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THE EVOLUTION OF SEISMIC DESIGN PROVISIONS OF U.S. BUILDING CODES

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ABSTRACT

Relative to most seismically active regions of the world, the U. S. has a short recorded history of earthquakes damaging to the built environment. However, frequent damaging events, particularly in California, have provided impetus for the steady development of seismic protection policies and technical regulations officially beginning with the 1927 Uniform Building Code. Although the San Francisco earthquake of 1906 created an infrastructure of technical interest groups and improvements to building design on an individual building scale, the earthquake in Santa Barbara in 1925 created the critical mass to produce seismic provisions for the building code, although it was initially optional. Trends in the general philosophy of U. S. seismic provisions are tracked by studying the evolution of performance objectives, either implied or stated.

Introduction

A detailed history of the evolution of seismic provisions in U. S. Building Codes, including the development processes used, the technical background, and the provisions themselves, is already contained in the literature. An Annotated Bibliography is included at the end of this paper describing much of this documentation. Of particular interest is the Theme Issue: Seismic Design Provisions and Guidelines, of Earthquake Spectra (Hamburger and Kircher, 2000) published in February, 2000, that describes in great detail the history and development of most aspects of U. S. seismic provisions. Table 1 summarizes code development in the U. S. with a list of milestones. Details of each milestone can be found in one or more entries of the Annotated Bibliography. The table begins with several entries from outside the country to give context to developments in this country. The first documented written provisions (written provisions as opposed to the practice of simply revising construction practice due to failures), were developed in Portugal and Italy and are similar descriptions of masonry reinforced with wood framing. The first suggested design for lateral forces proportional to weight was in Italy and used 1/12 the weight of the building--not at all unlike current provisions.

Although code officials and engineers were aware that seismic provisions in the code were possible and probably appropriate before the 1925 Santa Barbara earthquake, that event led to development of the first provisions in this country, an appendix in the 1927 Uniform Building

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Code (UBC). The code did not change appreciably until the forties, when dynamic concepts were developed for practical use. The SEAOC Bluebook (SEAOC, 1996) was first published in 1959 and the "modern" era of codes began in 1961 when the UBC adopted the Bluebook provisions.

Table 1. Summary history of U. S. seismic code development (adapted from Holmes, 1998).

Year	Event
1667	1666 fire in London causes first comprehensive and enforced building code
1755	Lisbon: First seismic provisions-prescriptive detailing called *gaiola*--due to 1755 event
1783	Calambria, Italy: series of events results in *la casa baraccata*--prescriptive detailing
1906	San Francisco earthquake: notable for lack of subsequent code action
1911	Messina, Italy earthquake: Resulting from observations, designs starting using lateral forces of 1/12 W
1923	Kanto, Japan earthquake: Confirmed to Japanese that design for about 10% W was satisfactory
1925	Santa Barbara earthquake galvanizes need for seismic requirements for buildings in the U. S.
1927	First UBC provisions (probably based on Japanese recommendations) require 7.5% (10% at poor soils)
'28-29	SEAOSC and SEAONC are formed, primarily due to earthquake design issues
1931	Professor Suyehiro of Japan is guest lecturer in the U.S. and confirms Japanese recommendations
1932	J. R. Freeman's book, *Earthquake Damage and Earthquake Insurance*, published
1933	Long Beach earthquake; Field Act (schools) and Riley Act (most other buildings) in CA. are passed
1943	LA Building Code adopts first provisions in US based on height or flexibility of building
1952	ASCE's "Separate 66" (SEAONC/ASCE) published: forces proportion to 1/T
1959	First SEAOC "Bluebook" published--to reconcile SEAONC and SEAOSC positions
1961	Uniform Building Code (UBC) begins to adopt Bluebook Provisions
1971	San Fernando earthquake damage suggests changes are needed in codes resulting in ATC 3 project.
1976	UBC has significant increases in basic design force levels (based on San Fernando data)
1978	ATC 3-06 published introducing formula relating design forces to "real" elastic response
1979	BSSC formed to provide ongoing support for ATC 3 and to nationalize seismic code provisions.
1985	First NEHRP Provisions published--resulting from initial review of ATC 3-06
1988	SEAOC converts to "R Factor" format (from ATC 3) but maintains working strength design basis
1989	Loma Prieta earthquake: Issues of acceptable performance identified by public
1994	Northridge earthquake surprises by severely damaging several "modern" building types
1995	ICBO, SBCCI, and BOCA join to form the International Code Council (ICC)
1997	1997 UBC converts to ultimate strength R factor level, introduces near field factor for ground motions..
1997	1997 NEHRP Provisions adopt contoured hazard maps of spectral ordinates and introduces MCE
2000	2000 IBC, published by the ICC, contained the primary seismic model code in the U. S.
2003-5	ASCE 7 begins to adopt recommendations of NEHRP Provisions, becomes accepted alternate in IBC 2003
2005	IBC 2006 adopts ASCE 7 as its standard for seismic loading and system classification provisions
2003-07	Next Generation Attenuation (NGA) relationships developed by PEER
2009	NEHRP Provisions Update Committee adopts recommendations for use of NGA and risk targeted hazard
2009	ASCE 7 committees adopt hazard mapping methodology recommended by NEHRP

