Let’s start with some general issues.
There must be a realisation that there is a real risk that “design” forces may be exceeded. This is particularly so in the case of earthquakes where, largely for perceived economic reasons, the design force is deliberately determined to be less than that expected during the anticipated life of the building. This leads to a requirement for redundancy in the structure and for “toughness” - the ability to absorb overloads without collapse.
On May 22, 1960 at 19:11:14 UTC, with the epicenter in Valdivia, about 700 kilometers south of Santiago, Chile – the world's largest instrumentally recorded earthquake since measurements began in 1899 – The magnitude: an earth shaking 9.5
Wind storms and earthquakes are open-ended phenomena

6.3 (M\text{\textcircled{L}})
Canterbury
22 Feb 2011
TTIA CPD Seminar on Conceptual Design for Earthquakes

17 September 2018

Tony Gibbs FREng
Soil-structure Interaction

Response of different components and contents of a building during an earthquake

T. Guevara, 1999
Examples of Non-structural Components affected by earthquakes
Damage to partition components can also cause damage to the basic components that go within, along, or across them, such as gas pipes, water pipes, electrical wiring.

Special attention must be paid to fragile partitions in critical areas, such as in hospitals, exit routes, etc.
Suspended ceilings - particularly vulnerable in earthquakes.

Placement of restraints for suspended ceilings, lighting fixtures and air-conditioning units.
The disruption of documents necessitates the use of human resources for cleanup when they are required for priority tasks in the aftermath of an earthquake. (PAHO)
Cladding damaged in the Mexico earthquake of 1985 (PAHO CD-ROM)

Architectural components that run across seismic joints must be correctly detailed.
Basic services may be interrupted due to failures associated with the inappropriate crossing of seismic joints.

Plumbing damaged because of the absence of a flexible connection.

*(PAHO CD-ROM)*
Interaction between structural and nonstructural elements

Interaction of masonry walls with reinforced concrete frame, causing failure due to short columns
Short columns can and should be prevented

Architecture and Engineering
**Configuration** encompasses:

1. architectural shape and size;
2. type, size and location of structural elements;
3. type, size and location of non-structural elements.

Buildings are designed by architects and engineers. In reality, in most cases, buildings principally for human occupancy are designed conceptually by architects. That is to say that architects are the ones principally responsible for the configuration of buildings for human occupancy.
Configuration has to do with the shape and size of the building. Inevitably shape and size to a large extent determines (or greatly influences) the type, shape, arrangement, size, location and most other aspects of the structural concept.
In the words of Geoffrey Wood (one of the five founding partners of Ove Arup & Partners):

“Earthquake-resistant design is really a problem for architects.”
Either the architect has a better-than-usual knowledge of the basic principles of the conceptual design of earthquake resisting systems

or

The architect should involve the structural engineer in the initial discussions and development of the building concept.
The Tri-services Manual of the USA Army, Navy and Air Force states:

“A great deal of a building’s inherent resistance to lateral forces is determined by its basic plan layout. . . .

“Engineers are learning that a building’s shape, symmetry and its general layout developed in the conceptual stage are more important than the accurate determination of the code-prescribed forces. . . .”

Irregularities in the floor plan
Irregular floor plan

Use of seismic joints for structural designs of buildings with complex floor plans

(A) CONCENTRATION OF STRESSES IN STRUCTURES WITH COMPLEX GEOMETRY

CONCENTRATION OF STRESSES

SEISMIC JOINTS

SEISMIC JOINTS

(B) SEISMIC JOINTS RECOMMENDED FOR COMPLEX FLOOR PLANS
Structural engineer William Holmes, writing in 1976, states:

“It has long been acknowledged that the configuration, and the simplicity and directness of the seismic resistance system of a structure, is just as important as the actual lateral design forces.”

Discontinuity in the elements and the flow of forces
Henry Degenkolb is emphatic in stressing the importance of configuration:

“If we have a poor configuration to start with, all the engineer can do is to improve a basically poor solution as best he can. Conversely, if we start off with a good configuration and a reasonable framing scheme, even a poor engineer can't harm its ultimate performance too much.

