Geotechnical, Geological and Earthquake Engineering

Rajesh Rupakhety
Símon Ólafsson *Editors*

Earthquake Engineering and Structural Dynamics in Memory of Ragnar Sigbjörnsson

Selected Topics

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To Ragnar: our mentor, source of inspiration, and friend.

Preface

This book is a collection of invited papers presented at the International Conference on Earthquake engineering and Structural Dynamics (ICESD) that was held in Reykjavik, Iceland, from 12th–14th June, 2017. The conference was held in honour of late Professor Ragnar Sigbjörnsson. Ragnar received his formal education in structural mechanics, which he applied in solving practical engineering problems and advancing the state-of-the-art in areas such as wind engineering, engineering seismology, earthquake engineering, and offshore engineering. Application of structural dynamics principles in wind and earthquake engineering was his main area of research and teaching. He had a very keen interest and deep understanding of modelling and analysis of random fields, which combined with his knowledge and skills in structural mechanics, established him as a leader in research areas such as structural dynamics and earthquake engineering. Ragnar was also keenly interested in safety science and reliability, and actively studied and pursued research in disaster risk management. Although Ragnar maintained a very diverse and cross-disciplinary research portfolio, his main focus was on (i) earthquake engineering and seismology (ii) dynamics of special structures such as floating bridges, long-span suspension bridges, submerged floating tunnels, and offshore structures, and (iii) earthquake risk evaluation, perception, and management.

This book includes contributions in these three fields. Due to the vast nature of these fields, it is impossible, in a small volume like this, to thoroughly and rigorously address all the issues they deal with. We merely present selected topics within these fields: topics which Ragnar was most interested in and contributed to. Many of the chapters are written by his collaborators, close friends, and colleagues, presenting methods and results that cover and extend beyond the state of the art in structural dynamics and earthquake engineering. Of the 19 chapters presented here, 7 are written by invited Keynote Speakers at the ICESD, who are among the most distinguished scientists and researchers. These chapters showcase, not only the historical perspective of the state-of-the-art, but also the most recent developments and provide a glimpse into the future of research in earthquake engineering and structural dynamics. Other chapters are written by renowned researchers, many of whom were also close collaborators of Ragnar. Some of the chapters are based on the work initiated and led by Ragnar himself. The book will be useful for both researchers and practising engineers who are interested in the recent advances and future directions in these fields of scientific research and engineering practice.

The book starts with a short biography of Ragnar, entitled, “Ragnar Sigbjörnsson: A Scientist who went from a Tiny Town to World Reknown”. The chapter is written by one of Ragnar’s daughters, S. Ragnarsdóttir, together with his long-time collaborators S. Ólafsson and Svein Remseth, and his student and apprentice R. Rupakhety. The chapter highlights aspects of Ragnar’s life as a scientist and educator, as well as a person and a family man; the latter is perhaps not as well-known to the readers as the former. This is a short description of his fascinating and inspiring journey from a small village of Borgarfjörður Eystri in North Iceland, to become one of the most distinguished scientists not only in Iceland and Norway, but worldwide.

The rest of the chapters are divided into three parts. The first part includes selected topics in earthquake engineering and engineering seismology. It starts with the chapter written by P. Gülkan and M. A. Sözen, presenting a genealogy of performance-based seismic design. This chapter is a must-read for anyone interested in the history of performance-based seismic design (PBSD), its evolution and maturation, as well as uncertainties and challenges in its practical application. The focus is on using structural drift as a central parameter in performance evaluation, which is although a positive influence of PBSD, the authors review and present compelling evidence on the lack of knowledge and tools to accurately estimate seismic drift demands of, for example, reinforced concrete structures. They highlight important considerations for practical use of PBSD, and advise its cautious use with a proper understanding of uncertainties in structural calculation, which may be, to non-specialists, masked by the sense of false confidence offered by advanced structural analysis methods. The second chapter of Part 1, written by Michael N. Fardis, addresses the important issue of structural design to multiple extreme hazards. The chapter describes how the vast knowledge of research and development in seismic design of structures that has accumulated since the 1970s can provide a baseline for structural design for extreme loads such as larger blasts and fire. Ignoring extreme events in structural design is projected as a defeatist stance which is not in lieu with the spirit of modern performance based design. At the same time, the futility to associate probabilities to extreme threats, which are by definition *unknown*, is highlighted and emphasis is placed on consequence-based design method. Design decisions for such extreme events are more rationally based on the expected consequences. Issues such as progressive collapse and unexpected loss of a structural member and its consequences on the global stability of structures are addressed, and are illustrated with experimental and numerical investigations. Based on detailed investigations and thorough analysis of experimental results, the chapter provides guidelines on design features which enhance structural resilience to multiple hazards in contrast to those that are efficient against some hazard but detrimental against others. These guidelines are stipulated in simple terms and serve practical conceptual design of structures resilient to multiple hazards.

Moving on from the philosophy and intricacies of PBSD in Chap. 1 and structural design for extreme loads in Chap. 2, Chap. 3 by A. Ansal et al. addresses a very important issue in seismic design of structures: the definition of design loads considering local site effects, in particular, the effect of site response in design acceleration spectrum. The chapter addresses the problem of deriving a uniform hazard spectrum (UHS) at the surface of a site based on the UHS at the bedrock. The chapter introduces a simplified procedure to derive a response spectrum at surface based on UHS at the bedrock and probabilistic treatment of uncertainties in site amplification through site response analysis using multiple hazard-compatible ground motions and Monte Carlo simulation of soil layer thickness and shear wave velocities. Modelling of damping in nonlinear time history analysis of structures is addressed in Chap. 4 by A. J. Carr and A. M. Puthanpurayil. Modelling damping at global level, by using models such as mass and/or stiffness proportional models has been found to be unrealistic in many studies. In lieu of stiffness and inertial properties, formulation of damping properties at element level, and subsequent assembly of global damping matrix is desirable, and consistent within the general framework of finite element analysis. This chapter presents the formulation of damping matrix at element level, both for discretized elements and continuum models, and illustrates the advantages of this approach against the conventional damping models based on global structural mass and stiffness matrices.

Challenges in modelling the seismic response of reinforced concrete (RC) walls, which are very effective in carrying lateral forces due to wind and earthquakes, is discussed in Chap. 5 by T. Isakovic and M. Fischinger. This chapter underlines the limitation in modelling inelastic response of structures referred to as a difficult obstacle in successful implementation of PBD, as discussed in Chap. 1 by P. Gülkan and M. A. Sözen. Isakovic and Fishinger present the basic features of a macro element capable of modelling flexural-axial-shear interaction in RC walls. They also present experimental results that demonstrate the efficacy of the proposed macro element to model complex axial-flexural-shear interactions and capture global response of the experimentally tested walls. In Chap. 6, I. Takewaki et al. address one of the most pressing contemporary issues in earthquake engineering: modelling of near-fault ground motions and their effects on structures. They use double- and triple-impulse excitations to represent near-fault ground motions and derive approximate closed-form solutions for response of elastoplastic system subjected to such motions. The approximate solutions are shown to be close to that obtained from inelastic analysis of recorded near-fault ground motions. Closed-form solutions of these kind are very valuable to study a large number of structures, to conduct reliability analysis, as well as in parametric analysis to understand the effects of different ground motion and structural parameters in seismic reliability of structures. Effect of near-fault ground motions on seismically isolated liquid storage tanks is addressed in Chap. 7 by S. Öncü-Davas et al. This chapter investigates the effectiveness of simple analytical models of near-fault ground motion in predicting the seismic response of base-isolated liquid storage tanks. Their results indicate that not all analytical models match the response induced by actual near-fault ground motion equally well. The success of the analytical models was found to be dependent on the response quantity being investigated: bearing displacement, isolation system shear force, and fluid-tank shear forces were found to be represented more accurately than sloshing displacements.

Wave height and total energy of landslide-generated tsunamis is addressed by J. Eliasson in Chap. 8. Submarine landslides triggered by even small earthquakes can cause large tsunamis. Eliasson uses translatory wave theory, which was originally proposed by him, to estimate the initial wave height and the associated wave energy. Equations to estimate these parameters are given and a general outline to use the results in estimating their exceedance statistics, which essentially constitute a probabilistic tsunami hazard curve, is presented.