Significant input to code development was obtained from the 1971 San Fernando earthquake resulting in development of a completely new set of design provisions as published in

ATC 3-06 in 1978. ATC 3 led to creation of the nationally oriented Building Seismic Safety Council and the NEHRP (National Earthquake Hazards Reduction Program) Provisions, intended to eventually integrate the ATC 3 recommendations into codes. Both the Blue Book/UBC and NEHRP Provisions continued to develop, culminating in 1997 editions that are quite similar. In the year 2000, the International Building Code (IBC), was published by the International Code Council intended to provide the country with a unified model building code. The seismic provisions were based on the 1997 NEHRP Provisions. By 2005, a seismic code development process had evolved in which the recommendations of the NERHP Provisions were generally adopted into an American Society of Civil Engineers (ASCE) Standard, ASCE 7, which was in turn adopted as a recognized standard by IBC.

Evolution of Performance Objectives for U. S. Seismic Design Provisions

(adapted from Holmes, 2008)

Background

A devastating fire in London in 1666 resulted in the first comprehensive building code enforced by government. Its purpose was clearly and narrowly framed to prevent another such disaster. Government control of design and construction--focused on buildings--gradually spread throughout the world largely based on the London precedent. However, each country has its own, often unique, history and legal authorization for building code development and implementation (Meacham, 2004).

In the U.S., an important principle of the Constitution, resulting from the original compromises concerning federal and state control of government, is the delegation of police power to the states. Police power is the authority to regulate for the health, safety, and general welfare of its citizens. Building codes have always been interpreted to fall under the police power of the states, which is why the federal government does not promulgate building codes in the U.S. Although the exact wording has varied between model codes, a typical statement of purpose in U.S. building codes is as shown below:

> The purpose of this code is to provide minimum standards to safeguard life or limb, health, property, and public welfare by regulating and controlling the design, construction, quality of materials, use and occupancy, location and maintenance of all buildings and structures...

The development of seismic provisions in building codes has also been in reaction to catastrophic events, beginning after a 1755 earthquake destroyed much of Lisbon, after which prescriptive rules for construction of the most common building type (gaiola construction) were promulgated. Earthquakes in Messina, Italy (1908) and Tokyo, Japan (1923) resulted in development of more technical guidelines suggesting design of buildings for lateral forces of about 10% of their weight. These developments were no more sophisticated than attempts to minimize the death and destruction observed in these events in future earthquakes.

