infilled RC frames has been thoroughly analyzed and implemented in this study. Characteristic methods of construction, types of structural morphology and typical types of damage in past earthquakes are reviewed. Modelling conventions for the analysis of this type of structural system are underlined, with emphasis on the damage response prediction capability, the reliability of various analysis methods and the sources of prediction uncertainties.

A.M. Memari discusses in his work issues associated with seismic evaluation of building envelope systems and presents relative innovative designs. Although building envelope systems are normally designed or specified as non-structural components, not intended to participate in lateral load resistance, past earthquakes have shown that these components are vulnerable to damage. For this reason, initially various types of damage sustained by envelope components in past earthquakes are described, followed by the explanation of racking behavior of cladding panels. Subsequently, an overview of recent studies involving development of innovative solutions to mitigate seismic damage to building envelopes is presented. Finally, the chapter discusses building seismic provisions and special design guidelines for building envelope systems.

In their chapter K. Nakatsu, H. Furuta and Y. Nomura advocate the efficiency of optimal restoration scheduling for earthquake disaster mitigation plans. In seismic countries it is necessary to develop an effective disaster prevention program based on the recognition that road networks may be unavoidably damaged when very strong earthquakes occur. The main purpose of this work is the early restoration of road networks after earthquake disasters. To achieve this goal the focus is given in two crucial issues. The first is the allocation problem of which components to restore when disaster occurs and the second is the scheduling problem of optimum restoration actions. In order to solve these two problems simultaneously in an optimum manner genetic algorithms (GAs) have been applied. In addition, to deal with additional issues (uncertainties, changeable aftershock circumstances, economic constraints, etc), an efficient decision support system of the optimal restoration scheduling has been developed using improved GAs.

Y. Tsompanakis, V. Zania, P.N. Psarropoulos describe in their contribution the recent advances in seismic slope stability analysis of earth structures. Current practice performs slope stability assessment of geostructures using simplified procedures, which evaluate either the factor of safety or the seismic slope displacements. In this work after a short description of the existing methods, an advanced decoupled method was applied and the seismic coefficients and displacements were calculated for two types of failure surfaces after an extensive parametric study. The results indicate that a seismic coefficient spectrum for circular failure surfaces, based on the accepted seismic displacements may be produced. Moreover, coupled analyses of a SDOF system with sliding potential along its base (models commonly used to simulate base sliding) reveal some important aspects of their seismic performance. Finally, base sliding appears to be a rather complicated issue dependent on several parameters including the geostatic stress field, and it is related to seismic distress of geosynthetic layers placed along the base of earth structures.

P.N. Psarropoulos describe analytical and computational issues related to seismic design of retaining walls and bridge abutments. Despite their structural simplicity, retaining walls and bridge abutments comprise complex soil-structure interaction systems, the dynamic behavior of which depends mainly on the geometrical and mechanical properties of the structure (wall or abutment) and the soil, the kinematic constraints of the system and the characteristics of the seismic excitation. Seismic design of retaining systems worldwide is most frequently performed via a direct or indirect application of the well-known Mononobe-Okabe method, which is based on the two rather simplistic concepts of “limit equilibrium” and “pseudo-dynamic acceleration”. This chapter, after an extensive review of the current practice and norms in this field, illustrates the potential design errors that may stem from the drawbacks of the limit-equilibrium methods and describes certain important “open issues” in this field that have to be resolved in the future.

The aforementioned collection of chapters provides an overview of the present thinking and state-of-the-art developments on the application of advanced computational techniques into the framework of structural dynamics and earthquake engineering. The book is targeted primarily to researchers, postgraduate students and engineers that are active in areas related to earthquake engineering and structural dynamics. It is hoped that the collection of these chapters in a single book will be found useful for both academics and practicing engineers.

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