Building Design for Extreme Events

Natural Hazards

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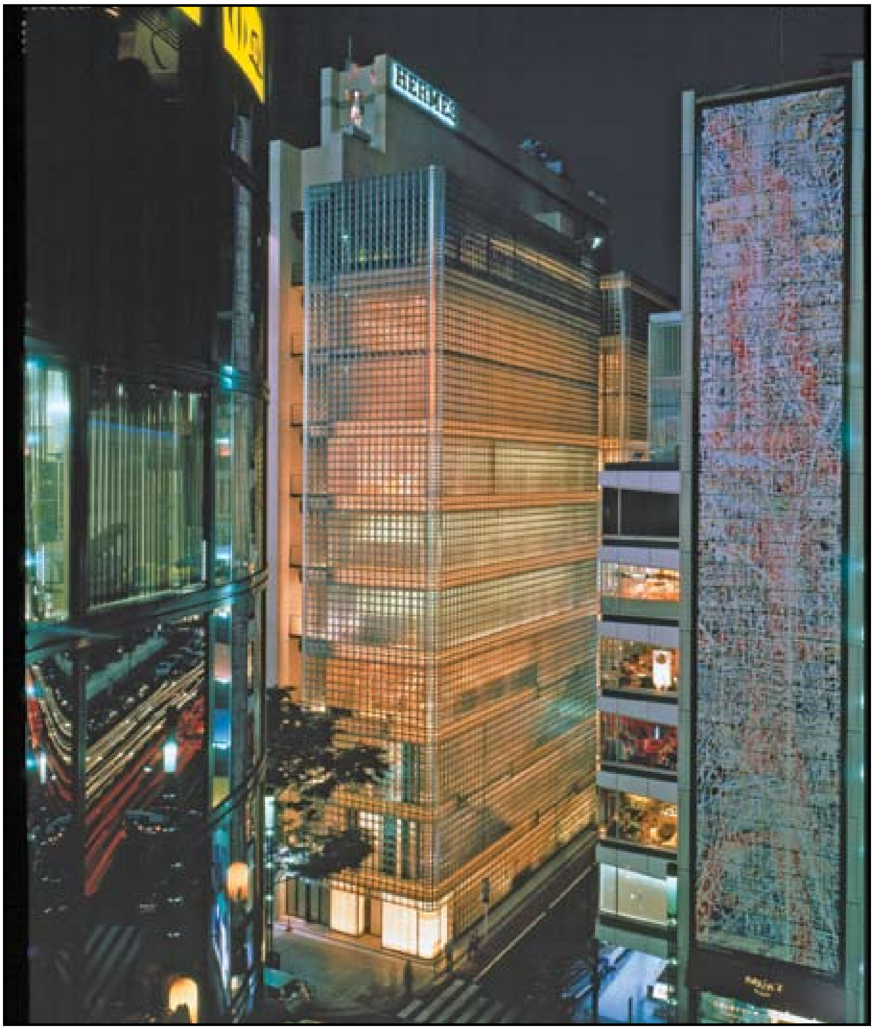

Maison Hermes Building in Tokyo, Japan, which includes a visco-elastic damper that allows the structure to 'rock' during an earthquake. ©Arup/Michel Denance

Great catastrophes like earthquakes, fires, floods, and other natural events are a reality of existence on our planet. Tools that aim to reduce the risk posed by natural hazards have led to significant improvements in our ability to design natural hazard-resistant structures in recent years. In disciplines like earthquake engineering, the field is mature because past events have taught valuable lessons that are now incorporated into design practice. In other cases, current knowledge could be improved significantly with greater funding to support scientific study.

This article is the fourth in a series on designing buildings to protect against extreme events. The previous articles have dealt with fire and blast events. The focus of this article is the assessment and mitigation of hazards associated with natural events, such as hurricanes and earthquakes. For more details on designing for natural hazards, see Chapter 7 of the book *Extreme Event Mitigation in Building - Analysis and Design*, from which this article is derived.

Risk Assessment for Natural Hazards

Risk assessment techniques can be used to understand the level of impact possible for various natural hazard events and to prioritize scarce resources for protection. The risk assessment seeks to answer the following set of questions:

- What can happen?
- What is the likelihood that it will happen?
- What are the consequences of it happening?

Consequences could be loss of life, direct financial losses, and/or indirect financial losses associated with business interruption.

The matrix in *Figure 2* provides a framework for a risk assessment. The categories along the top describe impact, which can be estimated based on evaluation of the building's performance. Events in dark shading are unacceptable and require mitigation. Events in lighter shades are of less concern, but all scenarios will benefit from exploration of risk-reduction options.

Figure 2 can also be set up with Performance Groups along the top axis, if goals were defined according to desired performance rather than acceptable damage.

