

## The Development and Fundamental Principles of Seismic Building Codes\*

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### Abstract

Reviewed here is the conception, development and refinement of seismic codes intended to provide the minimum safety for all components of the built environment.

**Keywords:** building codes, safety standards, response spectrum and history methods

### 1. Introduction

Selected key elements of modern seismic codes are reviewed here, along with a brief review of their historical development. What can be considered a single seismic code pertaining to a nation or a subdivision thereof consists of dozens of pages of provisions, and by reference includes thousands of pages of standards that relate to loads, testing procedures, manufactured building products, and materials. As used in this general discussion, "code" includes these other documents. Thus, it is far beyond the feasible scope here to provide an encyclopedic review of current seismic codes. Instead, we attempt to delineate key features of most modern seismic codes and trace the development of their underlying concepts as they have evolved through the decades.

Preparing a global review of seismic codes runs the risk of turning out to be country-specific and omitting other important references or milestones. This chapter will attempt to avoid that. Instead we will describe what a code should look like, and what its important elements should contain. A building code places legal requirements on designers and constructors. Codes that fail to keep up with technological change and the advancement of knowledge become irrelevant. Building codes must be revised frequently, often at about three-year increments. As more earthquakes occur and related building performance is observed, and as more research is conducted, the seismic provisions of a code often are one of the sections that change the most from one edition of a building code to the next.

The main purpose of building codes is to protect public health, safety, and general welfare as they relate to the construction and occupancy of buildings and structures. The building code becomes law of a particular jurisdiction when formally enacted by the appropriate governmental or private authority. The parts of a building code that relate to special requirements that must be fulfilled in order to inject a desired level of protection against the effects of ground shaking are called a seismic code. This broad description applies also to other types of construction, e.g., bridges, water tanks, towers, and port facilities. There are often additional codes or sections of a building code that have more specific requirements that apply to particular occupancies, for example providing simplified requirements for the typical dwelling and more extensive requirements for the school, theater, or hospital.

## **2. Overview of Model Codes**

A model building code is a convenient resource that can be adopted by the appropriate public authority as its legal requirement. This makes the cost of maintaining and updating a code more economical and also provides 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 materials 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.

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 the 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 significant variations, is left to the states 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 small 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 materials industries are guided by consistent provisions.

## **3. Prescriptive and Performance-Based or Objective-Based Codes**

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 inter-story drift and then design concrete cladding to accommodate that building-specific distortion. In recent years there has been a move amongst many building codes to move to 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 test 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 buildings codes. Rather than prescribing specific details, objective-based codes lists 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 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.

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 centers or 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. Some voluntary above-code ("performance-based design") approaches lead an owner to invest in the cost of greater 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.

#### **4. Geologic and Geotechnical Topics**

Mentioned briefly here are geologic and geotechnical engineering aspects to the seismic provisions of a building code. Construction regulations that deal effectively with earthquake vulnerabilities must include within their purview geologic hazards such as surface faulting and liquefaction. Geologic and geotechnical engineering provisions to deal with those hazards came later than structural provisions. In 1972, the state of California passed the Alquist-Priolo Fault Zoning Act (the current name, which has changed over the years), and slightly before that the city of Portola Valley, which is bisected by the San Andreas Fault, passed its own legislation. Surface fault zoning is the most clearly delineated of the earthquake ground failure hazards, and thus it was logically the first to be subject to regulations. Liquefaction was not a word that soils engineers (then the term for geotechnical engineers) used prior to the 1964 Alaska and the closely following 1964 Niigata Earthquake, but in the following decades, areas of a jurisdiction that were suspect in terms of poorly compacted granular soils and high water table were frequently zoned as requiring special geotechnical investigations. Geotechnical engineers now have at their disposal field and laboratory investigation techniques and a knowledge base about how soils behave in earthquakes that did not exist in the 1960s. Codes and standards of practice can now require geotechnical evaluations that would have been impossible to perform a few decades ago.