Estimation of surface strain rate tensor field from GPS network, and the subsequent interpretation of seismicity of Iceland is presented in Chap. 9 by R. Sigbjörnsson et al. Based on GPS measurements from the base stations of the National Land Survey of Iceland, the methodology of estimating strain rate tensor and vorticity tensor is demonstrated. The results, based on data assembled between 1993 and 2004, indicate a velocity field governed by rigid plate motion of the North American Plate and the Eurasia Plate. Significant strain rates exist in the rift between the two plates. The largest shear strain is in the South Iceland Seismic Zone, where the epicentral areas of the two ~Mw6.5 earthquakes in June 2000 conform to the regions of largest strain rates. Stochastic modelling of strong ground motion due to earthquakes in South Iceland Seismic Zone (SISZ) is presented in Chap. 10 by Ólafsson et al. Ground motion records from the recent earthquakes were found to have a source spectra which fit well with the point source model of Brune. Source parameters of the four largest earthquakes in Iceland for which accelerometric records are available are estimated and used to construct theoretical models of peak ground motion parameters. Such models are based on source spectra of point source, with incorporation of attenuation in the near- and far-field, and provide closed-form solutions for root-mean-square (rms) acceleration, which can be converted to peak acceleration through peak factors that depend on duration of shaking. The resulting model is shown to fit the recorded data better than purely empirical Ground Motion Prediction Equations (GMPEs), and can also be used to simulate artificial ground motion models, stochastically equivalent to the data they are calibrated from.

Seismic vulnerability of Icelandic residential buildings is presented in Chap. 11 by B. Bessason and R. Rupakhety. Based on damage data collected during recent earthquakes, the chapter provides a review of the types of damages sustained by buildings and their corresponding frequencies. Fragility and vulnerability curves for different building typologies, and their application in scenario risk estimation are presented. Buildings in South Iceland are found to be very resilient to earthquakes of magnitude 6.5 or lower, even in the near-source area where ground acceleration as high as 80% of acceleration due to gravity has been recorded. Most of the damage was of non-structural type, which indicates that despite the good structural performance, considerable risk of injury/casualty exists due to movement of household objects. This risk was somewhat mitigated due to the fortunate timing of the earthquakes in June 2000 and May 2008. Measures to improve seismic safety in South Iceland should focus on prevention of hazardous movement of building contents, which is more easily accomplished than improving structural performance, but perhaps, overlooked due to complacency and lack of safety culture.

Damage to non-structural elements and the subsequent loss of function and cost of repair are a growing concern in earthquake engineering research. Infill walls constitute a major concern in this regard. Damage and failure are not only costly, but may also cause serious injuries to the occupants. M. Vailati et al. present in Chap. 12, a novel technology of earthquake resilient and energy-efficient infill panels using hollow concrete or clay blocks that are dry-juxtaposed, rather than joint with mortar layers. The joints consist of recycled-plastic elements forming a preferential sliding plane to accommodate horizontal displacements imposed by ground shaking. Experimental and analytical results presented in the chapter show that the proposed infill panels are not only structurally more resilient than traditional mortar-joined brick walls, they are also more energy efficient.

The second part of the book contains three chapters written by Ragnar's colleagues and collaborators at Norwegian University of Science and Technology (NTNU). These chapters are related to structural dynamics, design, and monitoring of special bridges; namely long-span suspension bridges, floating bridges, and marine bridges. These chapters are based mostly on research carried out at NTNU to find innovative solutions to make the E39 Highway in Norway ferry-free under the Coastal Highway Route E39 Project, in collaboration with the Norwegian Public Roads Administration (NRPA). The highway needs to cross many deep and wide fjords where conventional bridges are not feasible, and more challenging modern solutions are being sought. The first chapter in this section, Chap. 13 by A. Fenerci and O. Øiseth, is about the Hardanger Bridge, which Ragnar studied as a young engineer during his early career at NTNU. The bridge is the longest suspension bridge in Norway with a main span of 1310 meters. The chapter presents full-scale measurements and analysis of wind-induced vibrations of the bridge, which lies in a complex terrain. The results indicate that mean wind speed and vertical turbulence intensity are the two most important wind parameters influencing dynamic response of the bridge. Lateral response is controlled by the along-wind turbulence while cross-wind turbulence was found to produce torsional vibrations. The results show that variability in wind field in complex terrain can result in large scatter in dynamic response. Modelling of such effects is essential in reliable design and is being actively pursued at NTNU.

In Chap. 14, K. A. Kvåle et al. present methods of simulation and monitoring of a floating bridge dynamics. The bridge discussed in this chapter is the Bergsøysund Bridge, a 931 m long arch-shaped pontoon bridge. The chapter presents the theoretical framework of dynamic modelling of floating bridges considering fluid-structure interaction, modelling of random water waves, as well as time- and frequency-domain solution strategies of the governing equations of motion. Results of dynamic simulation of the Bergsøysund Bridge using the finite element method are presented, and compared with results of operational modal analysis carried out from an extensive structural monitoring system installed on the bridge. Stochastic dynamic second-order response analysis of marine bridges is presented in Chap. 15 by B. J. Leira. This chapter presents the formulation of basic equations of motion of second-order wave-induced loading on floating and submerged bridges, and demonstrates a simplified procedure to estimate second-order loading. The simplified procedures for a submerged tunnel bridge with surface pontoons are compared with more refined methods, namely, the numerical panel model. A case study of the 3700 m long Sognefjord Bridge is presented, and the results from simplified analysis methods were found to be in good agreement with those obtained from refined models.

The last part of the book is related to selected topics in seismic risk assessment, risk communication/perception, and management. This part consists of four chapters. The first chapter of this part, Chap. 16 by C. S. Oliveira et al. discusses new tools and methods for the analysis of generalized impacts of earthquakes. The chapter is based on research carried out in the last decade by the Group of Seicmic Risk of Instituto Superior Técnico (IST), Lisbon, Portugal. The chapter focuses on indicators of earthquake impact. Of particular interest is the newly developed idea of Disruption Index (DI) which is a holistic measure of earthquake impact, that incorporates the physical damages to different elements of an infrastructure, the loss of function due to such damages, and the complex interactions and interdependencies between these elements including the cascading effects of loss of functionality of an element due to damage in another element. The chapter also provides a framework for incorporating the impact indicators with performance indicators such as risk reduction worth and risk achievement work to mitigate risk. Chap. 17 by G. Musacchio et al. presents the main findings of the UPStrat-MAFA (Urban Disaster Prevention Strategies using Macrosiesmic and Fault sources) project, that incorporated a multi-disciplinary approach to disaster prevention encompassing strategies based on the analysis of level of risk and information. Ragnar was one of the key persons in the project, and was very enthusiastic about it. Uses of macroseismic information and its probabilistic treatment for hazard analysis are presented. A holistic approach to risk assessment, through the DI (see Chap. 16) was one of the most important contributions of the project, and some of its applications are detailed in this chapter. The project strongly emphasized prevention strategies based on education and communication of risk, and developed video games for children, and audio-visual products for the general public. A summary of these achievements and products is presented in this chapter.

Chapter 18 by R. Sigbjörnsson et al., is the penultimate chapter of this book, and is related to gender-dependence on the perception of earthquake effects and residential safety. The chapter presents statistical analysis of response to a questionnaire survey campaign carried out in the epicentral area of the two ~Mw 6.4 earthquakes in South Iceland. The questions addressed in this chapter are the actions taken by people inside their houses during earthquakes. The results indicate that a significant proportion of the respondents (~15%) could not move during the earthquakes. While majority of male did not seek shelter, most of the female respondents sought shelter. The results also showed that female take more time than male to recover from the negative experience of earthquakes. It was also observed that the female respondents were biased towards higher intensities (macroseismic, Modified Mercalli Intesnity), while the male respondents were biased towards lower intensities.

