Useful Architectural and Structural Considerations for Earthquake Resistant Design

Contents

- Introduction
- Regularity of structures
- Structural wall configuration in structures with dual wall-frame lateral load resisting systems
- Uniform distribution of mass and stiffness
- Effects of non-structural components
- Multiple defense lines
- Balanced stiffness, strength and ductility
- Desirable features of structural materials for Earthquake resistant design
- Basic Design Guidelines from Past Earthquakes

Introduction

- Buildings are designed by architects and engineers.
- Architects are responsible for the architectural configuration of buildings at the start.
- Configuration has to do with the size, shape and proportion of the 3D form of the building.
- Architectural configuration determines the location, shape and approximate size of structural and non-structural elements of the building
- Any architectural design should incorporate effective seismic design to minimize EQ hazards.

While the provision of earthquake resistance is accomplished through structural means, the architectural design and the decision that create it, play a major role in determining the building's seismic performance

C. Arnold

Importance of Conceptual Design

- In order to reduce uncertainties of the estimation of the seismic demands, more attention should be paid to the conceptual design
  - Control or decrease ductility demand by:
    - the use of base isolation
    - the use of energy dissipating device (Structural controls)
    - the proper selection of the structural configuration
  - Provide large ductility with stable hysteretic behavior
    - Achieve integral action of the whole structure by tying together the main components and detail the plastic hinge location carefully

27 December 2017 Addis Ababa University (Dr. Adil Z.) 5

Selection of proper system configuration for the superstructure

27 December 2017 Addis Ababa University (Dr. Adil Z.) 6

Appropriate Configurations

- Simple configuration → simple behavior
- Building and its structure Should
  - be Simple Symmetric and Regular in Plan and Elevation
  - have a uniform and continuous distribution of mass, stiffness, strength and ductility.
  - have the largest possible number of defense lines.
  - have well separated non-structural components
  - be detailed so that the inelastic deformations can be constrained (controlled) to develop in desired regions and according to a desirable hierarchy
  - be provided with balanced stiffness and strength between its members, connections and supports.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 7

Optimal structural configuration

Attributes	Benefits
Low width-to-depth ratio	Low torsional effects
Low height-to-base width/depth ratio	Low overturning effects
Similar storey heights	Elimination of weak/soft storey
Short spans	Low unit stress and deformation
Symmetrical plan shape	Elimination/reduction of torsion
Identical resistance on both axes	Balanced resistance in all directions
Uniform plan/elevation stiffness	Elimination of stress concentrations
Uniform plan/elevation resistance	Elimination of stress concentrations
Uniform plan/elevation ductility	High energy dissipation
Perimeter lateral resisting systems	High torsional resistance potential
Redundancy	High plastic redistribution
Direct load path, no cantilevers	Elimination of stress concentration

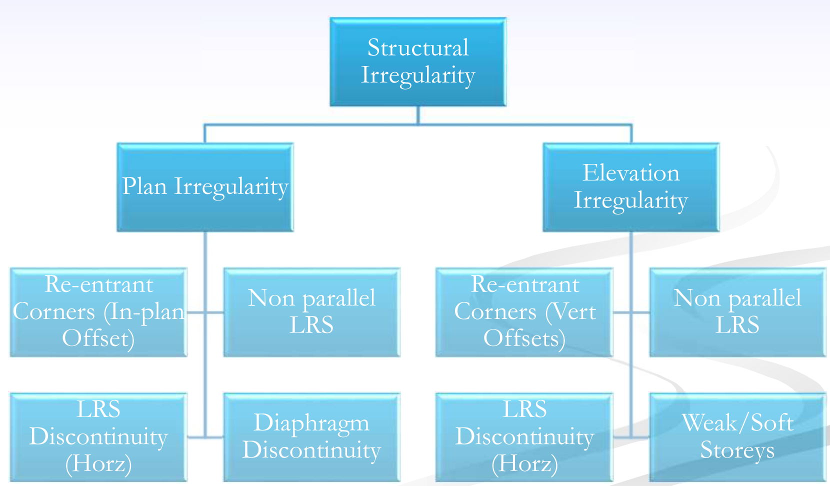
27 December 2017 Addis Ababa University (Dr. Adil Z.) 8

Regularity

- An aspect of seismic design of equal if not greater importance than structural analysis is the choice of building configuration.
- Lack of symmetry (in mass distribution and/or in stiffness, strength and ductility)
  - leads to torsional effects
  - difficult to assess properly
  - can be very destructive
- A regular rectangular plan building with asymmetrical stiffening → irregular (torsion)