A comparison of building code performance to the performance levels defined in the matrix reveals that a typical code-

	Catastrophic 1	Very Serious 2	Serious 3	Not Serious 4
Certain A	1A	2A	3A	4A
Highly Probable B	1B	2B	3B	4B
Probable C	1C	2C	3C	4C
Improbable D	1D	2D	3D	4D

Risk Acceptability Key

Generally Unacceptable	Sometimes Acceptable	Generally Acceptable

Figure 2: Qualitative Risk Assessment Performance Matrix

complying building likely behaves at Level 3 (i.e., threat to human life is minimal but the building is both structurally and non-structurally damaged, causing downtime to operations). Special buildings, such as hospitals and schools, are required by code to perform better. Designing to code is the 'minimum' baseline for conventional building structures.

Once the risk is understood, it can then be managed. The decision of whether or not to accept the risk is made by stakeholders. If the outcome is unacceptable, a diverse range of risk mitigation measures can be explored. It is generally not possible to reduce the likelihood of natural events. Efforts are usually aimed at reducing the severity of the consequences of the event, usually through engineered or operational solutions or perhaps through simply selecting a new site for the building. The risk may also be transferred through either insurance or other financial methods.

It is often necessary in risk management to predict the financial losses associated with natural-hazard events. Financial risk management can target the most appropriate risk mitigation methods. Various forms of loss estimation exist to account for direct physical damage, economic loss, and social impact. Loss estimations are often quoted as a percentage of value of the building or contents. Various catastrophic loss methodologies are available, some incorporating advanced computer modeling. Caution must be used when applying these models at site-specific levels as most have been developed for the insurance industry using highly generalized data.

Techniques for building design to mitigate risks from natural hazards have substantially improved in recent years, and designers now have various tools, from life-safety design measures to financially-driven performance-based analysis techniques. Design decisions must ultimately be made with both up-front and life-cycle cost in mind. A design that incorporates additional risk-reduction measures almost always results in increased up-front costs, although life-cycle costs may be greatly reduced. If mitigation measures are incorporated early in the design process, they will likely be less intrusive and have a lower cost impact.

Costliest Natural Disasters 1980-2006

Event	Year	Total Losses (US $M)	Fatalities
Hurricane Katrina, US	2005	125,000	1,322
Kobe Earthquake, Japan	1995	100,000	6,430
Northridge Earthquake, US	1994	44,000	60
Floods, China	1998	30,700	4,159
Niigata Earthquake, Japan	2004	28,000	46
Hurricane Andrew, US	1992	26,500	62
Floods, China	1996	24,000	3,048
Hurricane Ivan, US	2004	23,000	125
Mississippi Floods, US	1993	21,000	48
Hurricane Wilma, US	2005	20,000	42

(Source: Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE, (c) 2007)

Design Methodologies for Natural Hazards

Building codes rely on simple analysis methods and prescriptive details to achieve a reasonable level of life safety during hazardous events. Building codes provide a minimum performance level to ensure pubic safety. Although several prescriptive code provisions exist for improved performance of critical facilities (e.g. importance factors for hospitals), design provisions are for standard types of structures and often do not take specific aspects of the structure into account.

Performance-based design provides a means of making decisions on life safety, damage reduction, and business continuity under exposure to natural and man-made hazards. In performance-based design, the unique qualities of each building can be considered in meeting the stakeholders' particular needs. Stakeholders should be involved from the beginning of a project and should be educated in the tradeoffs of design decisions so they can establish the acceptable level of risk.

The performance-based design procedure begins with establishing the acceptable risk and appropriate performance levels for the building. The basic concept of acceptable risk is the maximum level of damage that can be tolerated for a realistic risk event scenario. For each type of natural hazard, there are methods of measuring the magnitude of events and their probability, as well as terminology to describe levels of damage or performance levels.

Design for Seismic Hazards

Seismic-resistant building design has evolved significantly over the past 75 years. Based on California's earthquake experience, regulation through a properly enforced seismic code has largely fulfilled the intent of ensuring an acceptable level of safety against death and injuries.

In the traditional prescriptive code-based approach, lateral loads for structural design are determined for a certain earthquake level. The earthquake level, or "design basis earthquake" (DBE), is selected based on the probability of exceedance or return period: measures of occurrence frequency of a certain earthquake magnitude. In many code-based seismic applications, the life of the structure is intended to be 50 years and the level of earthquake with probability of exceedance equal to 10 percent in 50 years is selected for design. The corresponding return period is 475 years. The structure is designed such that the strength capacity is more than the demand due to the lateral loads imposed by the design basis earthquake, reduced for the expected ductility and reserve strength in the framing system.

Many buildings in the epicentral region of the 1994 Northridge, California earthquake had been designed to the current standards of the time. These structures performed well, as there were relatively few deaths (58). However, there were approximately 100,000 people displaced from their homes following the earthquake, with losses estimated at $20 billion.