In the final chapter in this book, Chap. 19, S. Platt discusses and analyses the factors affecting the speed and quality of post disaster recovery and resilience. The chapter provides an insight about post-disaster resilience and recovery from a comparison of ten recent earthquake disasters. The analysis indicates that speed of recovery is, at least for the disaster studied in this chapter, not strongly dependent on exogenous factors of size of impact, population demographics and economics factors. Both speed and quality of recovery are shown to be strongly related to the post-disaster management and decision making. The chapter provides key issues to be considered by governments and decision makers in hazard prone countries to "build back better" after a disaster. Despite growing knowledge, research and development in seismic resilient construction, earthquakes are a serious threat to our society. While some countries are better prepared to mitigate and manage disasters, others are very poorly prepared. In the latter case, post-disaster recovery becomes a very complicated process with several national and international actors. Lack of local leadership and a clear and rational vision for recovery and reconstruction makes disasters more disastrous. It is our belief that earthquake engineers have a prominent role to play, not only in designing and constructing resilient infrastructure, but also in shaping the reconstruction plan, as they are well equipped with the knowledge to learn what went wrong during a disaster, and how it can be fixed. Involvement of earthquake engineers in academic research as well as practical participation in disaster mitigation planning and post-disaster reconstruction decision-making will be vital for our future earthquake resilient societies.

We wish to extend our gratitude to all the authors of the included chapters for their contributions to this book. We are thankful to Professor Atilla Ansal, who proposed the idea of the ICESD, and provided us continuous support and encouragement in preparing this book. Special thanks are due to Petra van Steenbergen, Springer executive editor of Earth Sciences, Geography and Environment, for her support in preparing this book. We are grateful to the international scientific committee of the ICESD and other colleagues for reviewing the chapters presented in this book, and for providing valuable comments and suggestions for improvement.

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Ragnar Sigbjörnsson: A Scientist Who Went from a Tiny Town to World Renown

Ragnar Sigbjörnsson was born on May 7, 1944, in Borgarfjörður Eystri, a small village in the northeast of Iceland. This village remained very dear to him. His parents were Sigbjörn Jakob Guðmundsson (1904–1970), a carpenter and an organist, and Jónanna Steinsdóttir (1906–1979), a housewife. Ragnar was one of three brothers: Bjarni, the eldest (1938–1981); Ragnar, the middle child; and Guðmundur Ingi, the youngest (1947) (Fig. 1).

Fig. 1 *left* Ragnar with his maternal grandmother Guðrún **right top**: Ragnar‘s parents Jónanna and Sigbjörn **right bottom** The three brothers (from left) Guðmundur Ingi, Bjarni and Ragnar

Ragnar's family home in Borgarfjörður Eystri was named Ásgarður. There, he grew up in a big family with his parents, brothers, both grandmothers, and two maternal uncles. From a young age, he was greatly influenced by Jóhannes S. Kjarval (1885–1972) who was, and still is, one of Iceland's most beloved artists. Kjarval grew up in Geitavík, also in Borgarfjörður Eystri, and went there every summer to stay at his summer cabin. Ragnar often followed him around, watching him paint in nature. On one occasion, Kjarval gave him a piece of string in the colours of the national flag. Ragnar treasured this string and tied a knot on both ends so it would not unravel. Many years later, when Ragnar was at university, he met Kjarval again. Kjarval asked him if he still had the string. Ragnar had to tell him, with great sadness, that it had gone missing. Ragnar, who picked up a few tricks from Kjarval, was himself a good painter and even sold paintings during his school years. This experience shaped him and gave him a great love of and appreciation for art.

As a child, Ragnar already had the strong urge to ask questions, get answers and challenge things. He was always experimenting, for example, on how high a box kite or various types of balsa-wood aeroplanes could fly and asking what needed to be changed or improved so that they did better. He built all kinds of models, not to have on the shelf, but on which to experiment.

At the age of 13, he went to a boarding school called Alþýðuskólinn á Eiðum. It was not very common that children from his remote village would seek further education since the town lacked an overland connection during winter until 1965. However, Ragnar's desire and urge to know more drove him to pursue his education. To attend school, he had to make a two-day's journey. He had to walk or ski, sometimes in heavy snow or blizzards, for a day until he reached the farm, Unaós, where he stayed overnight and continued onward with a vehicle. Ragnar's diligence, endurance, and perseverance definitely came from this early hardship in seeking an education. These are traits that he carried throughout his life—always working as hard as he could, driven by desire to know more, and possessing a strong will and determination.

Ragnar moved to Akureyri, at the age of 16 to attend secondary school at Menntaskólinn á Akureyri (MA), where he met his future wife Bjarnveig Höskuldsdóttir (1946). Music was second nature to Ragnar, as he was brought up in a very musical family. He played classical guitar. During his years in Eiðar and Akureyri, he played in a few groups. During his life, the guitar was never far away from him. He loved playing either to relax or to be at the centre of a party, singing and strumming. Ragnar graduated from MA in June 1965. At that time, he and Bjarnveig moved to Reykjavík (Fig. 2).

During his MA and university years, Ragnar worked for the Icelandic Road Administration, building structures, for example, roads and bridges, during summer vacations. Ragnar was always thankful for the opportunity to work for the Icelandic Road Administration. He said many times that this made it possible for him to pursue his education at MA and the University of Iceland. He also worked for the National Land Survey of Iceland. While working there, he met Jón í Möðrudal (1880–1971) who taught him to sight-read music in the church in Möðrudalur. Jón once told Ragnar's parents that he had never taught such a quick-learning teenager.

Fig. 2 *left*: Ragnar on graduation day from MA *middle*: Ragnar was fond of music and played guitar from an early age *right*: Ragnar and Bjarnveig on their wedding day

In July 1964, Ragnar and his younger brother were building bridges across rivers in Njarðvík. Usually, everyone went home for the weekend, but, as the brothers lived in Reykjavík, it was not possible for them. Therefore, the brothers decided to climb the magnificent mountain of Dyrfjöll (Door Mountains, 1136 m, shown in Fig. 3). It was a warm, sunny day on that side (Fljótdalshérað). When they came up through the pass and looked over Borgarfjörður Eystri, they could only see the highest peaks of Staðarfjall and Svartfell due to heavy fog rolling in below. Jökuldalur (Glacier Valley), named after the small glacier situated below, is on this side of Dyrfjöll. The brothers decided to go down through the pass and jump onto the glacier. They followed the glacier until they found the glacial river that they knew would take them home. When they came down, the fog had lifted and they arranged for someone to drive them back to Njarðvík. Not many had done this before them, and it was considered quite a dangerous achievement at that time.

In the autumn of 1965, Ragnar began his engineering studies at the University of Iceland. In February 1966, their first daughter, Anna Birna, was born. Ragnar and Bjarnveig got married on September 30, 1967, and he finished his studies at the University of Iceland in June 1968.

After finishing his first engineering degree in Iceland, Ragnar and his young family headed to Denmark, where he earned his master's degree from the Technical University of Denmark (DTU) in 1971 and a PhD from the same university in 1974. Following his studies in Denmark, he was hired as a research engineer at SINTEF, the research foundation of the Norwegian Institute of Technology (NTH), which is now called the Norwegian University of Science and Technology (NTNU).

Ragnar had a solid mathematical background, which was important when it came to stochastic modelling of environmental loads, such as wind, sea waves, and earthquakes, and their associated effects on structures. His exceptional skill in applying knowledge to practical problems soon made him a prominent researcher at

Fig. 3 The Dyrfjöll (Door Mountains, 1136 m) in Borgarfjörður Eystri (photo credit: Hafþór Snjólfur Helgason)

SINTEF in the development of safe offshore structures for the oil and gas industry and long suspension bridges in cooperation with the Norwegian Public Road Administration. Ragnar worked at NTH/SINTEF until 1979. During this time, he and his family lived in Heimdal, Trondheim. Two more daughters were born in Norway, Sólveig (October 1977) and Bryndís (July 1979) (Fig. 4).

The family returned to Iceland in the autumn of 1979, when Ragnar initially took a research position and later a professorship at the University of Iceland. The family settled down in the beautiful town of Mosfellsbær, where they built a home designed by Ragnar.

Although Ragnar lived in Iceland for the remainder of his life, he continued to have strong contact and collaboration with his colleagues in Norway. In 1979, Ragnar and Ivar Langen published a textbook on the dynamic analysis of structures (*Dynamisk Analyse av. konstruksjoner*, in Norwegian). Ragnar had very close and productive collaboration with his colleagues and friends Erik Hjorth-Hansen, Svein Remseth, and Bernt Leira, among others, at NTNU, as well as at the Norwegian Public Roads Administration (NPRA). Ragnar held a professorship at NTNU until his death and had been supervising MSc and PhD students at NTNU for a long period. He was an excellent supervisor and was very much appreciated by the students and his colleagues.

