

**Summary
of
Lesson One
Lateral Forces
(Kaplan 2006)**

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Definitions

Plate tectonics: Frictional force between plates give way and plates slip past one another. Slip causes shockwaves which travel outward through rock and soil.

Fault: boundary between adjacent tectonic plates; breaks and fracture in earth's crust. Major fault is a system of faults.

Hypocenter (focus): Where the rock slippage begins.

Epicenter: Projection of the focus on the ground surface.

Richter Scale: Measures magnitude or amount of energy released. Logarithmic scale with each number representing 33x the number below. Doesn't provide indication of

potential damage. Great earthquakes cause damage usually last longer and damage greater area.

Major earthquake--7-7.75

Great earthquake--7.75 and above

Modified Mercalli Scale: measures intensity of earthquake.

Expressed in Roman numerals I-XII, and each number corresponds to description of earthquake's effects.

No precise correlation between Richter and Modified Mercalli Scales.

Soil liquefaction: transformation of soil into a liquefied state similar to quicksand.

Acceleration (ground): Ground velocity constantly changing during earthquake. Measured at a % of g (acceleration of gravity) or 10% g (3.2 feet per second).

Strong motion accelerographs: Records ground acceleration. Activated when strong ground motion occurs. Varying ground accelerations are applied to idealized structures which have different *natural periods*, which allows the maximum acceleration for these structures to be determined.

Response curve: Resulting curve produced by accelerograph, usually shown for different soils.

Period: Pendulum Principle. Takes certain amount of time for mass on a rod to move through one complete back-and-forth motion.

Natural period (fundamental period): Amount of time of period of "pendulum" to move. Independent of force used to push "pendulum."

Dependent on two factors: mass of pendulum and stiffness of rod. Increasing mass or pendulum or stiffness of rod changes natural period.

Building natural period measured in seconds and dependent on mass and stiffness.

Natural period building relationship: Stiffness and natural period relationship is inverse.

*The more rigid or stiff a building is **decreases** its period.

*The more flexible or less stiff a building is **increases** its period.

*Increasing the mass of a building **increases** its period.

*More flexible building will have a **longer** natural period and **lower** maximum acceleration.

As the period of the structure increases its peak acceleration also increases, reaching a maximum when the period is about 0.5 seconds. Maximum acceleration (generally) = 2x-3x

ground acceleration. As the period increases beyond 0.5 seconds, acceleration decreases and becomes less than ground acceleration.

Soils affect building acceleration--greater on soft soil and less on rock or stiff soil.

Inertia: Upper portion of building remains same place while base is moved.

Newton's Second Law of Motion: **F=Ma**, *Force = Mass x Acceleration*, where Mass is weight divided by *g* (acceleration of gravity-32 feet per second).

*Magnitude of inertia force is equal to the mass of the structure multiplied by its acceleration.

*Long period building = less acceleration = less force

*Heavy buildings (more mass) = more force

Conventional vs. Seismic Design

Conventional: Nature of applied dead, live, and winds loads are independent of the stiffness of structure.

Seismic: Seismic force dependent on stiffness of structure. Increasing structure's stiffness *increases* induced seismic force.

1994 UBC (Uniform Building Code) Code Requirements

- 1) Resist minor earthquake without damage
- 2) Resist moderate earthquakes without structural damage (some nonstructural damage possible)
- 3) Resist major earthquakes without collapse (structural and nonstructural damage possible)

Code is intended to safeguard against major failures and loss of life, not necessarily the protection of property.

Earthquake forces determined by two methods:

*Dynamic Lateral Force Procedure--Always acceptable for design. Dynamic uses a computer model that is subjected to various ground forces.

*Static Lateral Force Procedure--Only acceptable under certain conditions such as building regularity, occupancy and height (<240 ft.). Used in most buildings. Forces used in static analysis only simulate effects of the earthquake since no external forces are actually applied to building during earthquake.

1994 UBC (Uniform Building Code) Code Requirements Static Lateral Force Procedure

Static procedure = determining the total lateral force (shear) at the base (V):

$$V = \frac{ZIC}{R_w} W$$

V=total lateral force of shear at the base

Z=the seismic zone factor

I=the importance factor

C= a numerical coefficient--

$$= \frac{1.25S}{T^{2/3}}$$

R_w=a numerical coefficient

S=site coefficient for soil characteristics

T=the fundamental period of vibration, in seconds, of the structure in a given direction

W=the total dead load

V--is evaluated in the two horizontal directions parallel to the axes of the building. Resist force in each direction but not at the same time.