“This last statement is only slightly exaggerated.”
Those quotations above warrant discussion among the various disciplines involved in the design and building processes. Terán (Nicaraguan architect) recommends that buildings be “simple, continuous, symmetrical, straightforward, and repetitive”. This advice is given not as an absolute, but as a qualitative factor that influences the reliability of the structure. Terán asks for understanding and knowledge among the disciplines, not the imposition of mandatory constraints.
Specific conceptual design issues

Asymmetry (false symmetry) due to the location of rigid elements
Figure 4.21. False symmetry: Banco Central, Managua, Nicaragua. [Re-drawn, with permission, from John F. Meehan et al., "Engineering Aspects," in Managua, Nicaragua Earthquake of December 23, 1972, Reconnaissance Report (Oakland, California: Earthquake Engineering Research Institute, 1973).]
Irregularities in elevation

Soft stories
**Damage caused by shearing force on ground-floor columns**

![Image](image1)

**Soft story as a result of the discontinuity of walls on the ground floor**

![Image](image2)
Examples of structures with irregularities in elevation

- (a) ABRUPT CHANGES IN GEOMETRY
- (b) CONCENTRATED HAZARDS
- (c) LARGE DIFFERENCES IN THE STIFFNESS OF THE STORIES
- (d) LARGE DIFFERENCES IN THE MASS OF STORIES

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Examples of structures with irregularities in elevation

- (a) ABRUPT CHANGES IN GEOMETRY
- (b) CONCENTRATED HAZARDS
- (c) LARGE DIFFERENCES IN THE STIFFNESS OF THE STORIES
- (d) LARGE DIFFERENCES IN THE MASS OF STORIES

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Structural damage mechanisms
We need columns stronger than beams

(a) BEAM DAMAGE MECHANISM (RECOMMENDED)
(b) COLUMN-CONCENTRATED DAMAGE MECHANISM (NOT RECOMMENDED)

ANALYSIS OF VULNERABILITY

INTERNAL PROPERTIES

POTENTIAL PROBLEMS

Top-heavy structure vulnerable to distant earthquakes and resonance of thick soft soils because of vertical transition in mass. Rocking, overturning, and foundation failure enhanced.

Acue y Alcant

Water Tower
The pyramid is the optimal geometric shape for earthquake resistance.

Giza pyramid – – Indianapolis pyramids – – Dallas pyramid
Different structural systems

- Frames
- Shear walls
- Shear walls with boundary elements
- Confined shear walls
- Braced frames
Moment Frames:

They allow greater flexibility than shear walls and braced frames in the functional planning of the building – **positive**.

They exhibit greater deflexions than shear walls and braced frames so that the detailing of non-structural elements becomes more problematic - **negative**.

Seismic Resisting Systems

*Unbraced Frames*

“Rigid”, “Moment resisting” joints
- Special
- Intermediate
- Ordinary
- Not detailed

*Braced Frames*

- Concentric Bracing
- Eccentric Bracing
Materials

Desirable features of structural materials for earthquake resistance are:

- high ductility;
- high strength-to-weight ratio;
- homogeneity;
- ease in making full-strength connections.

Steel Structures
Steel Behavior

Ductility
- Material inherently ductile
- Ductility of structure < ductility of material

Damping
- Welded structures have low damping
- More damping in bolted structures due to slip at connections
- Primary energy absorption is yielding of members

Eccentrically Braced Frames

- Link
- Brace
- Beam
Special Truss Moment Frame

- Buckling and yielding in special section
- Design to be elastic outside special section
- Deforms similar to EBF
- Special panels to be symmetric X or Vierendeel

Leelataviwat et al (1998): retrofitting of moment resisting frames with ductile “fuse” in shear at mid-span (specially braced rectangular opening in the web) instead of modifying beam-to-col connections. Moves the plastic demands away from critical B-C regions, while ensuring that frames develop a ductile mechanism.
Conceptual Structural Design

- **Strength / Deformations** are of paramount importance to control the Life Safety and Collapse Prevention Limit States
- **Stiffness** is the fundamental response quantity to control the Damageability Limit State
- **Accelerations and/or Displacements** control is essential to check the Operational Limit State
- **Adequate Conceptual Design is a trade-off between Displacements / Accelerations / Strength / Stiffness**