A major effort made by Ragnar, when he went to NTNU in 2009, was the planning of a research program for fjord crossings along the highway route E39 on the western coast of Norway. The seven or eight major fjords require bridges to span between 2000 and 5000 meters. Ragnar's knowledge and experience from planning offshore struc-

Fig. 4 Ragnar with his wife and daughters in 2003

tures and various types of bridges, such as submerged floating tunnels, floating bridges, and suspension bridges, was of vital importance in defining the research required for the new bridges requiring extreme spans. The research program was planned for several PhD students and postdoctoral researchers, along with additional research by senior personnel acting as supervisors. At present, between 15 and 20 temporary positions at NTNU are financed by this research program. The project comprises the theoretical development of methods of analysis and numerical models of load processes based on meta-ocean data and integrated analysis of interactions between the bridge structure and the fluid, air, and soil environments. These are complex problems, and there is a definite need to compare numerical simulations with measurements. Ragnar played a vital role in the planning of the instrumentation on two bridges with relevance to the E39 project, the Hardanger Bridge and the Bergsøysundet Bridge (see Chaps. 12 and 14 for more details). Ragnar had, as a young researcher, worked on the analysis and design of Hardanger Bridge and was very excited when one of his first, major engineering projects was built and opened to traffic. The instrumentation program planned by Ragnar has already provided, and continues to do so, very valuable data that have proved important for the validation of load and interaction modelling.

When Ragnar came to the University of Iceland in 1979, he soon became a leader in engineering research. He was the director of the Engineering Research Institute during its starting phase of 1983–1990. Ragnar also headed the Applied Mechanics Laboratory, a small research group that focussed on research in structural mechanics. Gradually, he focussed his research on earthquakes and their effects on structures. Ragnar established the Icelandic Strong Motion Network in 1986. The Icelandic Strong Motion Network has recorded many significant earthquakes in Iceland, and it is the most important source of strong ground-motion data in Iceland. The Icelandic Strong Motion Network has tremendous value for seismic-hazard assessment in Iceland. In 2000, he founded the Earthquake Engineering Research Centre of the University of Iceland. He was its director until he retired in 2014 and the head of its Board of Directors until his passing. Ragnar contributed to the establishment of seismic design provisions of the most noteworthy, contemporary civil engineering works. He was very successful in applying the results of his research to solving practical problems and was consulted by various industries in Iceland regarding the safe design of their structures, most notably power plants near seismically hazardous areas in the south Iceland lowlands, as well as in northern Iceland. The advances in strong-motion monitoring, structural monitoring, seismic-hazard assessment, and structural design that he initiated are very important for Iceland, with the majority of its 330,000 inhabitants living close to seismically active areas.

While very active and productive in academic research and practical consulting, Ragnar was equally passionate about his teaching at the University of Iceland. He played an important role in shaping the current curricula of the civil engineering degree at both the BS and the MS levels. He was very ambitious as a teacher and designed, coordinated, and taught advanced courses, such as continuum mechanics, computational mechanics, stochastic mechanics, structural dynamics, earthquake engineering, risk analysis, etc. Many of these courses are still very relevant to the curriculum and are being taught following his vision and objectives. Ragnar spent a lot of time preparing lecture notes, slides, and other educational materials for his students. He continuously worked to provide his students with the most up-to-date information, not only on the classical theories that he taught, but also on their practical implications and developments at the forefront of research (Fig. 5).

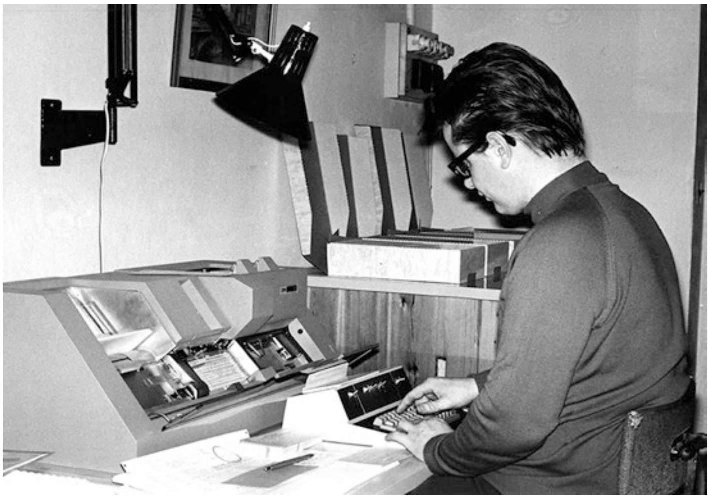

Fig. 5 Ragnar programming on a punching machine during his early career at University of Iceland

Fig. 6 Ragnar with his friend and colleague Prof. Athol J. Carr during his visiting professorship at the University of Canterbury

Ragnar was very active internationally and had numerous contacts worldwide. One of his most notable research collaborations was with the late Professor Nicholas Ambraseys at Imperial College London, where Ragnar was a visiting professor during 2001–2003. A review of an earthquake catalogue for Iceland was among the many works they completed. In 2006, he was a visiting professor at the University of Canterbury in New Zealand with Professor Athol Carr, a time he greatly enjoyed and fondly remembered. He participated in many international scientific conferences. In 2014, he attended the Second European Conference on Earthquake Engineering and Seismology (2ECEES) in Istanbul, Turkey. Ragnar was very satisfied with the conference and enjoyed his time in Istanbul by visiting its magnificent monuments, which brought back memories from earlier visits (Figs. 6 and 7).

Ragnar was very enthusiastic about the last international project he worked on, the EU project UPStrat-MAFA (Urban Disaster Prevention Strategies using MAcroseismic and FAult sources). He played a valuable role in this project, which produced many innovative methods and products for the prevention of urban disasters due to earthquakes and volcanoes. He worked very closely with his friends and collaborators, Carlos Sousa Oliveira and Gaetano Zonno, during this project. Ragnar played a very important role in producing the special issue of the prestigious journal of the Bulletin of Earthquake Engineering, presenting the research results of the UPStrat-MAFA project. He was a co-editor of this issue as well.

Fig. 7 *Left*: Ragnar and his colleagues with their spouses (*from left to right*, Bjarnveig, Ragnar, Carlos Sousa Oliveira, Isabel Oliveira, Gaetano Zonno, and Cecilia Zonno) during the gala dinner of the 2ECEES; *Right*: Ragnar and Bjarnveig enjoying their time in Istanbul during the 2ECEES

Fig. 8 *Left*: Ragnar on the deck of MSC Orchestra during the IZIIS-50 conference; he was very fond of offshore structures, bridges and wind turbines (in the background). *Right:* Ragnar delivering his last international conference lecture onboard MSC Orchestra during the IZIIS-50 conference

Ragnar's appetite for engaging in scientific work, initiating scientific dialogue, and disseminating research results was perhaps best exemplified by his strong will, despite his degrading health, to participate in his last international conference: The IZIIS International Conference on Earthquake Engineering and Engineering Seismology, which was held on the cruise ship MSC Orchestra travelling in the Baltic Sea May 12–16, 2015. He was very passionate about this conference and delivered a lecture on offshore-earthquake engineering (Fig. 8).

Ragnar was very fond of travelling and learning about various different cultures. He appreciated the natural beauty and sociocultural heritage of the places he visited. In 2012, he and Bjarnveig travelled to Nepal to attend the wedding of his student and apprentice Rajesh Rupakhety. Ragnar enjoyed the trip very much and often mentioned that he felt like he had been there before. He was touched by the landscape and mountains of the country and captured a magnificent photograph of the Machhapuchhre Mountain from the balcony of his hotel room in Pokhara early in

Fig. 9 Ragnar and Bjarnveig in traditional Nepalese dress, ready to attend the wedding ceremony of his student and apprentice

the morning, before the clouds started covering the mountain top. For many years to follow, Ragnar talked about his experience of waking up and seeing this magnificent mountain standing right in front of him (Fig. 9).

Ragnar's fondness for bridges is perhaps best exemplified by an adventure that took place in Nepal. After a long and tiring trip to Pokhara, Ragnar, Bjarnveig, Rajesh, and Puja (Rajesh's wife) made a late stop in Abu Khaireni for lunch on their way back to Kathmandu. Despite being tired, Ragnar spotted a suspension bridge over the Marsyangdi River. As soon as he spotted it, walking across the bridge and understanding its dynamic characteristics became his priority. Lunch could wait (Fig. 10).