In the U.S., earthquakes in the San Francisco Bay Area (1865, 1868, 1906), Charleston, South Carolina (1886), Santa Barbara (1925), and Long Beach (1933) all featured massive falls of masonry walls onto the streets and in many cases complete collapses of buildings. The intent of early U.S. codes clearly was to prevent such life threatening and destructive failures in earthquakes. The size or frequency of the events was not considered, partially because determination of these parameters was not generally possible, but also because it didn't matter to the code proponents—the serious damage was in any case to be avoided. The first code provisions in the U.S. appeared as a voluntary appendix (the Lateral Bracing Appendix) in the 1927 Uniform Building Code. The following introduction to that code indicates the lack of specificity in the intent:

> The design of buildings for earthquake shocks is a moot question but the following provisions will provide adequate additional strength when applied to the design of buildings or structures (PCBOC, 1928, p. 218).

The SEAOC Blue Book

The 1933 Long Beach earthquake resulted in strict seismic design for public schools in California (the Field Act) and began mandatory seismic design for most buildings in California (the Riley Act). These laws and the continuing occurrence of earthquakes in California generated continuous code development activity, primarily by the Structural Engineers Association of California (SEAOC), culminating with the publication of the *Recommended Lateral Force Requirements and Commentary* (the "Blue Book") in 1960 that contained a relatively clear performance objective:

> The SEAOC recommendations are intended to provide criteria to fulfill the purposes of building codes generally. More specifically with regard to earthquakes, structures designed in conformance with the provisions and principles set forth therein should be able to:
>
> 1. Resist minor earthquakes without damage;
> 2. Resist moderate earthquakes without structural damage, but with some nonstructural damage;
> 3. Resist major earthquakes, of the intensity of severity of the strongest experienced in California, without collapse, but with some structural as well as nonstructural damage.
>
> In most structures, it is expected that structural damage, even in a major earthquake, could be limited to repairable damage. This, however, depends on a number of factors, including the type of construction selected for the structure (SEAOC, 1960).

Since 1960 the Blue Book has continued to evolve, but the performance objective for new code-conforming buildings has remained similar. The parameter "earthquake" in the three-level description has been refined to "ground motion," the strongest level revised to include both "experienced" and "forecast" ground motions, and the somewhat speculative phrase, "expected that structural damage "…could be limited to repairable damage" further diluted by adding "In some instances, damage may not be economically repairable." Finally, due to a growing realization of the great uncertainty in the exact nature of ground motions as well as a rapidly expanding inventory of various structural systems and building configurations, it was clarified that conformance with the Blue Book provisions should not be taken as a guarantee of the protection of life and limb:

> …While damage to the primary structural system may be either negligible or significant, repairable or virtually irreparable, it is reasonable to expect that a well planned and constructed structure will not collapse in a major earthquake. The protection of life is reasonably provided, but not with complete assurance (SEAOC. 1988).

This addition is significant because it documented the concept that building codes cannot provide a zero-risk building inventory, even for the primary goal of providing life safety.

ATC 3-06 and Zero Risk

A major effort to update seismic design concepts and make them more applicable on a national level was funded by the federal government in the 1970s. The resulting document, *Tentative Provisions for the Development of Seismic Regulations for Buildings* (commonly known at ATC 3), continued the use of overall performance objectives previously developed in the Bluebook, but expanded and clarified the premise that seismic building codes should not be expected to produce a zero-risk environment. The commentary of ATC 3 includes the following discussion:

> It is not possible by means of a building code to provide a guarantee that buildings will not fail in some way that will endanger people as a result of an earthquake. While a code cannot ensure the absolute safety of buildings, it may be desirable that it should not do so as the resources to construct buildings are limited. Society must decide how it will allocate the available resources among the various ways in which it desires to protect life safety. One way or another, the anticipated benefits of various life protecting programs must be weighed against the cost of implementing such programs….
>
> If the design ground motion were to occur, there might be life-threatening damage in 1 to 2 percent of buildings designed in accordance with the provisions. If ground motions two or three times as strong as the design ground motions were to occur, the percentage of buildings with life-threatening damage might rise to about 10 to 50 percent, respectively (ATC, 1978, p. 309).