One tool that developed out of non-seismic slope stability concerns that later was seen to have a seismic benefit is the grading ordinance. The city of Los Angeles passed such a law in 1952 controlling how excavation and cut-and-fill could be performed. Such ordinances have become common, and the geotechnical engineering evaluations required in the design stage now typically include earthquake considerations in regions where a seismic code is enforced.

#### **5. Non-structural Code Provisions**

Coming later than structural regulations were provisions to protect the nonstructural features of a building. The first detailed report on an earthquake's nonstructural damage was done for the 1964 Alaska Earthquake (Ayres et al. 1973a), with a similar report on the 1971 San Fernando Earthquake (Ayres et al. 1973b). Nonstructural provisions are only briefly mentioned here, but are an essential part of the modern seismic building code. Approximately three-quarters of the initial value of a building's construction is composed of nonstructural components, such as enclosure systems, elevators, partitions, fire sprinklers, ceilings, and heating-ventilating-air-conditioning equipment. In general it can be said that the leading seismic codes of the world have increasingly included more and more detailed regulations for the calculations of loads that are used to design nonstructural bracing and anchorage, but we still see a lack of coordination of the implementation of these rules. Different design professionals work on their own systems – architects on partitions and ceilings, fire protection engineer on fire sprinkler system, mechanical engineer on the HVAC system, and so on, and yet it is the structural engineer with the most expertise for such work. And then different contractors and trades work on the

implementation phase, often with little guidance or oversight. Recent earthquakes have demonstrated that simply having nonstructural damage protection rules on the building code's books is not sufficient to actually protect that myriad of components. A common example is that some codes for many years have contained a clause stating that nonstructural components must be designed for the motions and deformations that the structure imposes upon them, but in actual practice, partitions and other components were constructed without this engineering.

## **6. Historic Context**

Some accounts of historic building code evolution claim that the Code of Hammurabi (a Babylonian king of some 3800 years ago who was considered by his subjects to be a god as well) engraved on stone is the first building code ever to have been put into effect. We wish to dispute that notion because the Code of Hammurabi is much more of a civil or penal code as it has only a few articles out of several hundred that even mention buildings. It has harsh penalties for builders of shoddy buildings, but the rest of the provisions are divine orders that deal with the trade of commodities, sale of slaves, marriage unions, inheritance regulations and the like. King Hammurabi informs a builder that if the house he builds should collapse and kill the person who owns it, then he too stands to lose his life, but there is no explanation for how one might build a house that does not collapse. Thus it fails the test of belonging to the family of codes because it has no stipulations for how things should be done; only penalties are listed that must have been intended to discourage negligence of good building practices.

Tobriner (1984a) provides a historical survey of the development of building codes, noting that they originated primarily in the form of fire-resistant construction requirements, and then only much later in most countries had seismic regulations 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 two 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 American cities. In Paris, under the reconstruction of much of the city by Baron Haussmann during the Second Empire (1852–70), great blocks of apartments were erected, and the height of buildings was limited by law to five or six stories at most. 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.

### *6.1 Construction Regulations Preceded Engineering Regulations*

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 1880 Luzon (Manila) Earthquake, 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, they 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 the 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 Pombalino system was not based on what today would be known as rational methods of analysis, applying engineering theory to a given case and calculating loads and resistances. It was an attempt at earthquake-resistant construction, not earthquake engineering per se, because the engineering techniques of the nineteenth and twentieth centuries were far off in the future. It was decreed in royal fashion for use in a city that had experienced one of the most destructive earthquakes in Europe, and was based on the construction tradition in the Mediterranean basin and may have borrowed construction lore developed by shipbuilders. It was used on the interior of buildings that consisted of timber frames with vertical and horizontal timbers of approximately 10 cm to 12 cm square, with internal braces, forming an “X,” referred to in Italy and Portugal as the “Cross of St. Andrew.” The timbers for the cross were 9 cm by 11 cm in section. The frame was then “nogged” (i.e., filled with brick) in the triangular spaces formed by the crosses with a mixture of stone rubble, broken brick, and square pieces of Roman brick in different patterns in each panel. The interior walls were then covered with plaster, hiding the infill and the timber frame. The exterior facades of the Baixa buildings were reconstructed with load-bearing masonry walls of about 60 cm in thickness, some of which had a timber frame on the inside face (Gülkan and Langenbach (2004).