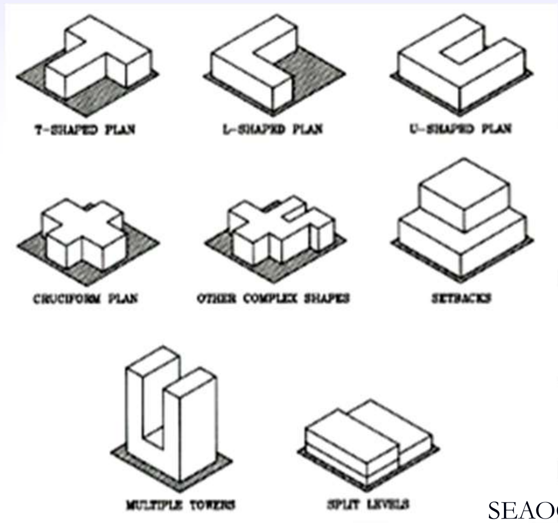
27 December 2017 Addis Ababa University (Dr. Adil Z.) 9

Structural Irregularities

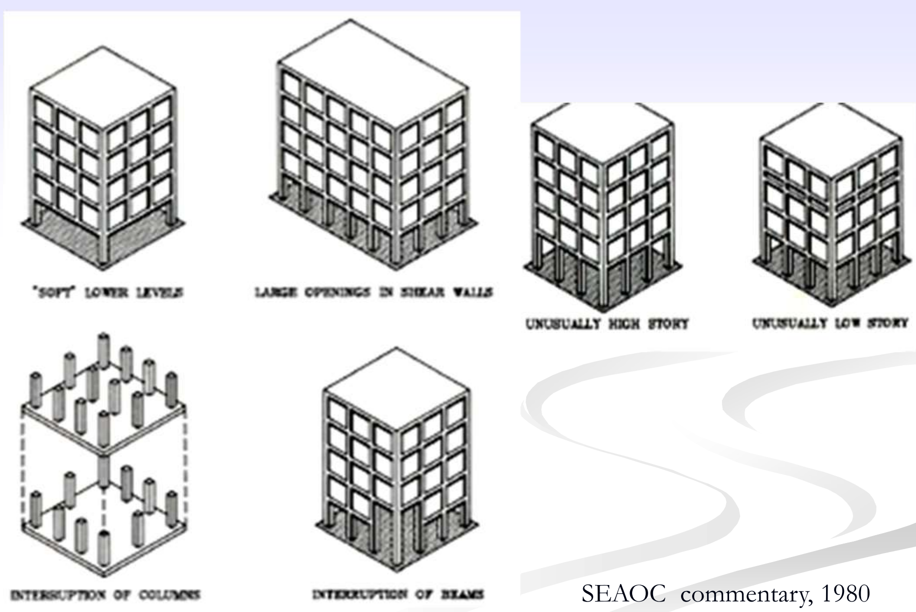


27 December 2017 Addis Ababa University (Dr. Adil Z.) 10

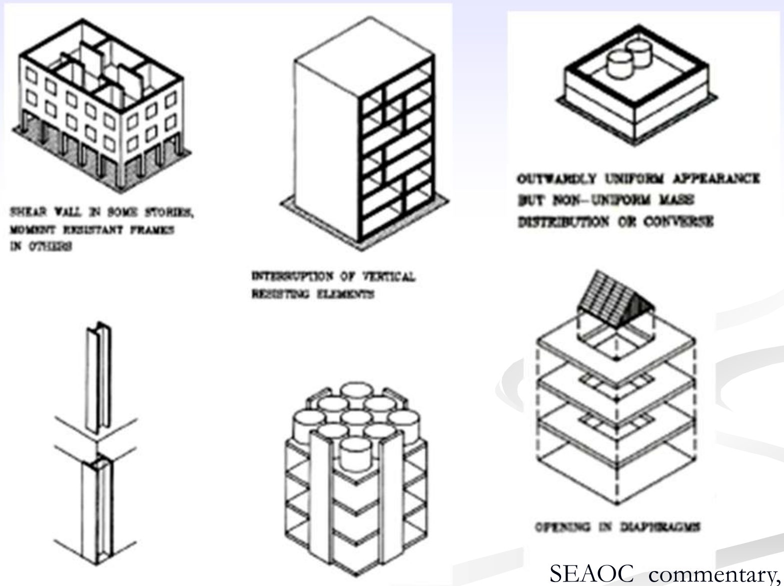
Irregular structures or framing systems



SEAOC commentary, 1980

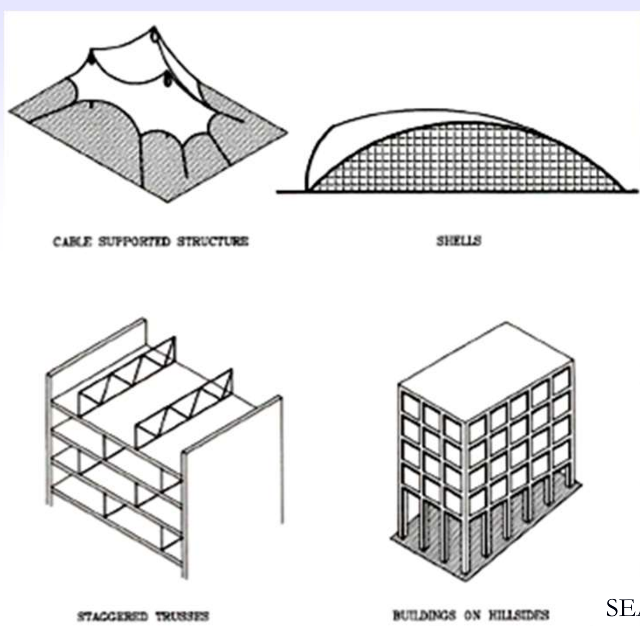


SEAOC commentary, 1980



SEAOC commentary, 1980

27 December 2017 Addis Ababa University (Dr. Adil Z.) 13



SEAOC commentary, 1980

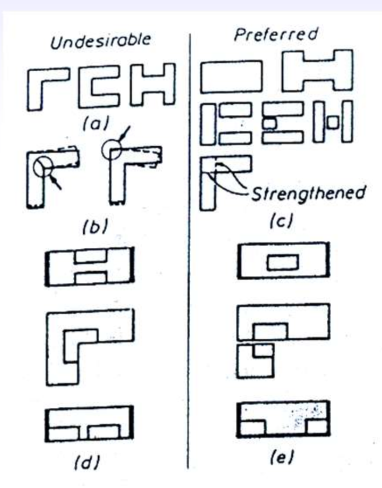
27 December 2017 Addis Ababa University (Dr. Adil Z.) 14

Regularity in Plan

- Simple & symmetrical building plans give
  - more efficient and
  - predictable seismic response
  - A prerequisite for the desirable interaction between lateral-force-resisting structural system
- Reentrant corners inviting stress concentrations, hence should be avoided.
- If necessary separation should be provided
  - This may lead to a number of simple, compact, and independent plans