There is no evidence that the writer of the above commentary calculated these probabilities based on detailed analyses of buildings designed in accordance with the provisions and there is certainly no indication that the writers of the ATC 3 provisions tuned each requirement to provide this level of safety. Similarly, code writers improving and expanding the basic concepts of ATC 3 since 1978 have not had the resources or the methodology to test each new or revised provision against the stated performance objectives. Rather, code changes have resulted from observation of performance judged unacceptable in earthquakes or inferred from research. In many cases, the relationship between the code change and the governing performance objective has been unclear.

The Definition of Ground Motions for Performance Objectives

An important aspect of defining performance expectations for code designed buildings is the definition of ground motions. Initially (e.g., the 1927 UBC), the threat was defined simply as earthquake shaking, and no intensity or probability was defined. The Blue Book used Minor, Moderate, and Major earthquakes, later revised to Minor, Moderate, and Major ground motion, but these levels were never defined in engineering terms. When the "code ground shaking" was finally tied down by specifying a 10% probability of exceedance in 50 years (both in ATC 3 and in the Blue Book), it was probably not coincident with any of the three SEAOC performance levels, but somewhere between level 2 and 3. This level of shaking, often called the Design Basis Earthquake (DBE) ground motion, remained the code design level from the late 1970s until 1997, when a new national mapping was completed using the parameter, Maximum Considered Earthquake Ground Motion (MCE). This work was associated with updating the *NEHRP Recommended Provisions for Seismic Regulations for New Buildings and Other Structures* by the Building Seismic Safety Council (BSSC, 1997). These provisions are a direct descendant of ATC 3 and form the basis of seismic provisions in the International Building Code, presently used as the basis for building design throughout most of the United States.

Development of the MCE maps was a collaboration between the United States Geological Survey (USGS) and the Seismic Design Procedures Group (SDPG) working under the NEHRP Provisions Update Committee (Leyendecker, 2000). Basic hazard mapping was provided by USGS and rules were developed for definition of the MCE by the SDPG. The MCE is mapped using probabilistic concepts (2% chance of exceedance in 50 years) except near well-defined active faults where ground motions are used based on the "characteristic event" of each fault. The characteristic event for each fault is defined by USGS as part of their hazard mapping. MCE ground motions in these regions are 1.5 times the mean attenuation from the deterministic events. The code design philosophy, as defined in the NEHRP Provisions, was then to provide a uniform margin against collapse for the MCE, which was implemented, in simple terms, by using traditional design methods for motions 2/3 of the MCE. The 2/3 factor is based on a presumed margin of collapse of 1.5 in traditional designs based on the less intense DBE. More significantly, preventing collapse even for very rare ground motions, became the key performance objective for normal buildings.

Quantification of Building Seismic Performance Factors (ATC 63/FEMA P695)

Only recently has a methodology been developed to calculate the expected performance of buildings designed in accordance with the current code in the probabilistic framework originally suggested by ATC 3. This method is contained in FEMA P695 (FEMA, 2008). Preliminary results of application of this methodology on several structural systems defined in current code indicate that for MCE ground motions (150% of code design level), about 10% of buildings could collapse. Interestingly, this is of the same order of magnitude as estimated in ATC 3 in 1978. However, when considering the wide variety of lateral force resisting systems included in the code over the years (over eighty systems), each controlled by a complex patchwork of prescriptive design requirements and limitations, the large configuration variations allowed for each system, and the large variation of seismic conditions in the U.S. for which they are designed, it is likely that this methodology, if implemented on every system, would show large inconsistencies in the code defined collapse margin.

Although not officially accepted by a Standards consensus process in the U. S., the FEMA P695 process is gaining traction, and in doing so, is providing evidence of the acceptability of a performance target of 10% chance of collapse in the MCE for normal buildings.