Z--Based on zone map showing six seismic zones. Z varies from 0-0.40 based on zone. Number corresponds with effective peak ground acceleration and expressed as % of g ($0.4 = 40\%$ of g).

I--Importance factor defined by IBC table. Either 1.0 or 1.25 based on occupancy of building.

C--Relationship of building period and acceleration and acceleration of building based on soil.

Relationship defined by C which is equal to

$$= \frac{1.25S}{T^{2/3}}$$

S accounts for the soil on the site and T accounts for the period.

S is determined by table of site coefficients that list soil profiles. The value is generally 1.0-1.5.

T is approximated by the following formula: $T = C_t(h_n)^{3/4}$

where:

$C_t = 0.035$ for steel moment resisting frames

$C_t = 0.030$ for reinforced concrete

moment – resisting frames and eccentric braced frames

$C_t = 0.020$ for all other buildings

$h_n =$ height of building

The maximum value of C is 2.75 and this value can be used for any structure regardless of soil type or building period.

The minimum value of the ratio C/R_w is 0.075.

R_w --Determined by the type of lateral load resisting system used. Measure of system's ability to accommodate earthquake loads and absorb energy without collapse.

Low R_w = stiff, brittle structure

High R_w = Resilient, ductile system

W--Total dead load and portions of other loads:

*storage and warehouse=25% of live load is added

*partition load used in design=10 psf is added

*snow load greater than 30 psf = load is included (subject to conditional reductions)

Lateral Load Resisting Systems

Function: absorb energy by moving or deforming without collapse.

Ductility (ductile): ability of structural systems and materials to deform and absorb energy without collapse. The converse to this is non-ductile or brittle.

Three basic resistances: bending (flexure), shear, or axial tension or compression. Systems that resist through bending are more ductile.

Three basic types of lateral load resisting systems: moment-resisting frames, shear walls, and braced frames.

*shear walls = most rigid = deflect least

*braced frames = less rigid than shear walls

*moment-resisting frames = least rigid

Moment-Resisting Frames--made from structural steel or reinforced concrete. Three types:

1) *Special moment-resisting frame (SMRF)*: Can absorb a large amount of energy in its inelastic range without failure or unacceptable deformity. Concrete frames in Seismic Zones 3 & 4 must be SMRF.

2) *Intermediate moment-resisting frames (IMRF)*: Less stringent concrete frame. Only used in Seismic Zones 1 & 2.

3) *Ordinary moment-resisting frames (OMRF)*: Steel or concrete that doesn't meet stringent ductile behavior requirements. Any zone for steel; only Zone 1 for concrete.

Shear Walls--resists lateral forces by developing shear in its own plane and cantilevering from its base. Simply: cantilever beam that develops flexural stresses as well as its basic shear stress.

*Foundation-wall connection must be enough to prevent sliding.

Made from: reinforced masonry, steel or facing of plywood, particleboard or fiberboard over wood studs.

Wood shear wall = wood structural panel in UBC, which provides a table.

Braced Frames--vertical truss that resists lateral forces by axial tension and compression in the truss members. Mostly made from structural steel.

Two types: eccentric and concentric

Concentric: centerlines of intersecting meet at a point; subject primarily to axial forces. Shear and axial forces limit amount of motion and energy absorbed.

Eccentric (EBF): steel-braced frame where at least one end is eccentric to beam-column joint or opposing brace. Properly detailed and designed can be as ductile as moment-resisting frames.

R_w Values (defined by UBC table)

Bearing wall system: vertical load supported by bearing or bracing and lateral forces by shear walls or braced frames. Shear wall and braced frames support vertical and lateral. Assigned low R_w value.

Building frame system: complete frame the provides support for vertical loads. No vertical load on shear walls or braced frames. Vertical frame provides some secondary resistance to lateral forces. Intermediate R_w value.

Moment-resisting frame system: an essentially complete framing system that provides support for vertical loads and resistance to lateral loads. SMRF have the greatest ductility and are assigned the maximum R_w value of 12.