The 1906 San Francisco Earthquake was something of a non-event in the history of seismic codes. Although the cause of the earthquake was accurately noted -- the San Andreas Fault had been mapped in several areas before the earthquake and its surface rupture was well documented afterward -- and although civil engineers trained in universities were in existence, no engineering consensus existed around provisions that would define how to calculate loads and then calculate the lateral resistance of a structure. Unreinforced masonry was not prohibited, and by the time the city took stock of its unreinforced masonry building seismic hazards in the 1980s, over 90% of the 2,000 buildings that required retrofits were dangers that were built after the earthquake, not before it. The San Francisco building code even reduced the wind load a few years after the earthquake. In that era, the wind load was sometimes thought to be a surrogate for seismic load.

A few years later, after the 1910 Cartago Earthquake in Costa Rica, a national code was passed that phased out adobe and trapia (rammed earth) structures, substituting bahareque construction (sawn lumber or bamboo framing with plaster). This was a similar but more regulatory approach to the substitution of wood for masonry that occurred in construction styles after some other earthquakes, such as the 1855 Wairarapa (Wellington, New Zealand) Earthquake.

## *6.2 The First Seismic Codes with Engineering Content*

Soon after the 1906 California earthquake, the 1908 Messina-Reggio Earthquake occurred in southern Italy, but it had a different and more beneficial impact on building codes. Sorrentino (2007, 2011) relates how a committee of engineers developed an equivalent lateral force analysis method that was adopted into the building code of the disaster region. It even had the refinement of applying a different lateral force coefficient (rapport

sismica) to the ground story (1/12) than the story above (1/8), accounting for greater acceleration in the second or third stories. After the 1915 Avezzano (or L'Aquila Earthquake), the code was changed to have factors of 1/8 for the ground story and 1/6 for the upper stories. These Italian seismic provisions applied only to the area affected by the earthquakes, a pattern that was common in early codes prior to the availability of national maps depicting the hazard of seismic ground shaking.

At the turn of the nineteenth-twentieth century, Riki Sano was getting his PhD from the University of Tokyo on "Seismic Design Concept for Building Structures," and along with Tachu Naito, his student, Sano was to be instrumental in the development of the Japanese equivalent lateral force method. Their work came to fruition after the 1923 Great Kanto or Tokyo Earthquake of 1923, when the 1924 Urban Building Law Enforcement Regulations were passed. It used a 10% lateral force factor (shindo) applied uniformly up the height of the building. As an example of how engineering practice in some cases is in advance of the codes, when the 1923 earthquake occurred, three large buildings designed by Tachu Naito had already been built (and performed well in the earthquake, giving the new equivalent lateral force method a boost into the code).

An important threshold was crossed in Japan toward the implementation of scientifically determined national seismic provisions (Otani 2008). The objectives of the Japanese Building Standard Law, proclaimed in May 1950, were "to safeguard the life, health, and properties of people by providing minimum standards concerning the site, structure, equipment, and use of buildings." The law outlined the basic requirements, and the technical details were specified in the Building Standard Law Enforcement Order (Cabinet Order) and in a series of Notifications by Minister of Construction.

The seismic design provisions of the Building Standard Law Enforcement Order were significantly revised in 1981; major revisions in seismic design were listed below:

(1) Structural calculation is required to examine (a) maximum story drift under design earthquake forces, (b) lateral stiffness distribution along the height, (c) eccentricity of mass and stiffness in plan, and (d) story shear resisting capacity at the formation of a collapse mechanism,

(2) Earthquake resistance is specified (a) in terms of story shear rather than horizontal floor forces, (b) as a function of fundamental period of a building and soil type, and (c) separately for the allowable stress design and the examination of story shear resisting capacity, and

(3) Required story shear resisting capacity is varied for construction materials and with the deformation capacity of hinging members under earthquake forces.