The 2009 NEHRP Provisions (BSSC, 2009)

Revised Intent Statement

The proposed *Intent* statement for the 2009 update of these provisions generalizes performance to be consistent with overall code goals ("safeguard life or limb, health, property, and public welfare"), while emphasizing avoiding collapse. The wording is as follows:]

> The intent of these Provisions is to provide reasonable assurance of seismic performance that will:
>
> - avoid serious injury and life loss;
> - avoid loss of function in critical facilities;
> - minimize nonstructural repair costs when practical to do so.
>
> The *Provisions* seek to avoid such losses by allowing only a small risk of collapse for every building and structure covered, even in very rare extreme shaking at the site. For smaller, more frequent shaking levels, the provisions covering design and installation of both structural and nonstructural systems seek to reasonably control damage that would lead to risks to life safety, economic losses, and loss of function. These design requirements include minimum lateral strength and stiffness for structural systems and guidance for anchoring, bracing, and accommodations of structural drift for nonstructural systems.

Requirements for nonstructural seismic protection have been in U. S. codes since the mid-1970s, mainly affecting components and systems representing a perceived risk to life safety, although small in most cases. However, previously published code performance objectives have not suggested that anchorage and bracing of nonstructural systems is partially aimed at minimizing dollar losses, even for frequent events. However, the code's protection against economic losses is probably reliable only for more frequent events smaller than the DBE. Basic anchorage of components will easily satisfy demands of frequent ground motions in the 50 year return range, and structural drifts will be small, so it is reasonable to assume economic protection is provided. To clarify the public's expectation, it may be appropriate to also define nonstructural performance objectives for larger ground motions, such as the code level shaking.

Significant Revisions in Hazard Mapping

As part of the update process for the 2009 edition of the *Provisions,* FEMA funded a Seismic Design Procedures Reassessment Group (SDPRG) to review the recommendations for national hazard mapping made ten years earlier in the 1997 NEHRP Provisions (BSSC, 1997). The recommendations made in 1997 represented a major departure from previous mapping in that 1) a large infrequent event was used (2% exceedance in 50 years), and 2) deterministic ground motions were used near well defined faults (See previous section on *Ground Motions for Performance Objectives*.). The review was intended to assess the efficacy of use of the MCE, particularly in the eastern U. S. and to consider the ramifications of employment of the Next Generation Attenuation (NGA) relationships in hazard mapping. NGA relationships were the result of an extensive program carried out by the Pacific Earthquake Engineering Research Center over several years (Power, 2008). Early in the reassessment process, the USGS decided to use the NGA relationships for their probabilistic hazard mapping, particularly in the western U. S. The SDPRG recommended that for code design purposes, attenuation relationships should be used for the maximum direction of two component recordings rather than the rotated geomean used by the NGA developers. In addition it was recommended that very near active faults the MCE motions be defined by mean plus one standard deviation attenuations, rather than the factor of 1.5 used in 1997. Although controversial, these recommendations were accepted by the Provisions Update Committee and ASCE 7. Currently the most complete explanation of the development of the maps in contained in an EERI seminar paper (Peterson, 2009).

Perhaps more significant from the standpoint of evolving code seismic performance objectives, the SDPRG recommended use of risk-based mapping, rather than hazard-based mapping in all areas governed by probabilistic values. Rather than mapping ground motions with a 2% chance of exceedance in 50 years, ground motions will be mapped that yield a 1% chance of collapse in 50 years for code designs (Luco, 2007). The development of such maps is an iterative process that requires a collapse fragility for generic code designed buildings. Such a fragility was deduced from the FEMA P 695 document (see previous section) and improved data handling capabilities facilitated the iterative process. Similar "risk-targeted" procedures have previously been used for nuclear facilities in the U. S. but never for mapping seismic demand for building codes.

Conclusions

Life safety has a strong tradition, as well a legal basis, for being the primary goal of building codes in general and seismic provisions specifically. However, until recently, life safety had no definition and policy makers had great difficulty with the question, "How safe is safe enough?" Increase in use of probabilistic concepts in the last 20 years, not only for consideration of hazard, but also for consideration of uncertainty of structural response given a design response spectrum, has facilitated the development of tools to better define building code seismic performance objectives. Descriptions of expected performance of code designed buildings will continue to be enhanced using a full range of losses estimated by performance based design techniques. These developments may finally take basic code design performance decisions out of the hands of technical code writers and place them at the feet of policy makers.

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