27 December 2017 Addis Ababa University (Dr. Adil Z.) 15

Plan Regularity (Cont'd)

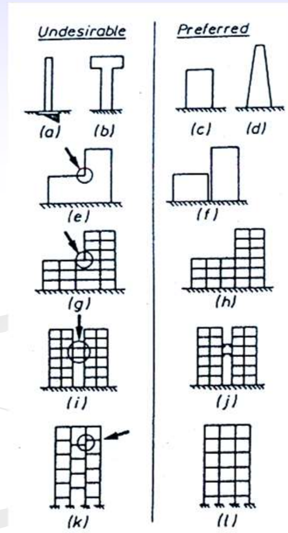


- Gaps separating adjacent structures must large enough to avoid hammering of adjacent structures due to out-of-phase relative motion of the independent structures
- Openings should not jeopardize diaphragm action of the slabs and be symmetrically placed

27 December 2017 Addis Ababa University (Dr. Adil Z.) 16

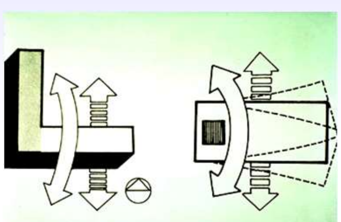
Regularity in Elevation

- Tall and slender buildings should be avoided
- Concentration of masses at the top of a building should be avoided
- Setbacks should be avoided
- If required, adequate structural separation should be provided.
- Irregularities within the framing system should be avoided
- Any connections (bridging) between two independent buildings should be such as to prevent horizontal force transfer between the two structures
- Staggered floor arrangements should be avoided