The framework of the law was also significantly revised in 1998, (a) introducing performance-based regulations wherever feasible, (b) allowing private agencies to execute the building confirmation and construction inspection works, (c) deregulating urban land use, and (d) allowing public survey of design and inspection documents. New technical specifications in the form of the Law Enforcement Order and a series of Notifications of Minister of Construction were issued in June 2000, including the definition of performance objectives at design limit states and the specifications for verification methods.

California's contribution to the development of the modern seismic code based on engineering calculations had a small start after the 1925 Santa Barbara Earthquake, and then after the 1933 Long Beach Earthquake statewide regulations were passed that was derived from the Japanese code. The 1930s was the decade when the lineage of seismic codes in several countries began. Provisional earthquake regulations were enacted in Chile in 1930 after the Talca Earthquake and became more institutionalized after the 1939 Chillán Earthquake. In New Zealand, following the 1931 Hawke's Bay Earthquake, the 1935 New Zealand Standard

Model Building By-Law included earthquake regulations. India adopted its first seismic code in 1935 following destructive earthquakes in 1931 and 1935 in Quetta (now part of Pakistan). And the 1939 Erzincan Earthquake in Turkey led to its first engineering regulations for the earthquake hazard.

### *6.3 Equivalent Static Elastic Lateral Force Method*

A seismic load on a building is actually dozens of different significant seismic loads that occur during the 20 to 60 seconds during which the ground is strongly shaking. The earliest practical way to "put a number" on that bewildering set of loads, which are not well-known in advance of the earthquake, was to represent the worst loading effect as a percentage of the weight of the structure, recognizing that seismic shaking causes inertial loads, and inertia is a product of mass and acceleration. The full descriptive name of the method is the equivalent static elastic seismic lateral force analysis method. It is intended to be equivalent to or adequately represent the actual earthquake forces; the method computes a single static force to represent the changing dynamic forces; that force is applied to an analytical structural model that remains elastic, even though inelastic behavior obviously occurs; and it is an analysis method for determining only the design loads, not for distributing them through the structural components and connections that provide the resistance to the loads. And finally, the only design loads were lateral or horizontal, whereas strong motion records routinely measure some vertical motions as well. Each of these limitations was to be worked on in the following decades. From these first incarnations, the equivalent lateral force method was refined to include several necessary considerations.

Instead of applying seismic regulations to a region after it had an earthquake, earth scientists compiled maps showing where earthquakes should be expected. This was first done with a small number of large-scale zones for a country, each zone defining the force factor to be applied. Then beginning in the 1950s in Japan, a probabilistic basis to the maps was developed, Kawasumi (1951) developed three maps, depicting the shaking that should be expected to occur in exposure periods of 75, 100, and 200 years. The Applied Technology Council in its ATC-3 document (Applied Technology Council 1978) included national maps produced by S.T. Algermissen that had a probabilistic basis. In China in 1977 a national seismic design map was based on shaking with 3% and 10% probabilities of exceedance. Formats such as these for tying the probability of occurrence to the severity of shaking have become standard in seismic codes today. Another refinement has been microzonation: zoning small areas as having different ground shaking severities, or ground failure hazard (e.g., liquefaction), based on local soils. It became increasingly known that in general soft soils amplified ground shaking, though the large differential response between soft and hard ground as measured in low-level shaking was not found to be linear up through high levels of ground motion: a column of soft soil 30 meters high simply can't move back and forth rapidly enough to track rapid and severe motion of the underlying strata, and soil can behave nonlinearly just as structural materials do. The limiting case of microzonation is the site-specific evaluation, where the construction to be placed on a site is designed for a customized set of earthquake criteria, a more expensive approach usually reserved for major facilities.

On the structural side, knowledge of different structural systems and materials had to evolve for codes to seismically regulate them, and a growing body of structural laboratory research provided that information. The steel and concrete industries in particular were the settings for a large amount of research conducted in the 1950s and later. Research on reinforced concrete in great part conducted at the University of Illinois was the technical basis for an important document that advanced the use of that material in seismic codes (Blume et al. 1961). The other kind of research that provided this knowledge was actual earthquake performance. Earthquake reconnaissance or field surveys of the effects of earthquakes became increasingly common in the 1960s.

