RESEARCH UPDATE

Designing for and mitigating earthquakes

Earthquakes cause loss and suffering every year in large parts of the world. Most of this loss and suffering is due to lack of, or inadequate, structural design for the forces that earthquakes impose on buildings and other structures. Earthquakes impose vertical and lateral forces on structures, due to the inertia of the structure. While vertical forces are significant, most structures have substantial capacity to resist vertical forces, since their primary structural design is for the force of gravity. Therefore, the primary problem for most structures is force in the horizontal, or lateral, direction, which tends to subject buildings to large horizontal distortion (**Fig. 1**). When these distortions get large, the damage can be catastrophic. Therefore, most buildings are designed with lateral-force-resisting systems (or seismic systems) to resist the effects of earthquake forces. In many cases, seismic systems make a building stiffer against horizontal forces and thus reduce the amount of relative lateral movement and consequently the damage. Seismic systems are usually designed to resist forces that result from horizontal ground motion, as well as from vertical ground motion.

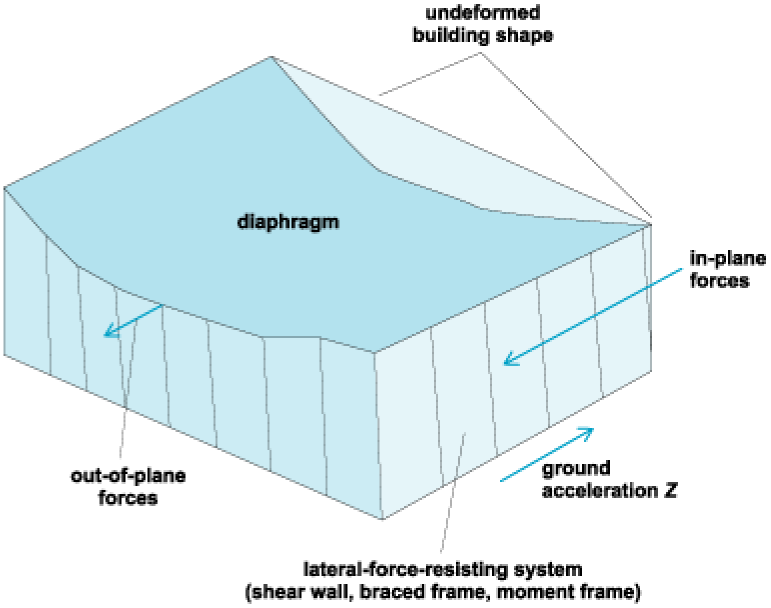

Fig. 1 Building deformation due to lateral seismic forces.

When strong earthquake shaking occurs, a building is thrown mostly from side to side, as well as up and down. That is, while the ground is violently moving from side to side, taking the building foundation with it, the building structure tends to stay at rest, similar to a passenger standing on a bus that accelerates quickly. Once the building starts moving, it tends to continue in the same direction, but the ground moves back in the opposite direction (as if the bus driver first accelerated quickly, then suddenly braked). Thus, the building gets thrown back and forth by the motion of the ground, with some parts of the building lagging behind the foundation movement and then moving in the opposite direction. The force F that an upper floor level or roof level of the building should successfully resist is related to its mass *m* and its acceleration a, according to Newton's law, F = *m*a. The heavier the building, the more the force is exerted. Therefore, a tall, heavy, and reinforced concrete building will be subject to more force than a lightweight, one-story, wood-frame house, given the same acceleration. The combined action of seismic systems along the width and length of a building can typically resist earthquake motion from any direction. The earthquake-resisting systems in modern buildings take many forms (**Fig. 2**).