27 December 2017 Addis Ababa University (Dr. Adil Z.) 17

Common Failures caused by Irregularities



Torsional effects created by irregular shape of building plan (L configuration) and by a very stiff off-center core area in a rectangular (regular) plan building

Typical example

Hotel Terminal, Guatemala City. Overall view of this 6-story hotel, illustrating the torsional failure of the second story during the 1976 Guatemala Earthquake.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 18

Common Failures caused by Irregularities (Cont'd)

View inside the above building showing the collapse of the second story due to shear failure of the second-floor columns. Note the significant lateral displacement (interstory drift to the right) due to the torsional rotation of the upper part of the building.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 19

Common Failures caused by Irregularities (Cont'd)

Close-up of one of the collapsed columns of the above slide. Note that the upper floor has displaced to the right and dropped, and the top and bottom sections of the column are now side-by-side. Although the columns had lateral reinforcement (ties) these were not enough and at inadequate spacing to resist the shear force developed due to the torsional moment which originated in the second story.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 20

Common Failures caused by Irregularities (Cont'd)

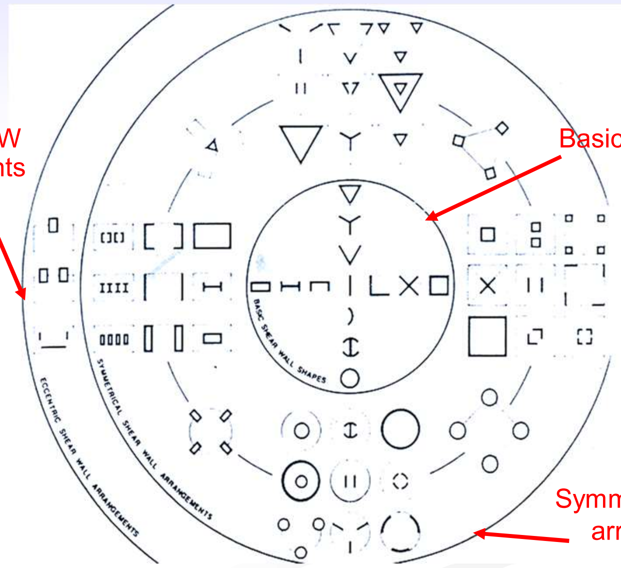
Bridge failure

Pounding

Soft story

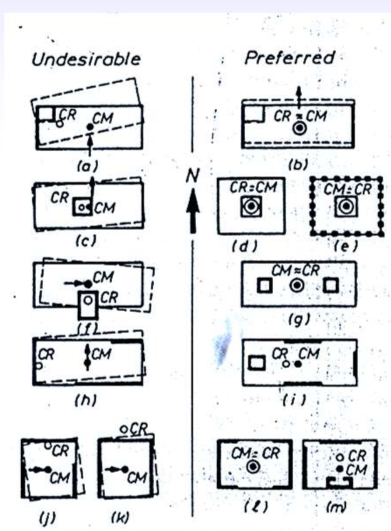
Structural wall Configuration in structures with dual wall-frame lateral load resisting systems

Possible Shear wall shapes & arrangements



27 December 2017 Addis Ababa University (Dr. Adil Z.) 23

Configuration in wall-frame system



Examples for both preferable and undesirable positioning of major lateral-force-resisting elements, consisting of structural walls and moment resisting frames.

➢In all cases the distance between the CM and CR should be reduced in order to minimize torsional effects

27 December 2017 Addis Ababa University (Dr. Adil Z.) 24

Uniform Distribution of Mass and Stiffness

Distribution of Mass in a Building

- Dynamic response of a structure depend on
  - distribution of its reactive masses
  - amount and distribution of the masses
- The smaller the reactive masses, the smaller the earthquake forces will be
- The use of unnecessary masses should be avoided.
- i.e. reactive masses are masses that will react to the shaking of the building foundation.

Uniform Mass Distribution (Cont'd)

Damage to a wooden house due to a heavy roof supported on a flexible frame. 1971 San Fernando Earthquake.

Damage to the old portion of the Olive View Hospital in the 1971 San Fernando Earthquake. This building had a very heavy tile roof supported on unreinforced brick masonry and was neither designed nor detailed to resist seismic effects

27 December 2017 Addis Ababa University (Dr. Adil Z.) 27

Uniform Stiffness Distribution

Olive View Hospital, Psychiatric Unit, San Fernando, California. 1971 San Fernando Earthquake. This unit was a 2-story reinforced concrete building. The structural system was a moment resisting frame. However, in the second story there were masonry walls that added significantly to the stiffness of this story.