Apart from music, Ragnar was very interested in poetry and knew an enormous number of poems. He enjoyed reading poems and found it to be relaxing for the soul. One of his last and most consuming projects was to publish the book *Gengin Spor* in cooperation with his younger brother Guðmundur Ingi. This book is a tribute to their maternal uncle, Bjarni Steinsson (1902–1963), and contains poems by Bjarni that Ragnar's mother collected over the years. Ragnar visited his birthplace of Borgarfjörður Eystri in June 2014, where a special ceremony was held to celebrate the release of *Gengin Spor* (Fig. 11).

Fig. 10 *Main photo*: The Abu Khairini Suspension Bridge over the Marsynagdi River in Gorkha, Nepal **inset**: Ragnar with Rajesh following him, crossing the bridge and investigating its vibrational characteristics

Fig. 11 Ragnar in his hometown Borgarfjörður Eystri, on his way to celebrate the release of *Gengin Spor*

Fig. 12 Ragnar receiving the Knight's Cross of the Order of the Falcon from the then president of Iceland, Olafur Ragnar Grimsson

All those who knew Ragnar were aware that he was very skilled and passionate about his work. Ragnar was open to new ideas and was not afraid to venture into new research territory. He was aware of the human element of engineering, and his interdisciplinary work set an example for others to follow. Ragnar was a popular teacher. As a mentor, he had tremendous influence on numerous engineers and researchers, both in Iceland and abroad. Ragnar was among the most active and productive researchers at the University of Iceland, and he received numerous awards for his work. In 2003, the president of Iceland awarded Ragnar the Knight's Cross of the Order of the Falcon for his work in the fields of science and education. Ragnar was a Rotarian and had received the highest award in Rotary, the Paul Harris Award, for his outstanding contribution (Fig. 12). He was also a Freemason. He found these societies to be both rewarding and immensely enjoyable.

Ragnar passed away on July 15, 2015, after a short battle with cancer. Ragnar was a very influential teacher and researcher at the University of Iceland in applied mechanics, earthquake engineering, and engineering seismology. He was also a family man who loved his wife, daughters, and their families. He enjoyed hosting banquets and trying new things in the kitchen. If a celebration contained a four- to five-course meal, it was perfect. His elegance and accuracy shone through when he was setting a table for a celebration; it was always exquisite. He worked until the day he died; he never gave up, and he taught people around him to never give up. The evening before he passed away, he was still working hard to finalize a research article and a special volume of the UPStrat-MAFA project that was published in the Bulletin of Earthquake Engineering.

Ragnar leaves behind a large legacy, and his work has led to great progress in engineering education and in earthquake research. His contributions have opened numerous doors for engineers and researchers to come. Memories of him, filled with love, inspiration, motivation, sympathy, and elegance, will be cherished by many for the rest of their lives.

Reykjavík, Iceland	Solveig Ragnarsdóttir
Selfoss, Iceland	Rajesh Rupakhety
Reykjavík, Iceland	Símon Ólafsson
Trondheim, Norway	Svein Remseth

Part I
Earthquake Engineering and Engineering Seismology

Chapter 1
Genealogy of Performance-Based Seismic Design: Is the Present a Re-crafted Version of the Past?

P. Gülkan and Mete A. Sözen

Abstract Structural engineering for earthquake resistance is undergoing a major revision in its approach toward the fulfillment of seismic safety and utilitarian serviceability in design. Rather than sticking to the established precepts of prescriptive design rules, design has turned toward the achievement of specific results through procedures that are tailored for different buildings and uses. These procedures represent notable research contributions, but they are complicated conceptually for implementation in structural engineering practice, and nonlinear building response estimates, frequently assumed to be performance, can vary within broad limits even for simple applications.

In this text we relate the history of code developments. We focus on the two main requirements of earthquake-resistant design of building structures: (1) Life Safety and (2) Protection of the Investment and relate the two demands to current concepts of Performance-Based Building Design. While we provide a personalized vision for the way in which the PBSD framework developed and matured during the last half century, a thorough historiography is not within the scope of the text. We nominate drift to serve as the prime metric for performance judgment.

Keywords Performance-based seismic design • Base shear • Drift ratio

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1.1 An Unofficial History of Building Codes

Performance based structural design has been with us for much longer than is recognized. A good example is the design and construction of the cathedral at Beauvais, France. The construction of the cathedral was initiated in 1225 with the desire of "reaching heights taller than all existing cathedrals." In 1284, as the vaulting reached 48 m, supporting walls collapsed during construction. Another effort was made to go higher, but it also was terminated by another collapse. It was then decided not to go any higher because satisfactory performance was clearly elusive. The tools of the building trade that existed then did not meet the challenge of the objective.

Following the repair of the cracks in St. Peter's dome in Rome in the eighteenth century using a procedure related to what is currently called virtual work, structural design has been (as Cross called it) a craft, or something between science and art, that is based on experience. This important linchpin is sometimes sacrificed to the false exactness provided by computerized, nonlinear analysis of approximate models of the structure.

It was the extreme damage from the Messina earthquake of 1908 that inspired the Italian engineering community to develop a scientific base for the design of earthquake resistant building structures. Knowing better, but realizing that the engineering community of early twentieth century would be more comfortable with force related design, they based their design procedure on mythic/imaginary lateral forces of which demands could be readily combined with requirements of gravity forces. The approach was endorsed by the Japanese engineering community and then readily accepted by the international earthquake engineering community because it permitted prescriptive provisions to be drafted for codes. It took around a century to realize that drift, and not force, was the primary driver for the earthquake performance of most buildings. Drift controlled the force, not vice versa (Sozen 1981). Recognition of drift as a design criterion put the emphasis on performance that could be seen and measured. In principle, this works for existing buildings as well as in the design stage of new buildings.

A historic survey of prescriptive requirements on how to build for better seismic performance shows that these landmarks were always reached after cataclysmic experiences. These early regulations, such as were passed after the 1509 Istanbul Earthquake, 1755 Lisbon Earthquake, or the 1880 Luzon (Manila) Earthquakes, were limited to descriptions of allowable building materials and building heights. They predated the extensive use of reinforced concrete and steel. Unreinforced masonry was an allowable material in these early regulations, and no quantitative method was provided for calculating either demands or capacities. Thus they are primitive seismic codes in today's light, regulating some features of construction but not employing the quantitative methods civil engineers would later develop. That notwithstanding, these efforts are impressive for making such early attempts to improve the building stock's earthquake resistance.

The major earthquake that shook Istanbul in the summer of 1509 led to the banning of stone masonry construction in the city, because most deaths had occurred when such buildings collapsed. This decision paved the way for the emergence of another form of disaster that plagued the city for the next four centuries: fires consumed not only timber construction but also much of the cultural heritage. Following the 1755 earthquake in Lisbon, which destroyed the city center area known as Baixa, the Marquis of Pombal gathered a group of builders to determine the best manner of earthquake-resistant construction to use for rebuilding. The type of construction selected became known as the Pombalino wall. In its complete form, it is also referred to as “gaiola” or “cage” construction. Most, if not all, of the buildings reconstructed in the reconfigured planned Baixa area were constructed with Pombalino walls, and sometimes (but not always) with complete “gaiola” timber frames, Tobriner (1984b), Langenbach (2003).

The practice of developing, approving, and enforcing building codes varies considerably among nations. Several countries have adopted model codes, including earthquake regulations, on a national basis, such as Japan, New Zealand, and Italy. In such countries, building codes are developed by government agencies or quasi-governmental standards organizations and then made to apply across the country by the central government. Until 2000, the USA had three major model codes and associated seismic regulations, and even after their integration into the International Building Code, the process of adopting and enforcing the regulations, sometimes with substantial variations, is left to state and local governments. Similarly, in India each municipality and urban development authority has its own building code, which is mandatory for all construction within its jurisdiction. In Europe, the Eurocode is a pan-European building code that has all but superseded the older national building codes. Each country must now develop its own national country annex to localize the contents of the Eurocode. The seismic component of the Eurocode is only one part of that model code. While the consistency of the regulations across European national boundaries provides a better technical basis for its seismic and other provisions, the more important motive for such a code of European scope is economic. The Euro economic block can compete more effectively against the nations outside it if its design, construction, and building material industries are guided by consistent provisions.