The early codes provided loads computed with a slide rule that were low enough to keep the structural model that was on the engineer's drawing board in the elastic range. (Computers did not become widespread in seismic design or other civil engineering practice until the 1970s). Slowly, inelastic behavior was included in codes by including requirements for ductility. Classifying structural systems and materials was an approximate first approach. A structure thought to have greater ductility was designed for lower elastic-level forces, because there was confidence in how it would perform when pushed into the inelastic range. The ability of ductile connections and members to absorb punishment without failure, and also the softening effect (period lengthening) and its beneficial effect on response, became increasingly recognized in the 1960s, 1970s, and 1980s. Today, the choice of structural system is heavily influenced by how the code defines its ductility. Seismic structural codes are all aware that ground motions are random, and can be determined only approximately in advance. For this reason their requirements are expressed in such a way that unexpected surprises do not lead to catastrophic failures. Lessons that have been taught by past earthquakes for how building components behave under ground shaking are embedded in their verbiage. As theory and experiment combine to lead to more refined ways of seismic protection they must be incorporated into the newer versions of codes for continuous improvement.

## **7. The Response Spectrum Method**

Yet another improvement in seismic codes was consideration of the dynamic properties of the structure, its period or periods of vibration and the amount of damping. The tendency of the structure to respond at its natural frequency was only useful information if the frequency content of the ground shaking was also known: in structural dynamics, it takes two to tango. Because the first strong motion seismograph (accelerograph) was only deployed in 1932, it took years for records to accumulate to provide a statistical picture of earthquake severity in terms of frequency content. Trifunac (2006) traces the history of the response spectrum method of analyzing earthquake ground motions and producing design spectra that engineers could use to proportion required resistance of the structure. Two of the most influential developers of the method were Maurice Biot and George Housner, whose doctoral theses at the California Institute of Technology (1932 and 1941, respectively) were devoted to this topic. The theory became widely applied in engineering practice in the 1970s and 1980s when several conditions were favorable. First, there were more earthquake records. Second, engineers could afford to have the new, more powerful electronic computers on their desks that could do the extensive mathematical work. Housner (1997, p. 33) notes a third factor: "Because of the practicing engineers' reluctance to employ the design spectrum, I think it was essentially the nuclear power business that got the spectrum into widespread use."

Concerning the growing number of earthquake records, the City of Los Angeles played an important role when it passed a revision to its building code in 1965 requiring that three strong motion instruments be installed in buildings six stories or taller (one at the base, one at mid-height, one at the roof). This resulted in the large harvest of ground motion and structural motion records from the 1971 San Fernando Earthquake. The City of Los Angeles also was precocious in its 1943 adoption of a formula in its code that related period of vibration as represented by number of stories to the base shear coefficient calculation in its equivalent lateral force method: the taller the building, the lesser the base shear. In 1957, Los Angeles also had a strong effect on the development of earthquake codes, even though it was not an earthquake code revision: the zoning code was revised to allow buildings taller than 150 feet. Engineers in California thought that taller, more flexible (longer period) buildings could be designed for lower force coefficients, and they also knew that if the same coefficients as were used for low-rise buildings (typically 10% to 13%) were applied to every story in a tall building, the large amount of strength, and thus area taken up by shear walls and other structural material, would have very negative architectural and real estate implications.



When it seemed that engineers in the two large urban regions of California, centered on Los Angeles in the south and San Francisco in the north, could be diverging toward significantly different provisions for dealing with the tall building question and the modernization of seismic codes, the statewide structural engineering organization, Structural Engineers Association of California (SEAOC) began its influential set of editions of the "Blue Book," the Recommended Lateral Force Requirements and Commentary (SEAOC, 1959). Its requirements became the seismic provisions of the Uniform Building Code used in various editions and adaptations throughout California and the Western United States until the year 2000 when the UBC was folded into the IBC, as previously described.