OMRF and IMRF are much less ductile and have lower R_w values(5-8). Only steel OMRF are permitted in Seismic Zones 3 and 4 and limited to 160' high.

Dual system: complete frame that provides support for vertical loads. Based on relative rigidities, both MRF and shear walls or braced frames are also used. The MRF must resist 25% of the total lateral force independently.

Distribution of Base Shear

After base shear (horizontal force), must distribute this force at various levels of the building.

Portion of V , called F_t , is considered to be at the top of building:

$$F_t = 0.07TV$$

$F_t \leq 0.25V$ and may be zero When T is 0.7 seconds or less.

F_t = "whiplash effect" and applies to long period buildings

The force applied to any level $x =$

$$F_x = \frac{(V - F_t)w_x h_x}{\Sigma wh}$$

where

$w_x =$ the dead load located at or assigned to level x

$h_x =$ the height in feet above the base to level x

$\Sigma wh =$ the summation of the wh quantities
for each level.

"Triangle shaped" shear distribution: if weights of all stories are equal, with zero at base and maximum at the top level, when horizontal force is applied to each level.

Overturning

All buildings must be designed to resist overturning moments. Only **85%** of dead load may be used to resist uplift.

Deflection and Drift

Earth quake causes structure to deflect and story-to-story horizontal movement called *story drift*. Stiff systems have small drifts; flexible MRF's tend to have larger drifts.

Pounding: when buildings collide during an earthquake. To minimize pounding, *seismic separation* must be equal the sum of the expected drifts of the two buildings.

P-Delta Effect: if story drift is Delta (Δ) and the vertical load in a column is P , the bending moments in the story are increase by an amount equal to $P \cdot \Delta$ or P-Delta. Must be taken in account unless very low relative to the story bending moments.

Diaphragms

Diaphragm: horizontal floor or roof system that distributes lateral forces to the vertical resisting elements (shear walls, braced frames, MRFs). Similar to horizontal girder spanning between vertical resisting elements.

$$\text{Max. Diaphragm Shear} = \frac{F \div 2}{d}$$

F = horizontal force

d = depth of diaphragm

Flexible diaphragm: acts as a simple beam while distributing horizontal forces to vertical elements, which resists horizontal forces on a tributary area basis. Wood and some steel deck diaphragms are considered flexible. Rigidity of walls not considered. End walls may resist $1/4$ of the lateral loads and middle wall $1/2$ of lateral load.

Rigid diaphragm: distributes horizontal forces to vertical elements in proportion to their relative rigidities (resistance to deformation). Concrete and some steel deck diaphragms are considered rigid.

If three walls have a rigidity of 2 (end), 1 (middle), and 2 (end), $\Sigma R = 2 + 1 + 2 = 5$. End walls resist $2/5$ of total lateral load, and middle wall resists $1/5$.

Wood structural panels (including plywood) are shown on Table in UBC. Plywood is often used as a diaphragm in small and lightweight buildings.

Shear values of steel deck diaphragms vary from 100-2600 pounds per lineal foot, depending on thickness, welds or other attachments, framing between deck sheets, and span.

Concrete slabs can be used as diaphragms. A 6" concrete slab has an allowable shear of about 10,000 lbs. per lineal foot.

Deflection: must be considered in diaphragms. as span between vertical resisting elements increases, the deflection of the diaphragm comes at a greater rate.

Connections of vertical resisting elements to diaphragm must:

- 1) Transfer the diaphragm sheer force, which is parallel to the shear wall, into the wall.

- 2) Connect the diaphragm to the chord or flange.
- 3) Connect the wall to the diaphragm for seismic forces perpendicular to the wall.

Collectors

Collector (strut or drag strut): when shear resisting element is discontinuous, it collects seismic load from diaphragm and delivers it to the shear resisting element.

Torsion

Torsion: rotation caused in a diaphragm when the center of mass (where resultant load is applied) does not coincide with center of rigidity (where the resultant load resisted). Only occurs in rigid diaphragms.

Forces in shear resisting elements caused by torsional moment is directly proportional to:

- 1) magnitude of torsional moment
- 2) distance of shear resisting element from center of rigidity

3) rigidity of shear resisting element

*If torsional moment (same) \rightarrow applied seismic force, add forces

*If torsional moment (opposite) \leftarrow applied seismic force, not subtracted.