- Lightweight concrete was used in the construction of this building. Note that the building collapsed completely at the first (soft) story and the second floor dropped to the ground after moving laterally about 2 meters

27 December 2017 Addis Ababa University (Dr. Adil Z.) 28

Uniform Stiffness Distribution (Cont'd)

- Imperial County Services Building. Overall view of this modern 6-story reinforced concrete building. Not the continuous shear wall at the east end of the building which was discontinued (offset) at the second floor level, resulting in a severe discontinuity and in a practically open first story (soft story in the E-W direction).

Uniform Stiffness Distribution (Cont'd)

- View of the first story columns located in the east end of the building. Note that the explosive type of failure just above the ground and the offset between the columns and the solid shear wall.

- Close-up of the failure at the bottom of the column at the southeast corner of the building. The failure occurred in the zone of the column where there was not adequate confinement of the concrete and shear reinforcing steel.

Effects of non-structural components

27 December 2017 Addis Ababa University (Dr. Adil Z.) 31

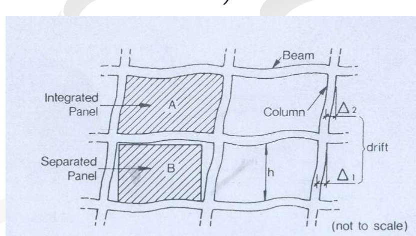
Non-structural infill panels and partitions

- Earth quake produces story drift.
- Causes vertical deformations ⇒ Change in height
- Any infill panel should be designed to deal with both these movements either by:
  - Integrating (very stiff frame with flexible infill)
  - Separating (more preferable for flexible frames)

In the absence of computed values use the following minimum separations

20mm for horizontal

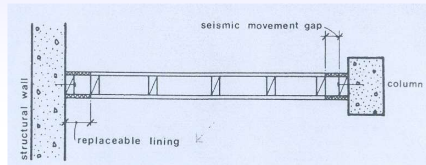
40mm for vertical



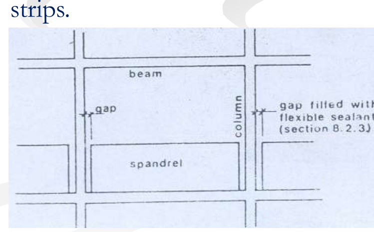
27 December 2017 Addis Ababa University (Dr. Adil Z.) 32

Cladding, wall finishes, windows and doors

- In flexible buildings, precast concrete cladding should be mounted on fixings which ensure separation from horizontal drift movements of the structure
- Brittle or rigid finishes should be avoided or specially detailed
- stairwells should be free of material which may spall or fall
- Window sashes should be separated from frame action



Lightweight partition detailed so that earthquake hammering by the structure will damage limited end strips.

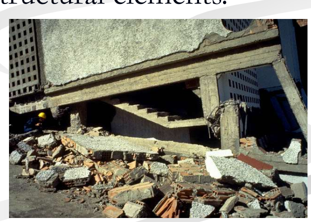


Detail of external frame showing separation of spandrel or parapet from columns to avoid unwanted interaction.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 33

Effect of Non-Structural Components

Two-story reinforced concrete building, Managua, Nicaragua, damaged in the 1972 Managua Earthquake. The slide shows a reinforced concrete column which was part of the structural system and which failed due to its shortening because of the effect of the masonry wall. The masonry walls were considered as non-structural elements.



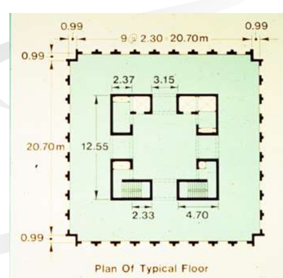
Medical Clinic in El Asnam, Algeria.Close-up of column failure of this new 4-story reinforced concrete building induced by the response of the building to the 1980 El Asnam Earthquake.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 34

Multiple Line of Defense

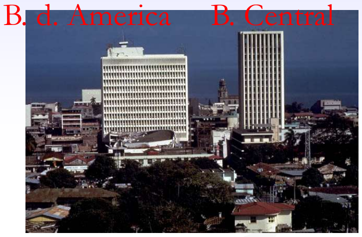
Multiple defense lines

- A structure should have the largest possible number of internal and external redundancies. While a high degree of static indeterminacy is desirable, this is not sufficient. In order that a building be efficient in resisting severe earthquake shaking, it should have sufficient ductility, toughness and stable hysteric behavior under repeated cycles of deformation reversals
- Plan view of the Banco de America, Managua, Nicaragua. This building generally performed very well during the 1972 Managua Earthquake. Its excellent performance can be attributed to the symmetry and uniformity of distribution of the masses and structural stiffnesses throughout the building.