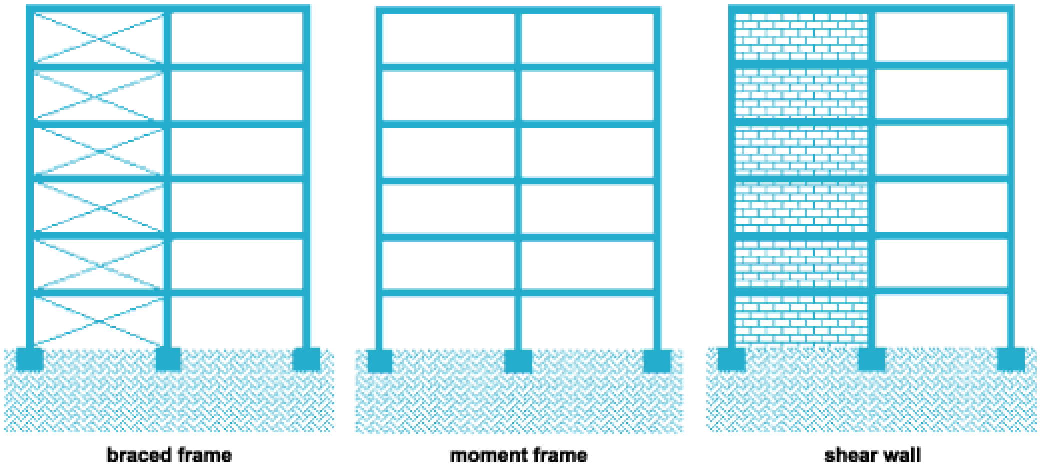

Fig. 2 Earthquake lateral-force-resisting systems.

In moment-resisting steel frames, the connections between the beams and the columns are designed to resist the rotation of the column relative to the beam. Thus, the beam and the column work together and resist lateral movement and lateral displacement by bending. Steel frames sometimes include diagonal bracing configurations, such as single diagonal braces, cross bracing, and K-bracing, which resist forces through tension and compression in the braces. Steel buildings are sometimes constructed with moment-resistant frames in one direction and braced frames in the other.

In concrete structures, shear walls are sometimes used to provide lateral resistance in the plane of the wall, in addition to moment-resisting frames. Ideally, these shear walls are continuous walls extending from the foundation to the roof of the building. They can be exterior walls or interior walls. They are interconnected with the rest of the concrete frame and thus resist the horizontal motion of one floor relative to another. Shear walls are most often reinforced concrete walls but can also be reinforced masonry walls constructed of bricks or concrete blocks with steel reinforcing.

Damage can be structural and nonstructural, both of which can be hazardous to building occupants. Structural damage means degradation of the building's structural support systems (that is, vertical- and lateral-force-resisting systems), such as the building frames and walls. Nonstructural damage refers to any damage that does not affect the integrity of the structural support systems. Examples of nonstructural damage are chimneys collapsing, windows breaking, or ceilings falling. The type of damage is a complex issue that depends on the structural type and age of the building, its configuration, construction materials, the site conditions, the proximity of the building to neighboring buildings, and the type of nonstructural elements.

Design

Traditionally, engineers have designed structures to resist earthquake forces, intending the strength of structural members to be equal to or greater than the seismic demand placed on them (Fig. 2). In earthquake analysis and design, a structure is commonly assumed to remains elastic (that is, the design neglects the effects of damage), although inelastic analyses which take into account material nonlinearity are increasingly being used in the practice. The procedures for earthquake design are required by building codes and are provided in the same building codes or related documentation. In the United States, the primary source for seismic design for buildings is ASCE 7 (2005), in the European Union the primary source is Euro code 8 (1998), and in Japan AIJ (1994) and PWRI (1998). An excellent source for codes for most countries is IAEE (2004), while IAEE (1986) is a guide for seismic design and construction of nonengineered buildings.

For ordinary design, the actual earthquake forces are reduced via a response modification factor, which varies depending on the assumed inherent ductility of the structure, based on its lateral-force-resisting-system's material (wood, steel, concrete, etc.) and system (moment frame, braced, shear wall, etc.). These reduced forces, with appropriate safety factors, are combined with gravity and other loads for the design of the overall structure. Pseudostatic or linear dynamic analytical methods are used to determine member forces for design. Pseudostatic methods are based on the structure's natural period (that is, first mode of vibration) and are appropriate only for simple structures. Linear dynamic methods account for the first and higher modes, which are usually more quickly performed in the frequency domain using techniques based on the fast Fourier transform. For larger and more important structures, nonlinear dynamic analyses are employed, typically in the time domain. In a nonlinear dynamic analysis, the structure is subjected to earthquake acceleration time histories (actual or synthesized records, scaled to match the site hazard), and member response into the inelastic range is taken into account, including P-Δ effects (that is, the increase in overturning moment due to the structure's weight P times its lateral deflection Δ). Dynamic analysis has become common due to the advent of more powerful computers and specialized software—ETABS, SAP2000, ANSYS, STAAD, and LARSA are some of the structural analysis packages more commonly employed today.

