Briefing Paper 1

Building Safety and Earthquakes

Part B: Earthquake Forces in Buildings

Introduction

This Briefing Paper 1, *Building Safety and Earthquakes*, consists of four parts describing earthquakes and their effects on buildings. Part A describes the causes of earthquakes and resulting ground motions. This Part B describes how earthquake ground motions create various forces acting on a building and explains how those forces result in building drift. Parts C and D discuss structural systems that resist earthquakes and the "load path" of earthquake forces within buildings.

Earthquake forces are called lateral forces because their predominant effect is to apply horizontal loads to a building.

Forces and Accelerations

Designing buildings to resist earthquakes requires that ground motions be translated into forces acting upon a building. Earthquake forces are called lateral forces because their predominant effect is to apply horizontal loads to a building. Although earthquake waves do impart a vertical component of force to buildings, the weight of the building normally provides sufficient resistance. Therefore, vertical earthquake forces are usually only accounted for in special cases.

The general method for determining the total lateral earthquake force to be applied to a building is based on a simple equation, $F = ma$. It relates the force (F) to the mass (m) of the building and to the horizontal acceleration (a), imparted from the ground shaking. The building mass consists of the sum of the weights of all its structural and nonstructural components. The acceleration is expressed as a fraction of the acceleration due to gravity, commonly called "g."

We all experience the force associated with 1.0 g of constant vertical acceleration everyday due to the earth's gravity. The presence of this force, and hence the gravitational acceleration, is noticeable when we perform work that requires lifting, such as climbing stairs or moving objects from a lower to a higher level. The physical exertion involved in these activities is in response to the force that must be overcome, which we can call the resisting force. The resisting force is equal to the mass of the object times the acceleration due to gravity. Because gravity is constant, one must overcome a greater resisting force to move heavier objects. This concept of objects resisting movement, actually in any direction, derives from the object's "inertia."

We all experience inertia in response to the horizontal acceleration that occurs while traveling in a vehicle. When quickly accelerating from rest, the inertia of a person's body resists moving forward, and there is pressure from the seat back. During braking, the resisting force can be felt as the pressure from a seat belt. Figure 1

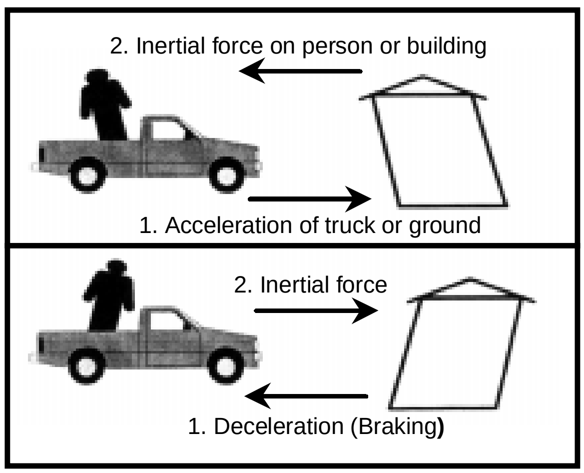

Figure 1. Inertial forces are a reaction to acceleration.

illustrates this familiar experience and relates it to the effect of building inertia during an earthquake.

In-Plane and Out-of-Plane Forces

Regularly shaped buildings and many irregular buildings have their structural elements oriented in two perpendicular directions. These directions are known as the primary orthogonal axes. When designing for earthquakes, lateral forces are assumed to be split into their orthogonal components, and to act parallel to each of these directions. This assumption is made because there is no specific orientation of the seismic waves that will pass through a building site. Furthermore, once a building begins to shake, the internal forces that are generated will be transmitted in components aligned along the primary orthogonal axes.

Earthquakes produce both in-plane and out-of-plane forces.

A force acting along one axis of a building causes resisting forces in walls or frames parallel to that direction. These are called in-plane forces, because the direction of force is parallel to the plane of the wall or frame. Forces that are perpendicular to this direction are known as out-of-plane forces. Earthquakes produce both in-plane and out-of-plane forces, as shown in Figure 2.

For example, in-plane forces acting on a plywood-sheathed wood-frame wall are resisted by the nails attaching the sheathing to the top plate, studs, and sill, and by the anchor bolts attaching the wall sill plate to the foundation. The out-of-plane forces acting on this same wall are resisted by nailed connections between the top plate of the wall and the adjacent floor or roof framing and at the bottom by anchor bolts in the sill plate. Most building seismic elements are not designed to resist forces from both these directions simultaneously. However, the forces in each direction must be separately accounted for, and structural elements must be provided with adequate capacity to resist forces acting in both in-plane and out-of-plane directions.