In the performance-based approach, the theorized condition of the structure after an earthquake is used to assess the "performance" level of the structure based on engineering judgment. Defined performance levels of a reinforced concrete frame, for example, may be as follows:

- Operational – no visible damage
- Immediate occupancy – minor cracking in the members without any crushing
- Life safety – spalling of concrete from columns and extensive cracking in beams
- Collapse prevention – extensive cracking in columns and formation of hinges; permanent deformation of the structure.

Performance is quantified through deformation demands on the structure, often calculated by a lateral load analysis. The target performances of the structure for different earthquake levels are selected from a representative matrix, such as that shown in *Figure 4*.

Earthquake Level (Probability of Exceedance)	Return Period (Years)	Target Structure Performance Levels			
		Operational	Immediate Occupancy	Life Safety	Collapse Prevention
50% in 50 years	72				
20% in 50 years	225				
10% in 50 years	474				
2% in 50 years	2475				

Figure 4: Performance Matrix for Seismic Loads

Design for Flood Hazards

The degree of research on earthquakes is not likewise available for other natural hazards. Most design is based on prescriptive code-based methods, some of which are effective for life safety but may not be reflective of stakeholder interests.

Existing minimum requirements in model building codes and regulations are based on the National Flood Insurance Program (NFIP) dating back to 1968. Buildings that pre-date the NFIP requirements are not necessarily constructed to resist floods. NFIP reports that buildings meeting minimum NFIP requirements experience 70% less damage than buildings that pre-date the NFIP. The NFIP performance requirements for site work are as follows:

- Building sites shall be reasonably safe from flooding;
- Adequate site drainage shall be provided to reduce exposure to flooding;
- New and replacement sanitary sewage systems shall be designed to minimize or eliminate infiltration of floodwater into the system and discharge from the systems into floodwaters;
- Development in floodways shall be pro hibited unless engineering analyses show that there will be no increases in flood levels.

Designing for floods is usually based on a specific return period, typically 100 years for design. To determine the magnitude of the hazard, a probabilistic assessment is usually conducted, considering meteorological sources such as precipitation and storm surge. In some areas, run-up from tsunami is also included in the probabilistic analysis. Failures of dams and levees are not considered in regional probabilistic studies of flooding. Other magnitudes of events often considered are shown in *Table 1*.

Magnitude of Event	Frequency of occurrence
Very Large	Determined on a site-specific basis
Large	Determined on a site-specific basis
Medium	500 years
Small	100 year

Table 1. NFIP/ASCE 24/ICC Criteria for Flood Hazard

Design for Wind Hazards

Design for wind in US building codes has been greatly expanded since the 1980s, particularly for roof coverings and equipment. Most codes added provisions following Hurricanes Hugo (1989) and Andrew (1992). The 2003 editions of NFPA 5000™, *Building Construction and Safety Code*, and the International Building Code (IBC) were the first model codes to address wind loads on parapets and rooftop equipment. ASCE 7, *Minimum Design Loads for Buildings and Other Structures*, is more reflective of the current state of knowledge for wind design than model codes. Adoption of ASCE 7 for wind design loads has typically resulted in higher design loads.

The 2000 edition of the IBC was the first model code to address glazed protection or windborne debris requirements for buildings located in hurricane-prone regions. The 1995 edition of ASCE 7 was the first edition to address wind-borne debris requirements.

The 2003 editions of the IBC and NFPA 5000 are considered reasonable for design against hurricanes except that the IBC does not account for water infiltration due to puncture of roof membranes, nor does it adequately address vulnerabilities of brittle roof coverings (such as tile) to missile-induced damage and subsequent progressive cascading failure.

NFPA 5000, the IBC, and ASCE 7 do not require buildings to be designed for tornadoes, nor are occupant shelters mandated in buildings located in tornado-prone regions. Because tornados may produce extremely high pressures and missile loads, constructing tornado-resistant buildings is very expensive. When tornado design is considered, the emphasis typically is on occupant protection, which is achieved by "hardening" portions of a building for use as a safe haven. FEMA 431 should be used for guidance.

Assessment of the wind resistance of the building envelope and rooftop equipment is a challenge, and analytical tools are currently not available for most system types. Many elements require physical testing to understand their load-carrying capacity. Finite element simulations might begin to replace physical testing in the future.

Summary

Natural hazards are recurring events with relatively predictable recurrence, making them ideally suited for risk-informed performance-based design. The risk can be assessed, quantified, managed, and designed for in a relatively direct manner. More research is needed, especially for flood and high wind loads, to more accurately quantify the nature of the hazards and associated building response. When possible, a multi-hazard approach should be taken in risk assessment and design, both with other natural hazards and other extreme events, such as technological accidents and deliberate destructive attacks.

Further details and in-depth descriptions of the approaches described here are provided in *Extreme Event Mitigation in Buildings - Analysis and Design*. The next (and final) installment of this series will focus on the mitigation of chemical and biological hazard events in buildings.▪

A visco-elastic damper provides for a "stepping column" base connection in the Maison Hermes Building in Tokyo, Japan. ©Arup/Frank la Riviere

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