Code requires an arbitrary amount of accidental torsion even if building is symmetrical. Mass of at each level assumed to be displaced 5% of building dimension at that level perpendicular to force.

Simplified example for a rectangular building:

$$x = V \cdot .05L \text{ (length of building)}$$

$$y = V \cdot .05W \text{ (width of building)}$$

$(x, y) = \text{displace center of mass} = \text{accidental torsional moment}$

Irregular buildings have the worst torsion. Locating shear resisting elements at perimeter and making building and shear resisting elements more symmetrical reduces torsion.

Parts of Structures

UBC requires parts of structures and their attachments use the following formula:

$$F_p = ZIC_pW_p$$

F_p = lateral force on part of structure

Z & I = seismic zone and importance factor for building

C_p = horizontal force factor based on UBC table

W_p = weight of part of the structure

Typically, moment would be figured also.

Combined Vertical & Horizontal Forces

UBC requires the following load combinations for all building components:

*Dead load + floor live load + seismic

*Dead load + floor live load + snow load + seismic

Roof and wind loads are not considered to be occurring the same time as seismic so are not figured.

If earthquake forces are considered to be acting alone or combined with vertical loads above, stresses can be increased $1/3$.

Regular & Irregular Structures

Regular structures—no significant discontinuities in plan, vertical configuration or lateral force resisting systems.

Irregular structures—Significant vertical and plan discontinuities.

Vertical irregularities:

- *Stiffness irregularity-soft story
- *Weight (mass) irregularity
- *Vertical geometric irregularity

- *In-plane discontinuity in vertical lateral-force-resisting elements

- *Discontinuity in capacity (weak story)

Plan irregularities:

- *Torsion irregularity-to be considered when diaphragms are not flexible

- *Reentrant corners

- *Diaphragm discontinuity

- *Out-of-plane offsets

- *Nonparallel systems

Base Isolation

Since ground motion is transmitted during an earthquake directly to the structure, base isolation isolates the building from the ground through the use of specifically-designed bearings and dampers that absorb earthquake forces.

Base isolation helps reduce the building's acceleration from ground motion.

Tubular Concept

Pioneered by Fazlur Khan of SOM.

Consists of closely-spaced columns at the perimeter of the building connected by deep spandrel beams at each floor to form a perforated wall at each facade.

Examples: John Hancock Building and Sears Tower in Chicago and the World Trade Centers.

Nonstructural Considerations

Nonstructural elements must be considered when designing a building. Doors and objects that may be damaged and impinge evacuation need to be considered. Mechanical and electrical systems should be designed to survive and earthquake.

Various methods of securing nonstructural components includes straps and bracing.

Existing Buildings

(see FEMA 154 for detailed analysis)

Seismic concepts apply to new and existing buildings.

General evaluations are as follows:

- 1) There should be a complete lateral force resisting system
- 2) Deteriorated existing lateral and structural systems may need to be corrected.
- 3) Projects such as chimneys, cornices, and parapets may need to be reinforced.
- 4) Exterior cladding should be adequately attached.

- 5) Large diaphragm openings should be reinforced for sufficient strength and stiffness.
- 6) Walls with large openings may be inadequately reinforced.
- 7) Glazing should be isolated from building.
- 8) Wood frame buildings generally perform well but may be badly damaged and contents destroyed.
- 9) Wood stud walls should be properly anchored to prevent slippage away from foundation
- 10) Wood cripple walls should be properly braced to prevent collapse

- 11) Straight sheathing on wood framed walls and roofs may not provide adequate diaphragm strength and may need to be reinforced with rods or plywood
- 12) Properly connect split level floors
- 13) Concrete and masonry walls should be properly reinforced and anchored
- 14) Unreinforced masonry walls are very susceptible to collapse and damage.
- 15) Anchor wood diaphragms to concrete or masonry walls with ties. Don't rely on a wood ledger.

16) Analyze diagonal cracks in masonry or concrete walls for previous seismic damage.

17) Metal deck floors and roofs without a reinforced concrete topping may not have adequate diaphragm strength.

18) Restoration of historic buildings in seismic zones by reinforcing existing elements is preferred.