Multiple defense lines (Cont’d)

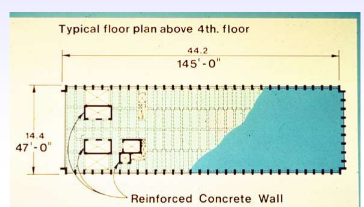
- The structural system, which can be considered as a combination of the ductile walls with a framed tube, is an excellent system for seismic-resistant design, providing several lines of defense whereby the behavior of the whole system can accommodate the demands of a severe earthquake.



- View of the core service walls and floor area at the second story of the Banco de America, Managua, Nicaragua. Note that few of the marble tiles that cover the reinforced concrete shear walls have spalled off. This was the only visible damage in this story after the 1972 Managua Earthquake.

Multiple defense lines (Cont’d)

- Typical floor plan above the fourth floor of the Banco Central Building, Managua, Nicaragua. This building had a reinforced concrete frame as the basic structural system. Note that the overall configuration of the reinforced concrete system of the tower was not symmetric.



- View of the stairway after the 1972 Managua EQ. Most of the stairs were covered with debris that resulted from the failure of the hollow tile partitions surrounding the stairs. The damage (structural and non-structural) and the protection of the contents of this very flexible moment resisting frame building were in sharp contrast with those observed in the taller but symmetric combined coupled shear wall-tubular frame structural system of the Banco de America Building. There was also significant structural damage that resulted in the need to demolish the tower of this building.

Balanced Stiffness, Strength and Ductility

Balanced stiffness, strength and ductility

- "A chain breaks at its weakest link". It is not worthwhile using strong, stiff and ductile structural members if they are not properly connected. Collapse and severe damage of buildings due to lack of good connections is common.
- Galerie Algerienne Building, El Asnam, Algeria, 1980 El Asnam Earthquake. View of the unit of this four story RC building which collapsed in the earthquake. Lack of adequate reinforcement at the column-girder connections was one of the reasons for the collapse of this unit.

Balanced stiffness, strength and ductility (Cont'd)

- Naiguata Beach Club Building, Naiguata, Venezuela, 1967 Caracas Earthquake. This was a single-story building (approximately 7 meters high) with a mezzanine at 3 meters above ground. This slide shows the damage at the connection between the column and the girder supporting the mezzanine

- Mosque Building, El Asnam, Algeria, 1980 El Asnam Earthquake. View of the first story column and column-girder connection at the second floor level of the mosque.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 41

Balanced stiffness, strength and ductility (Cont'd)

- Four Season Apartment Building, Anchorage, Alaska, 1964 Alaska EQ. General view of the building after the EQ. The lateral resistance to earthquake ground motions was essentially provided by the two slender vertical reinforced concrete shafts. These shafts failed at the ground floor level where all the vertical reinforcing bars in the shafts were spliced

- Overall view of an Apartment Building, Anchorage, Alaska, 1964 Alaska EQ. This 14-story RC structure has as a basic lateral-resisting structural system a series of slender walls coupled by spandrel girders that worked as coupling girders. Unfortunately these spandrel girders were not designed (detailed) to work as coupling girders and therefore suffered significant damage in the EQ.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 42

Desirable features of Structural materials for Earth quake resistant design

- High ductility
- High strength-to-weight ratio
- Homogeneity
- Ease in making full-strength connections
- Possibility of suppression of brittle failure modes

Typical brittle failure modes of common construction materials

Material of construction	Brittle failure mode
Reinforced Concrete	Buckling of reinforcement bars Bond or anchorage failure Member shear failure
Masonry	Out-of-plane bending failure Global buckling of walls Sliding shear
Structural Steel	Fracture of welds and/of parent material Bolt shear or tension failure Member buckling Member tension failure Member shear failure

Suitable Construction Material for Moderate to High EQ Loading

	Type of building		
	High-rise	Medium-rise	Low-rise
Best Structural materials in approximate order of suitability Worst	(1) Steel (2) *In situ* reinforced concrete	(1) Steel (2) *In situ* reinforced concrete (3) Good precast concrete[1] (4) Prestressed concrete (5) Good reinforced masonry[1]	(1) Timber (2) *In situ* reinforced concrete (3) Steel (4) Prestressed concrete (5) Good reinforced masonry (6) Precast concrete (7) Primitive reinforced masonry

[1]These two materials only just qualify for inclusion in the medium-rise bracket. Indeed, some earthquake engineers would not use either material in these circumstances.