## **8. The Response History Method**

The equivalent static lateral force method leads the engineer to calculate a single quantity, the total shear at the base of the building, the base shear, and then proportion that load up the height of the structure according to procedures that attempt to represent the dynamic response of the building in a simple way. While there is dynamic thinking underlying the method, it still represents the series of motions that occur during the earthquake with a static view or "snapshot" of the overall effect of those motions. The response spectrum method similarly is a way to give the engineer a base shear to use in design. A given overall representation of one record, for example, the peak ground acceleration, might exceed that of another record and yet that other record might be more damaging to a particular structure. A record with greater duration, more pulses above a threshold such as the elastic limit of a portion of the structure, can create more demand than a record of smaller duration, even if the latter has a greater peak value (Johnson, 2013). The logical improvement was seen to be to calculate the various forces and deformations that occurred to a structural model split second by split second in response to the changing ground motion.

Three sources of research information that developed from the 1960s to the present day provided the basis for incorporating a fully dynamic method into seismic codes, subjecting the analytical model of the structure to the motions of several recorded earthquakes. One came from completely outside the earthquake engineering field, the development of the modern computer. A second prerequisite was a large library of earthquake records, conveniently supplied by growing coverage of highly seismic areas with strong motion instruments and, unfortunately, by Earth's frequent earthquakes. The third was improved knowledge of structural behavior, in particular of how structures behaved in the inelastic range. While computers played a role in that research on structural behavior, it has also required the traditional approach of subjecting specimens to simulated seismic loading in the laboratory. Computer simulation is not capable of substituting for the simulation of physical testing.

A 1973 benchmark for the development of the response history method is provided by the seismic design manual of the US military (Departments of the Army, the Navy, and the Air Force 1973, p. 3-3): "Since the mechanics of dynamic analysis requires that a separate solution must be obtained for each instant of time during the entire history of interest, computation by computers is necessary. This kind of analysis is generally beyond the kind of effort that can be afforded in the design of almost all but the most critical structures." Today, the method is more frequently used, though it still is applied to a small minority of all the structures being seismically designed. Chopra (2005, p. 107) provides an assessment of the future of the method:

At the present time, nonlinear RHA [response history analysis] is an onerous task, for several reasons. First, an ensemble of site-specific ground motions compatible with the seismic hazard spectrum for the site must be simulated. Second, despite increasing computing power, inelastic modeling and nonlinear RHA remains computationally demanding, especially for un-symmetric-plan buildings—which require three-dimensional analysis to account for coupling between lateral and torsional motions—subjected to two horizontal components

of motion. Third, such analyses must be repeated for several excitations because of the wide variability in demand due to plausible ground motions, ... and the statistics of response must be considered. Fourth, the structural model must be sophisticated enough to represent a building realistically, especially deterioration in strength at large displacements. Fifth, commercial software is so far not robust enough to predict response with high reliability. Sixth, an independent peer review of the results of nonlinear RHA is required by the FEMA-356 guidelines, adding to the project duration and cost. With additional research and software development, most of the preceding issues should be resolved, and nonlinear RHA may eventually become the dominant method in structural engineering practice.

## 9. Growth in Adoption of Seismic Codes

Figure 1 provides a quick way to see how seismic codes have spread from an initially small number of countries. The numbers are drawn from the various editions of *Regulations for Seismic Design: A World List*, published by the International Association for Earthquake Engineering (1960 and later editions).