A model building code is a convenient resource that can be adopted by the appropriate jurisdiction as its legal requirement. This makes the cost of maintaining and updating a code more economical and also provides more design and construction consistency from one city to the next than would be the case if each developed its own code. That multiplicity of codes in a country was the rule throughout the nineteenth century and in many cases, has only gradually trended toward nationally uniform provisions in the twentieth century. Two important interests that have pushed for uniformity are the construction and building material industries, which can operate more efficiently if they have one set of rules, and the insurance industry, which desires up-to-date code provisions that can be easily evaluated for rate-setting purposes.

Tobriner (1984a) provides a historical survey of the development of building codes, noting that they originated primarily in the form of requirements for fire-resistant construction in the increasingly more congested urban settlements, and then only much later in most countries had seismic regulations been added to them. The first systematic national building standard was the London Building Act of 1844. Among the provisions, builders were required to give the district surveyor 2 days' notice before building, and they contained regulations regarding the thickness of walls, height of rooms, the materials used in repairs, the dividing of existing buildings. The placing and design of chimneys, fireplaces, and drains were to be enforced, and streets had to be built to minimum requirements.

The City of Baltimore passed its first building code in 1859. The Great Baltimore Fire occurred in February, 1904. Subsequent changes were made that matched the contemporary fire-resistant regulations of some other large cities in the United States. In Paris, under the reconstruction of much of the city by Baron Haussmann during the Second Empire (1852–1870), great blocks of apartments were erected, and the height of buildings was limited by law to six stories. Though height limits were instituted for city planning reasons, they later sometimes became part of seismic codes in determining allowable structural systems for various heights.

1.2 Codes: Prescriptive and Performance-Based

Building code requirements are usually a combination of prescriptive requirements that spell out exactly how something is to be done, on the one hand, and performance requirements that just outline what the required level of performance is and leave it up to the designer how this is achieved, on the other. An example of the former would be a rule-of-thumb for spacing of anchor bolts in house construction. An example of the latter would be to have the engineer calculate interstory drift and then design concrete cladding to accommodate the specific distortion of the building. In recent years, there has been a move among many building codes towards more performance requirements and less prescriptive requirements. Performance-based code requirements still require tight definitions so that adequate performance can be evaluated by the building regulatory agency. The fire protection field has developed performance-based design approaches for many years, in which testing or other data can be used to provide alternate means of fire protection instead of following the prescriptive requirements of a code.

In recent years, several countries beginning with Australia, have moved to much shorter, objective-based building codes. Rather than prescribing specific details, objective-based codes list a series of objectives all buildings must meet while leaving open how these objectives will be met. When applying for a building permit the designers must demonstrate how they will meet each objective. This makes it necessary for approving authorities to employ correspondingly qualified personnel so that a productive synergy can be created between innovative designs and traditional safety concerns. It also requires a high degree of professionalism, because it gives the architect and engineer more leeway, as compared to more prescriptive requirements, and also requires a higher level of building code enforcement review. Seismic isolation, inclusion of damping devices, response history analyses, and displacement-based design are some of the innovative approaches currently in use in some places where this higher level of design and review capacity is present. Each of these represents challenges in analysis and design that require an intimate knowledge of the underlying mechanics-based mathematical theory and its limitations. As such, they are best performed by professionals with considerable experience because there are alternative approaches that require deep insight on the part of the engineer. These are individuals who know what they don't know.

Seismic codes begin with the goal of providing safety, and many stop there in most respects, but some include requirements for protecting the functionality of essential buildings, such as fire stations, hospitals, and emergency communications and data processing centers. This is discussed in the separate chapter on Essential Facilities and is only mentioned in passing here. Some of the most stringent regulations of this type were passed in California after the 1971 San Fernando Earthquake, when the Hospital Seismic Safety Act of 1972 was passed. The Veterans Administration adopted its own regulations after that earthquake, regulations that seek to not provide not only safe hospitals but also more functional ones placing an emphasis on drift. Some voluntary above-code (performance-based design) approaches lead an owner to invest in the cost of higher seismic protection to achieve less property damage in earthquakes, but the most common seismic design criteria that go beyond the goal of providing safety are related to protecting essential functions.

1.3 Performance-Based Building Design

It would be naïve to attempt to compose a timeline with appropriate citations for the way performance-based seismic design has evolved during the last 25 years. It also would be futile to assume that such a compendium would fail to offend a good many people who would likely feel to have been omitted or at least slighted. This is a criticism we are prepared to accept. A useful, if slightly dated, compilation devoted to performance-based seismic engineering has been assembled (Bertero and Bertero 2004).

Such has been the interest shown by the world's earthquake structural engineering community in the reformatted approach to the required performance to sizing structural systems for seismic effects on the basis of basic capacity design concepts that the sheer number of publications would be an overwhelming task for anyone to list. In contradiction of the title for this paper, it is also not easy to pin parentage on any single individual for having begotten the groundbreaking, seminal concept for performance or displacement-based design at any stage of the advance of the trade. There was no Biot, for example, to figure out the concept of the response spectrum as a design tool, work out its details, and place it in front of engineers for their use. Its growth was the usual pattern for scientific progress and technical development: a cross-fertilization of experience, concepts, and laboratory tests culminating in convergence, after having occasionally followed false leads, on the true path toward predefined performance. Seemingly random ideas become crystallized into unified methodology when they receive the acceptance of their peers. A history of performance-based seismic design is also strongly dependent on the geographic setting: differing visions exist in Europe, the USA, and elsewhere as to how it arrived at its current station (Priestley 2000).

Two contrasting visions have contributed to the birth of performance in reinforced concrete buildings. The 1960 earthquake in Agadir, a resort town in Morocco, wreaked shocking damage on buildings that had been designed to no seismic provisions (Clough 1962). In the interest of countering the undesirable impression that reinforced concrete buildings might be unsuitable in seismic regions, PCA had Blume et al. (1961) produce a book where the importance of deformability for acceptable performance was stressed. Much of the development during the last 30 years that has occurred in the USA has received the support of FEMA, a federal agency charged, along with other duties, with the management of risk from natural hazards. The driving need has been an issue of significant concern to earthquake hazard mitigation specialists in the expected poor seismic performance of older, seismically vulnerable concrete buildings, commonly referred to as non-ductile concrete buildings (ATC 2013). These buildings, which include older construction dating from the early 1900s, were predominantly constructed prior to 1980, after which U. S. seismic codes for concrete buildings were considered to have been improved. While not all non-ductile concrete buildings are hazardous, many have weak, brittle, or incomplete lateral force-resisting systems. These buildings may have gravity-load support systems that cannot accommodate potential lateral deformations or drifts if subjected to strong earthquake ground motions. The position expressed by FEMA (ATC 2012) was that “Performance-Based Seismic Design (PBSD) is a concept that permits the design and construction of buildings with a realistic and reliable understanding of the risk of life, occupancy, and economic loss that may occur as a result of future earthquakes. It is based on an assessment of a building’s design to determine the probability of experiencing different types of losses, considering the range of potential earthquakes that may affect the structure. The first step involves the selection of a desired performance level by a building owner or regulator. Then an input ground motion, scenario event, or earthquake hazard level is selected for which this performance is to be achieved. A designer then conducts a performance assessment, which is intended to determine if the selected performance level is met, or exceeded, at the selected hazard level. In the PBSD process, the building design is then adjusted until the performance assessment indicates a risk of loss that is deemed acceptable by the building owner or regulator.”

Those are fine words, but each of these tasks involves considerable uncertainty. Two hundred years of mathematical theory and a 100 years or more of research and development in reinforced concrete structural systems notwithstanding, our analytical ability to extract a tomographic understanding of how structures will respond to dynamic earthquake effects is still limited. A repudiation of Wilson’s dictum[1] does not appear to be imminent because materials have properties that can only be esti-

[1] Wilson (2000) observes that structural engineering must contend with many poorly known or estimated parameters in its pursuit of creating structures that serve communities in some way.

mated, forces are not accurately known, and structures can only be analyzed approximately. That is a rephrased version of the 25-century old Aristotelian counsel: "It is the mark of an educated mind to rest satisfied with the degree that the nature of the subject admits, and not to seek exactness where only an approximation is possible." The randomness and prior unknown nature of earthquake ground motions emphasize that exact references to return periods in the manner of performing rocket science probably have little credibility.