Dorwick 2009

Basic design guidelines from past EQ

1. Avoid unnecessary mass. Achieve a uniform distribution of mass.
2. Preserve symmetry. Avoid significant torsional motions.
3. Us as simple a structural system as possible. Make sure there is a complete load path.
4. Use a redundant structural system. Use a backup structural system where ever possible.
5. Structure should be compact and regular in both plan and elevation. Avoid structures with elongated or irregular plans; having substantial setbacks in elevation; or that are unusually slender.
6. Use a uniform and continuous distribution of stiffness and strength. Avoid nonstructural components that unintentionally effect this distribution. Avoid sudden changes in member sizes or details.

Prof. S. Mahin U C Berkeley

Basic guidelines (cont'd)

7. Permit inelastic action (damage) only in inherently non-critical ductile elements (i.e., in beams rather than columns).
8. Detail the members to avoid premature, brittle failure modes. Utilize capacity design principles to avoid undesired shear, axial or joint failures and to foster ductile flexural failure modes.
9. Avoid hammering (pounding) of adjacent structures.
10. Tie all structural components together. Anchor nonstructural components to structure to avoid falling hazards.
11. Avoid systems with low amounts of viscous damping. Absence of nonstructural components tied to structure may be indication of low damping in steel structures.

Prof. S. Mahin U C Berkeley

27 December 2017 Addis Ababa University (Dr. Adil Z.) 47

Building codes are useful design tools

Define "standard of care" ... important legal and professional concept.

But ... focus is on minimum standards needed for the protection of <u>life safety</u>

" 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 buildings."

- ✓ A detailed, prescriptive "deemed-to-comply" format used.
- ✓ Contains a mix of empiricism, simplified theory and expert judgment.
- ✓ Current codes provide little guidance on how various stipulations relate to performance.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 48

Codes improving, but not perfect …

Uneven performance of model code-compliant buildings noted in recent earthquakes. Some perform very well, while others are inadequate.

- ✓ Nearly 70% of new steel buildings shaken by the Northridge earthquake suffered brittle fractures in their welded beam to column connections. More than 10% of new steel welded moment frame buildings in Kobe collapsed.
- ✓ Several new reinforced concrete structures collapsed or were severely damaged during the Northridge and Loma Prieta earthquakes.
- ✓ Important buildings designed by well respected engineers, under stringent quality control conditions are frequently damaged.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 49

Architect – Engineer Relationship

- While the provision of earthquake resistance is accomplished through structural means, the architectural design and the decision that create it, play a major role in determining the building's seismic performance
- Seismic design is a shared architectural and engineering responsibility, which stem from the physical relationship between architectural forms and structural systems.
- The interrelation between issues of engineering and architecture demand that architect and engineer work together from the inception of the project.

27 December 2017 Addis Ababa University (Dr. Adil Z.) 50

Architect – Engineer cont'd

- In resistance to gravity loads architectural and structural decisions may be made independently of each other. But in resistance to EQ effects, separating the engineer from the architect is the formula for disaster.

M. Sozen 1978

References

1. Dowrick, D. J., "Earthquake Resistant Design," 2nd Edition, John Wiley & Sons, 1987.
2. Chen, W-F.; Scawthorn, C., "Earthquake Engineering Handbook", CRC Press, 2002
3. Naiem, F., "Seismic Design Handbook" Kluwer Press, 2001
4. Kramer, S., "Earthquake Geotechnical Engineering", Prentice Hall, 1995
5. Paulay, T., Priestley, M.J.N. "Seismic Design of Reinforced Concrete and Masonry Buildings," John Wiley & Sons, 1992.
6. Wolfgang Schueller, "High-Rise Building Structures," John Wiley & Sons, Inc New York, 1977.
7. Online material from the site http://nisee.berkeley.edu/