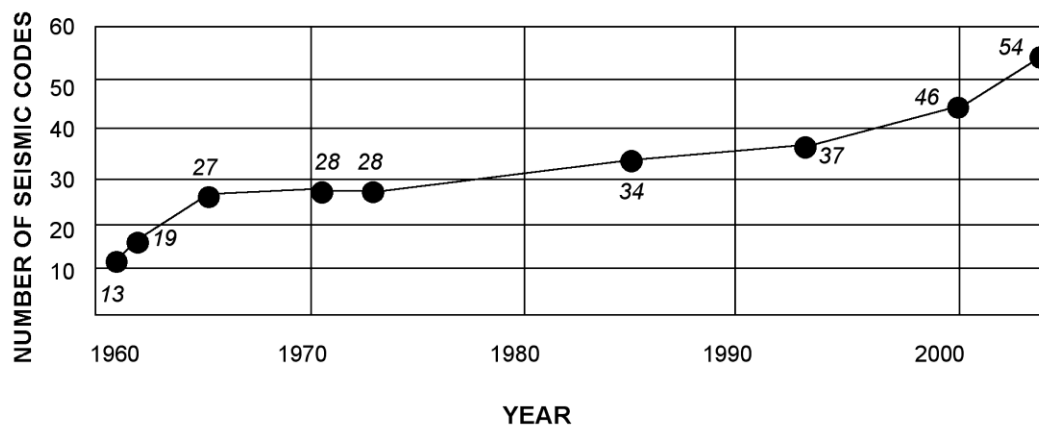


Figure 1. Growth in the Adoption of Seismic Codes  
(Reitherman 2012, p. 582)

One could argue that because seismic codes now cover most of the significantly seismic areas of the world, seismic safety has now been achieved on a global scale. This would be overly optimistic for two reasons. First, there are always older, pre-code buildings that did not benefit from a modern seismic code. Secondly, even today in countries with regulations “on the books,” legally binding laws that include the latest earthquake engineering thinking, those regulations are not always thoroughly carried out.

The seismic provisions in a code must be complemented with reliable implementation of the code, its effective enforcement. This remains one of the hardest issues to solve, especially in poorer countries but also in the most developed. Merely making seismic codes more sophisticated as each new edition is promulgated every few years is not a solution, unless comprehensive implementation also occurs. This includes the education and professional training of the engineers and other design professionals involved as well as the thoroughness of the quality control measures of building regulation agencies, such as in the plan review and construction inspection phases. In some instances, the comprehensive protection that the provisions in a building code seem to provide exist mostly on paper. Up until the 1990s, even the most advanced seismic codes listed only a few specific

nonstructural components that needed anchorage and then added a general phrase such as “all other equipment and machinery.” That sounds comprehensive, but in the absence of a well-defined definition of that all-encompassing phrase, it was not particularly meaningful. Another example is the accurate calculation of interstory drift, which in some codes was seemingly covered many decades ago but in practice was not well-implemented in standard practice. The engineer who diligently tried to meet that code requirement had inadequate analytical tools available because of the lack of underlying knowledge of the displacements that would actually occur. Conversely, some engineers incorporated design measures that were only required by the code much later. In the words of George Housner (1986 p. 25), “in some instances, earthquake requirements were adopted in building codes but were not used by architects and engineers. And in other instances earthquake design was done by some engineers before seismic requirements were put in the code.”

## 10. Summary

Model building codes are common around the world, although the consistency with which they are applied throughout a jurisdiction can vary greatly. In New Zealand and Japan, there is a high degree of consistency in how a nationally standardized set of seismic provisions are adopted and enforced at the local level. In India and the United States, there is greater variation. Seismic provisions in model building codes are usually a combination of prescriptive and performance-based procedures. Seismic provisions in building codes evolved from the earlier building codes that were typically motivated by concern over fire resistance and urban conflagrations. The first seismic regulations governed construction characteristics such as wall material or number of stories, but because they preceded civil engineering developments of the 1800s and 1900s, they lacked quantitative methods for calculating loads and capacities. In the early 1900s, the first seismic codes based on engineering methods were developed in Japan and Italy. The equivalent static elastic lateral force method originated in these codes. By the 1930s, seismic regulations based on the equivalent lateral force method were adopted in New Zealand, USA, Turkey, India, and Chile. Later, as earthquake engineering research accumulated, as strong motion records were collected, and as powerful and inexpensive computers became available, the response spectrum and the response history methods were added to the modern building code's seismic provisions. A fundamental problem in reducing earthquake risks through adoption of up-to-date building code provisions is enforcement and implementation. While the problem is most prominent in poorer countries, it is also an issue in the most technologically advanced areas of the world.

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