1.4 Considerations

Engineers need to work with imperfect knowledge much of the time. More often than not, the demands on and the capabilities of a particular structure are not known with the accuracy required by exact analysis. This is primarily why experience drives design, and that is why processes for proportioning, whether they are made into law in codes or whether they reside in text books, comprise an intricate and complex mix of methods. These methods may be categorized in three types:

1. *Methods that explain as well as predict*. An example is the flexural theory of reinforced concrete. If we ignore the flaws at the edges of its domain of application, such as conditions at a plastic hinge or for a very lightly reinforced section, the flexural theory may be considered a well-understood topic that can be used to predict the response of a range of sections with confidence, the range having been defined in the field and in the laboratory. Whether the section is rectangular or circular, its strength can be determined using the same fundamental concepts.
2. *Methods that predict but do not explain*. Examples are proportioning methods used for shear or bond strength in reinforced concrete. They are used with the implicit hope that they can be used to predict capacity but, even in the best instance, their first principles are derived from observation and their results have been calibrated through observations. As such, they do not lend themselves to projection outside of the range of parameters considered in their development. For example, determining the strength of a girder with a circular section from theory calibrated by data from girders with rectangular sections is not a straightforward procedure and requires knowledge over and above that contained within the method.
3. *Methods that neither predict nor explain*. Many of the minima and maxima specified in codes fall in this category. The required minimum amount of shrinkage and temperature reinforcement does not follow from any sort of first principle other than the common sense of having some reinforcement to counteract the probable effects of volume changes.

Most practicing engineers know instinctively in what manner these three types are to be used in design. Above all, they do understand that methods of Type 2 are one-way streets. One uses the method to arrive at proportions that are likely to provide safety and serviceability for the assumed demands. But it would be folly, for example, to use a crack-width expression that may be used to predict a characteristic crack width from a given reinforcement stress to determine reinforcement stress from a crack-width measurement. Minima/maxima included in Type 3 are not methods at all, although they may play a critical role in protecting engineers from themselves.

In the realm of proportioning for earthquake resistance, another layer of gauze, the equivalent static lateral force, is introduced. For proportioning to resist gravity loads, the demand may be exaggerated but it does represent the action. The force to be resisted exists with or without the structure. For earthquake effects, the assumed lateral force is a chimera. It cannot exist unless there is a structure in a state of deformation. Its magnitude depends, among other things, on the strength of the structure. Nevertheless, the tradition to this day in proportioning of earthquake resistant structures has been to initiate the proportioning exercise with a specified base shear. That pivotal beginning tends to lump all three types of methods used in design in the category of those that neither predict nor explain. The approach is pragmatic. It allowed proportioning for earthquake resistance of low- and even moderate-rise buildings without the need to understand structural dynamics at the beginning of the twentieth century. Its remaining in use in the twenty-first century is questionable. Despite the false start with virtual forces, existing methods are able to produce satisfactory structures because there is much experience subtly built into them and because, fortunately, strength is not a critical factor for earthquake resistance of most structures.

Given earthquake intensity, the response of the structure can be sensed from three indices listed below in order of importance:

1. *The ratio of lateral drift capability to height*. The drift-ratio capacity is a measure of the toughness of a structure. It is controlled by a myriad of methods involving all three categories listed above. The object is to avoid brittle failure. Contrary to early understanding, drift capability can be determined explicitly only for monotonically increasing displacement. If displacement reversals into the nonlinear range of response are involved, determination of limiting drift ought to be demoted to Type 2 in the categories listed above.
2. *The ratio of stiffness to mass*. This index value is best expressed in terms of the period for the first translational mode. For regular buildings, it is, without question, the most important index value indicating the suitability of the structure. Because the period is determined either using an expression based on tradition or calculated from a model that is only an approximation of the actual building, one does not expect the period to be actually that of the building. However, the second option is intelligible and can be improved to determine the period of the building quite closely, especially if the s sub-grade is firm and the nonstructural elements are either light or well defined in the model.
3. *The ratio of weight to strength*. The common index value is the ratio of the building weight to the base shear strength. It is appropriate to remember that the base shear strength, even if it is determined from a lengthy limit analysis to establish the minimum or from a so-called push-over routine, refers to an arbitrarily

selected story-force distribution and is not a general strength attribute of the structure. It is also relevant to note that, unless the engineer is especially creative and adventurous so as to maximize the tributary floor area per frame, even modest structures of low to medium height posses a base-shear strength coefficient verging on 10% or more. Daring the arbitrariness of the story-force distribution, the base shear strength coefficient is based on limit analysis, an intelligible procedure for determining the minimum base shear. The method may be classified as Type 1. But the base shear strength of the structure so calculated is not in the same category as the design base shear.

With the above discussion as a background, we enter the realm of Performance Based Design. We do not attempt a definition knowing that it is still in an embryonic state, but we do recognize its two liberating aspects: (1) The basic criteria for the structure will be determined by amicable concordance of a board of stakeholders including, but not limited to, the developer, the insurance carrier, the mortgage carrier (if any), the building authority(ies), the architect, the contractor, and the engineer; and (2) the choice of the framing and sizing will depend on a knowledge-based prediction of building response. The question of concern in this paper is the prediction of building response.

Although addressing an evaluation rather than a design task, the report prepared for the Building Seismic Safety Council by the Applied Technology Council Project 33 (1997a, b) is a comprehensive document that may have all the attributes, general and specific, of the building code of the near future. To capture all aspects of this document in a paper is out of the question. Its flavor is captured by the first ten actions listed in its Table 1.1 (pp. 2–3). The engineer of record, in concert with the owners, insurers, the local building authority, and other stakeholders is to undertake the following tasks:

1. Select Rehabilitation Objective
2. Select Performance Level
3. Select Shaking Hazard
4. Evaluate Other Seismic Hazards [such as geotechnical problems]
5. Obtain As-Built Information Including Historical Status
6. Select Rehabilitation Method
7. Select Analysis Procedure
8. Create Mathematical Model
9. Perform Force and Deformation Evaluation
10. Apply Component Acceptance Criteria

It is evident that the procedure could be applied in design simply by replacing the word “rehabilitation” by the word design and skipping Step 5. In the following, the focus will be on Steps 9 and 10.

The Commentary to FEMA 273 (ATC 1997a, b) provides a lucid picture of what is to be done (Fig. 1.1). Under increasing lateral deformation, the member or structural system goes through several states identified by level of damage. Initially, the

Table 1.1 Timeline for use of static equivalent lateral forces to calculate drift

Year	Source	Period, T	Base shear coeff., C	Base shear, V	Story-force distribution	Amplifier for soil	Cracked section?	Drift limits
1951	Anderson et al. (1951)	$\frac{0.05H}{\sqrt{b}}$	0.015/T	CW	Option A	No	No	No
1959	Blume et al. (1961)	N/10	$\frac{0.05}{\sqrt[a]{T}}$	0.67CW	Option B	No	No	No
1967	SC, SEAOC, (1967)	N/10	$\frac{0.05}{\sqrt[a]{T}}$	0.67CW	Option B	No	No	No
1972	VA 1972	0.08 N	$1.25A_{max}/T$	0.25CW	Option B	Yes	Yes	Note D1
1974	SC, SEAOC, (1974)	N/10	$1/15\sqrt{T} < 0.12$	0.67CSW	Option C	Yes	No	Note D2
1978	ATC (1978)	$0.025h^{0.75}$	$1.2A_vST^{0.67}$	0.14CW	Option C	Yes	No	Note D3
1994	IBC (1994)	$0.03h^{0.75}$	$1.5S/4T^{0.67}$	CW/12	Option C	Yes	No	Note D4
1997	IBC (1997)	$0.03h^{0.75}$	C_v/T	CW/8	Option C	Yes	Yes	Note D5

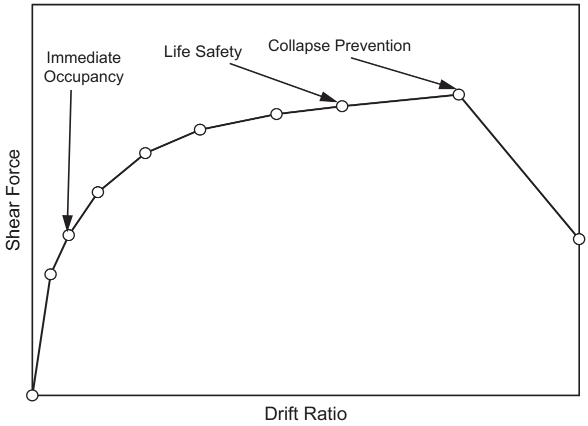

Fig. 1.1 The conceptual pushover curve tool

system responds linearly. Its response is above reproach. Within this range, response can be determined using Type 1 methods.