The Concept of Base Shear

The resisting force or inertia depends on the mass of an object, and the design of buildings must take this into account. Just as columns at the lower-story levels of a building must support the combined weight of the levels of the structure above them, lateral resisting forces also accumulate at lower levels. At the roof level, the inertia is based on the weight of the roof and the weight of one-half of the story height of the walls immediately below the roof. At the floor immediately below the roof, the inertia is based on the tributary weight of the floor and the walls halfway above and halfway below that floor. Figure 3 illustrates how the inertia at each level is calculated. The total resisting force increases at progressively lower levels, culminating at the

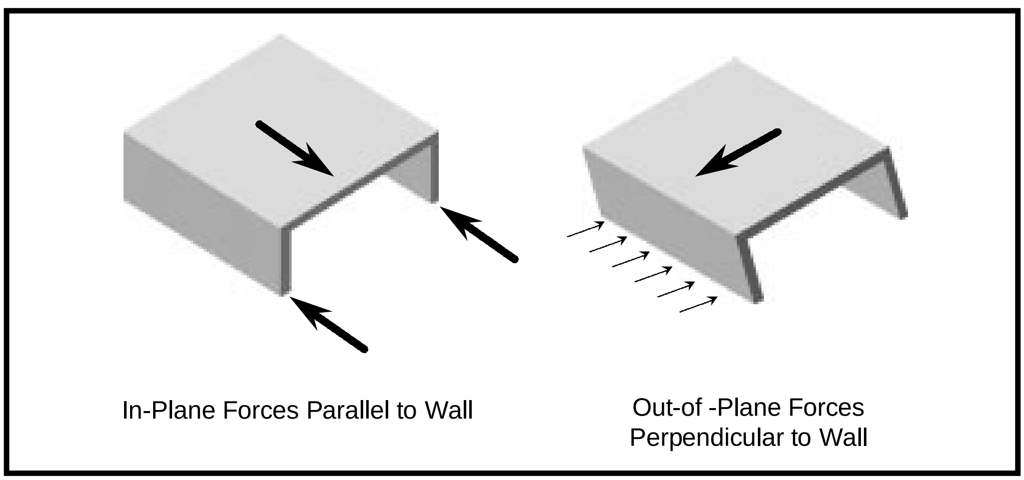

Figure 2. In-plane and out-of-plane forces on a shear wall.

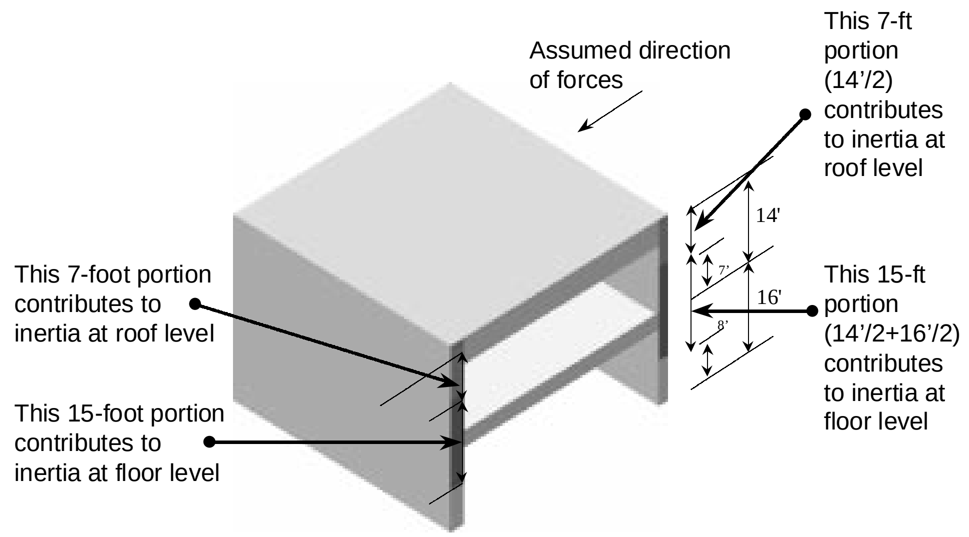

Figure 3. Calculating tributary forces at roof and second-floor levels.

foundation level. The resisting force at the foundation level is based on the sum of the contributing forces from each level and is known as the base shear.