During the 1980s and 1990s, new approaches to seismic design emerged which involved modifying the structural response to reduce earthquake loads to more tolerable levels. These included base isolation, supplemental damping, and active control. Base isolation involves placing special components called isolators within the structure, which are relatively flexible in the lateral direction, yet can sustain the vertical load. However, the isolators are not always at the base, so that the technique is more properly termed structural isolation. When the earthquake causes ground motions beneath the structure, the isolators allow the structure to respond much more slowly than it would without them, resulting in lower seismic demand on the structure. Isolators may be laminated steel and high quality rubber pads, sometimes incorporating lead or other energy-absorbing materials (**Fig. 3**), or parabolic dish-shaped base plates which rely on the structure's own weight trying to "climb" the sloping sides of the "dish" to counteract the lateral force of the earthquake. Other methods include supplemental damping and active control. The most recent development in earthquake engineering is performance-based design, in which the expected structural damage due to the maximum expected earthquake is quantified. If the expected damage is unacceptably high, the owner and the engineer may agree on a design in excess of the building code requirements.

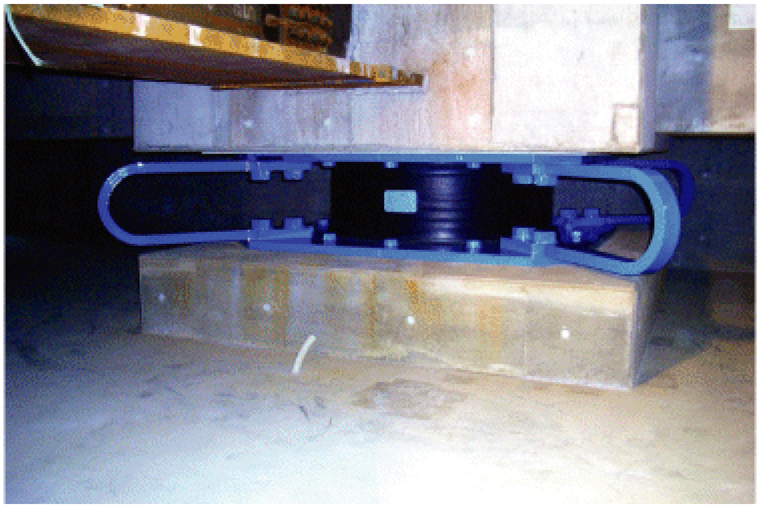

Fig. 3 Rubber isolator under concrete-encased column (note steel girder framing-in on the upper left). The "paper clip" steel bars are hysteretic dampers. As the building above the rubber isolator moves under earthquake motions, the steel bars flex, absorbing energy. (*Courtesy of C. Scawthorn*)

Mitigation

Mitigating earthquakes is a much broader field than simply designing for earthquakes. Mitigation is a several-stage planning and management process which involves (1) estimating the potential losses that earthquakes might cause; (2) deciding if the potential losses are acceptable or not; (3) if not, examining alternative loss reduction techniques, which involves identifying the effectiveness of each alternative in reducing losses and the associated cost; (4) setting some criteria for deciding which alternative is the most effective, such as benefit-cost, lives saved, least regret, or other paradigms, and applying the criteria to select the most effective package of alternatives; (5) developing a design and implementation program for the package of alternatives; and (6) implementing the program. A crucial and often difficult aspect of mitigation is finding the political will and resources to examine the risk of earthquakes and then to implement the program. Mitigation alternatives can be broadly grouped into four categories: structural, locational, operational, and risk transfer. Structural mitigation generally involves resisting or avoiding earthquake forces via hardware solutions. Locational mitigation typically avoids earthquake effects via alternative land uses.

Operational mitigation refers to emergency planning and related measures that respond to earthquake effects to reduce the impacts to acceptable levels. Risk transfer implies not reducing the loss in an absolute sense but only in a relative sense, where the loss is shared with others, typically via insurance but sometimes in other ways to reduce the loss to an acceptable level.

See also: Architectural engineering; Buildings; Earthquake; Loads, dynamic; Seismology; Structural analysis; Structural design; Structure (engineering)

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Additional Readings

- US Geological Survey
- Earthquake Information Network
- Multidisciplinary Center for Earthquake Engineering Research
- Applied Technology Council
- Earthquake Engineering Research Institute
- Global Seismic Hazard Analysis Project
- International Association of Earthquake Engineering
- Pacific Earthquake Engineering Research Center
- Consortium of Universities for Research in Earthquake Engineering

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