A certain amount of nonlinearity is tolerated (not defined quantitatively in Fig. 1.1) as indicated by "Immediate Occupancy." At this stage, "…the structure retains a significant portion of its original stiffness and most if not all of its strength." "Significant," perhaps the most insignificant adjective in engineering writing, is not quantified.

At "Collapse Prevention," the building has experienced "extreme damage" and "if laterally deformed beyond this point, the structure can experience instability and collapse." From that, it is understood the building should be stable as long as "Collapse Prevention" is not released, despite the qualifier "extreme" for the damage.

At the life-safety level, "substantial damage has occurred to the structure and it may have lost a significant amount of its original stiffness." Juxtaposing this definition against the definition of "Immediate Occupancy," it may be inferred that the fraction of the original stiffness lost at that stage may be equal to the fraction of the original stiffness remaining at this stage. But that does not help quantify either portion. The only quantitative reference is to the relationship between the useful drift limit and the actual drift limit. It is suggested that if the limiting drift is known, it should be reduced by one fourth to define the useful limit.

The hard and important truth in the softly composed Commentary is that the governing criterion for safety is identified as drift and not strength. It is the engineering equivalent of a revolution. The lines of Section C2.5.1 of the Commentary to FEMA-273 make light, indirectly, of the traditional requirements for a nominal base shear force or equivalent static lateral design forces. The concept has now become so deeply ingrained in the performance-based seismic design lexicon that all later versions of FEMA, Eurocode, and other national codes contain it, albeit expressed in different phrases. No unanimity exists yet for the quantification of these stages or their metrics.

1.5 Review of Drift Demand in U.S. Building Codes

Before attempting a policy for drift determination, it is instructive to make a brief survey of experience with drift, recognizing that engineering confidence depends, to a large extent, on experience.

Both the perceived impact and the anticipated magnitude of drift have changed with time since the 1930s, the time of the first movements in the U.S.A. toward the assembly of professional canons for earthquake-resistant design. Some of the highlights that pertain to drift in the development of model codes for earthquake-resistant design are recorded below.

In organizing the available experience and science on earthquake resistant design, the initial focus of the profession was exclusively on strength. We refer to two publications that capture the perspectives in the U.S.A. of the period from 1930 to 1960: Anderson et al. (1951) and Binder and Wheeler (1960). In the professional consciousness, drift was, besides being negligibly small, a concern related to preserving the investment and possibly to reducing the likelihood of pounding. But it did not impact safety. The attitude was made abundantly clear in the book by Blume et al. (1961), a text that arguably broke much new ground in many respects, that contained the statement, well in keeping with the spirit of the times, "… *lateral displacement is seldom critical in a multi-story reinforced concrete building*" [p. 200] despite the far-seeing suggestion made earlier in the book in reference to ascertaining the likelihood of pounding: "*A less rigorous appearing rule, but one which may in fact be both more accurate and more rational, is to compute the required separation as the sum of deflections computed for each building separately on the basis of an increment in deflection for each story equal to the yield point deflection of that story, arbitrarily increasing the yield deflections of the two lowest stories by multiplying them by a factor of 2*." Despite sensitivity to the contradiction of using a static analysis for a dynamic effect, professional documents have continued to use, exclusively or as an option, static equivalent lateral forces to calculate drift, although this process has taken different turns and magnitudes as summarized in Table 1.1. More recent code versions of the information in Table 1.1 are not easy to summarize in tabular form.

Notation and annotations for Table 1.1

T: Period
H, h: Total height
W: Total weight
N: Number of stories
A_v: Coefficient reflecting response in the range of nearly constant velocity response
C_v: Coefficient reflecting response in the range of nearly constant velocity response and varying with site characteristics
S: Coefficient reflecting site characteristics

Notes on Requirements for Drift Control for Table:

D1

The VA Code (VA 1972) used different factors for force and drift. For example, while the force reduction factor was ¼ for "ductile moment resisting" frames with light and flexible walls, the amplifier for the calculate drift using the reduced force was set at 3. In addition, the VA Code required that the stiffness of reinforced concrete frames be based on "cracked sections." The drift-ratio limit was set at 0.8%. The limit was reduced to 0.26% for frames encasing brittle glass windows.

D2

In 1974, the limiting story-drift ratio was set at 0.5%. In addition, the lateral force was amplified by 1/K, where K = 0.67 for properly detailed frames.

D3

Similarly to what was done in the VA Code, the ATC-3 Model Code recommended a force-reduction factor of 7 for shear in reinforced concrete frames and an amplification factor of 6 for deflection. It is interesting to note that these factors were set at 8 and 5.5 for steel frames.

D4

Calculated story drift ratio (for the reduced force) for a ductile frame shall not exceed 0.33% if the period is less than 0.7 s and 0.25% otherwise.

D5

Story drift ratio to be determined for the reduced force but then amplified by 70% of the force-reduction factor and to be limited by 2.5% for frames with calculated periods less than 0.7 s and by 2% for frames with higher periods.

Option A

$$F_x = V\frac{w_x h_x}{\Sigma\left(wh\right)}$$

F_x = lateral force at level x
w_x = weight at level x
h_x = height of level x above base
V = design base shear

Option B

$$F_x = \frac{\left(V - F_t\right)w_x h_x}{\sum_{i=1}^{n} w_i h_i}$$

$$F_t = 0.004V\left(\frac{h_n}{D_s}\right)^2 \text{ if } \left(\frac{h_n}{D_s}\right) > 3, \text{otherwise } F_t = 0.$$

F_i, F_x = lateral force at level i, x
w_i, w_x = lateral force at level i, x
h_n, h_i, w_x = height to level n, i, x
V = design base shear

Option C

$$F_x = \frac{\left(V - F_t\right) w_x h_x}{\sum_{i=1}^{n} w_i h_i}$$

$F_t = 0.07TV < 0.25V$ and $F_t = 0$ if $T \leq 0.7$ s

F_i, F_x = lateral force at level i, x
w_i, w_x = lateral force at level i, x
h_n, h_i, w_x = height to level n, i, x
V = design base shear

Table 1.1 contains different expressions for the base shear that has shown changes in relation to the coefficient representing the earthquake action but it provides a narrow perspective of professional opinion in the USA with respect to drift. It is compiled in reference to a specific structure, one that may be considered to be a seven-story frame with an infinite number of spans so that its response can be understood in terms of a tree as shown in Fig. 1.2. The structure is assumed to have the appropriate details to qualify as a special moment-resisting frame. Its calculated period is a little less than 0.7 s. All requirements included in Table 1.1 refer to a frame of seven stories with a calculated period barely less than 0.7 s.

The report by Anderson et al. (1951) implied that the drift should be calculated by using the lateral forces selected for design but provided no guidance as to what to do with the results. The decision was left to "engineering judgment," a sign that may be taken as the precursor of Performance Based Design. The 1959 issue of the Blue Book (SEAOC 1959) introduced the sensitivity of the design shear force to the type of framing. For the selected frame, the coefficient was 0.67. The nominal period for a frame was set at O.l N, where N is the number of stories. Distribution of the lateral forces over the height of the building was made linearly proportional to mass and height, the "linear distribution."

In 1972, the code developed by the Veterans Administration (VA 1972) was a landlord's code and set high standards in new directions. The design base shear coefficient was increased. It was made a function of the specific site. By itself, that is not so significant, because it can be reduced in the next step that involves the reduction of the design force. However, the Veterans Administration Code also prescribed a modest "response reduction factor" of 4 for ductile frames and an amplifier of 3 for the deflection obtained using the design shear. In addition, the designer was asked to use cracked sections in determining the stiffness of the structural elements of reinforced concrete. The drift requirement was increased substantially.