Distributing Base Shear

In the design of a multi-story building, a portion of the total base shear is applied, as a horizontal force, at each floor level and at the roof. The design lateral force applied at each level is based on both the tributary mass at that level and the height of that level above the base of the building. The result is a seismic force distribution over the height of a building that is larger at the top than at the bottom and is described as a triangular shape. This distribution is a simplified approximation that generally matches the actual distribution of forces during earthquakes. The distribution is derived from calculations using recordings from strong motion instruments installed at various levels within buildings. When designing tall structures or very flexible structures with long natural periods, an extra lateral load is added at the roof level to account for additional stresses, from the "whiplash" effect that occurs at the roof level of a building.

Building Drift Caused by Lateral Forces

A horizontal force applied to an object tends to push it sideways. If it is unrestrained at its base, it slides in the direction of the applied force. With buildings, sliding is counteracted by the frictional sliding resistance between the bottom of the foundation and the soil and by the lateral bearing resistance of the soil against the vertical faces of the foundation and piles. Lateral forces acting above the foundation push the superstructure sideways until the resistance of the structure reaches an equilibrium with that force. The amount of horizontal displacement that occurs is called drift. Drift causes stress in structural seismic elements and nonstructural elements because it forces them into deformed shapes. Maximum drift usually occurs at the top of a building, but each story level is subjected to a certain amount of story drift as shown in Figure 4.

Maximum drift limits and individual story drift limits are specified in building codes to control the horizontal displacement a building experiences during an earthquake. Because drift and associated accelerations increase toward the top of a building, the 1997 UBC requires roof-mounted equipment to resist forces four times larger than equipment located on the ground floor. The FEMA 273 N*EHRP Guidelines for the Seismic Rehabilitation of Buildings* have similar requirements. Building drift is also an important consideration when determining how closely two buildings can be spaced. Buildings must have adequate separation to avoid the damaging effects of pounding during earthquakes.

Drift considerations are particularly important for columns and for connections of heavy precast cladding components whose failure could lead to injuries or loss of life. All structural seismic elements and their connections must be designed to accommodate the expected drift, regardless of their role in resisting lateral forces. The collapse of a newly constructed parking garage at Cal State Northridge during the 1994 Northridge earthquake can be partly attributed to insufficient capacity in its interior concrete columns to accommodate the story drift.

Buildings must have adequate separation to avoid the damaging effects of pounding during earthquakes.

Adherence to drift limits can also reduce economic losses, especially with respect to nonstructural components.

Some older buildings with drift-sensitive brittle finishes have been retrofitted using a technique known as seismic isolation. Seismic isolation typically uses viscous bearings or sliding friction bearings to support and isolate the building from horizontal earthquake ground motion similar to the way a car's suspension isolates it from vertical bumps in the road. Seismic isolation can reduce both seismic forces and drift-induced damage.

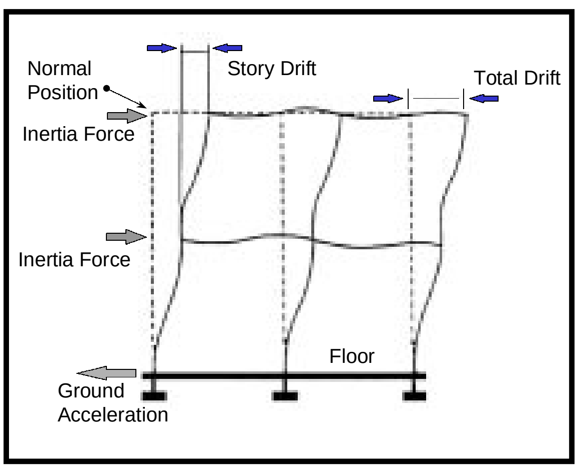

Figure 4. Drift in a building subjected to lateral earthquake forces.

References

ATC, 1997, *NEHRP Guidelines for the Seismic Rehabilitation of Buildings*, prepared by the Applied Technology Council for the Building Seismic Safety Council, published by the Federal Emergency Management Agency, FEMA 273 Report, Washington, DC.

ICBO, 1997, *Uniform Building Code*, International Conference of Building Officials, Whittier, California.

About this Briefing Paper Series

Briefing papers in this series are concise, easy-to-read summary overviews of important issues and topics that facilitate the improvement of earthquake-resistant building design and construction quality.

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