The need for base isolation and other energy-dissipating systems
Performance Basis
1997 BSSC NEHRP Provisions

Building Performance

Operational  Immediate  Life Safe  Near  Collapse
Occupancy

Frequent

Design

Maximum

Considered

Ground Motion

Ordinary Buildings

High Occupancy

Emergency Response

Recommended seismic behaviour objectives

Required behavior

<table>
<thead>
<tr>
<th>Level of seismic design</th>
<th>Permanent Operation</th>
<th>Immediate Occupation</th>
<th>Protection of lives</th>
<th>Collapse Prevention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequent (50% over 30 years)</td>
<td>✗</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Occasional (50% over 50 years)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Rare (10% in 50 years)</td>
<td></td>
<td></td>
<td>✗</td>
<td></td>
</tr>
<tr>
<td>Very Rare (10% in 100 years)</td>
<td></td>
<td></td>
<td></td>
<td>✗</td>
</tr>
</tbody>
</table>

- ✗ = Critical security, as in hospitals and fire stations
- ✦ = Essential or hazardous facility or component, such as telephone switchboards and buildings with toxic materials stored inside
- ✕ = Basic or conventional facility, such as offices or homes

Unacceptable performance (new facilities)
First evidence of base isolation for earthquake protection is in Pasargadae, a city in ancient Persia, now Iran. The **Tomb of Cyrus** is the burial place of Cyrus the Great of Persia (c. 590 BC; August 530 BC), founder of the Persian Empire.
Latest research on Pasargadae’s structural engineering has shown the Achaemenid engineers constructed the city to withstand a severe earthquake, at what would today be classified as a ‘7.0’ on the magnitude scale. The foundations are today classified as having a base isolation design, much the same as what is presently used in countries for the construction of facilities - such as nuclear power plants - that require insulation from the effects of a seismic activity.
Ancient Greek temples, Chinese monasteries, temples and bridges, as well as temples erected in Italy in the past appear to be protected by seismic isolation systems.

Gaius Plinius Secundus, *Naturalis Historia*: “Grecae magnificentiae vera admiratio extat templum Ephesiae Dianae CXX annis factum a tota Asia. In solo id palustri fecere, ne terrae motus sentiret aut hiatus timeret, ursus ne in lubrico atque instabili fondamenta tantae molis locarentur, calcatis ea substravere carbonus, dein velleribus lanae”.

Gaius Plinius Secundus (23-79 AD) in the *Naturalis Historia* states:

“A true wonder of Greek magnificence, the temple of Diana of Ephesus, built 120 years ago, stands out in the whole of Asia (Minor).

“In the ground they made it swampy lest it feel the movement of the ground or cracks might appear.

“Moreover so that the (mill)stone foundations not be placed in a slippery or unstable position they had trampled down fleeces of wool, and these remained underneath the foundation stones.”
Possible locations of base isolators

How does it work?

Main properties:
- Resist vertical loads of the superstructure;
- High lateral deformability;
- High energy dissipation;
- Recentering devices.

The behaviour of base isolated structures differs significantly from fixed base counterparts, because of:
- Elongation of vibration period;
- Increment of the structural viscous damping
**How does it work?**

**Period Elongation**

**Damping Increment**

Period Elongation & Damping Increment

**Horizontal seismic action**

**Horizontal seismic isolation**

*(case of High Damping Rubber Bearings – HDRB)*

---

**Conventional building**

\[ F_{c2} >> F_{c1} \]

**Base isolated building**

\[ F_{i2} \geq F_{i1} \]

**BRITE EURAM Project, 1993**

*Horizontal seismic isolation*

*Source: Alessandro Martelli*
HDRB Isolator

Source: Alessandro Martelli

Base-isolation technique

Center of Information on Natural Disaster Research
Energy dissipation

Tests with electroinductive dampers on the ENEA shake table.

Source: Alessandro Martelli

Method of “strengthening”: dissipation of energy used in the central offices of Instituto Mexicano del Seguro Social-México (PAHO)
Elastic-plastic dampers

Visco-elastic dampers

SMA load limiting devices

Shock transmitter

Source: Alessandro Martelli