Luis Esteva
President, National Academy of Engineering of Mexico, 1995 – 97

Areas of interest:

• Seismic hazard and risk analysis
• Structural reliability and optimization
• Performance-based seismic design
EVOLUTION OF SEISMIC DESIGN CRITERIA: AN OVERVIEW
EARTHQUAKE ENGINEERING DURING THE LAST FEW DECADES:

• Significant progress in criteria, methods and tools
• However, seismic-induced disasters continue to occur around the world

• Causes:
  - Excessively lax or insufficiently conservative engineering design and construction practices
  - Under-estimation of seismic hazard by engineering community or by normative groups
  - Small statistical samples of activity of potential seismic sources near the site
  - Lack of consciousness......local soil conditions ....
RECOGNIZED SOURCES OF SIGNIFICANT RISK

• Construction age
• Inadequate structural arrangement or details
• Initial damage conditions
• Obsolete or inadequately applied building codes and norms
• Non-engineered constructions

LESSONS LEARNED FROM EARTHQUAKES

Even for structures designed and built in accordance with state-of-the-knowledge seismic design norms
EVOLVING APPROACHES TO SEISMIC DESIGN

• CONVENTIONAL:
  - Focused on lateral strength (collapse prevention)
  - Recognizing importance of deformation- and energy-dissipating capacities
  - Insufficient attention to damage control
    Structural, non structural
    Direct, indirect,
  - Few explicit requirements oriented to favoring dominance of ductile failure modes

• MODERN:
  - PERFORMANCE-BASED
PERFORMANCE-BASED SEISMIC DESIGN

Objective:

- Specified reliability and performance targets for intensities associated with given return intervals

Many observed cases of severe damage or collapse are associated with the blind application of conventional seismic design criteria, ignoring these concepts and the uncertainties lying beyond them. Prevent occurrence of global brittle failure modes before ductile ones.
Some concepts deserving examination:

- Seismic hazard assessment
- Seismic vulnerability functions:
  - single and multiple components
  - symmetric and asymmetric systems
  - refined and approximate methods
- Along-height irregular systems
- Dual systems: frames, shear-walls
- Influence of initial damage: previous seismic events, differential settlements...
- Capacity design
- Life-cycle expected performance, multi-risk analysis
- From research results to practical engineering criteria
SEISMIC HAZARD AND RISK ASSESSMENT
LESSONS LEARNED WORLDWIDE
SEISMIC HAZARD ASSESSMENT: INFORMATION AND MODELS

• SOURCES OF INFORMATION
  - Instrumental ground motion records
  - Observed seismic intensities
  - Potential activity of near-by seismic sources
  - Intensity attenuation functions ...

• REASONS FOR UNDER-ESTIMATION
  - Insufficient historic evidence
  - Imperfect seismo-tectonic knowledge and models
  - Non-applicable intensity attenuation functions
  - Near-source ground motion features
INSUFFICIENT HISTORIC EVIDENCE: MEXICO CITY, before 1985

- 1957: first earthquake producing severe damage in the city
  - 5 buildings collapsed
  - Selective influence of local soil conditions on moderate and long period structures
- Lack of previous experiences
  - City founded by Aztecs in 1325; conquered by Spain in 1521
  - Aztec and Spanish colonial constructions had remained unscathed

But old Aztec codices included information about several high-intensity low-damage earthquakes!
MEXICO CITY, 1957-1985

- Emergency code
  - Micro-zonation map
  - Different design response spectra

- Network of strong-motion recording instruments

- Several moderate shocks
  - Few casualties
  - Moderate damage: First call about need to design for several limit states other than collapse

- Code revisions:
  - 1966, 1976
  - 1984: started

All inspired confidence!
Mexico City, 1985

From EERI photo gallery
MEXICO CITY, 1985: Collapsed optimism

- Second largest magnitude near the Southern coast of Mexico during XXth Century
- Long epicentral distance: 360km
- Low near-source peak ground accelerations
- Abnormally high energy radiated in the direction of Mexico City, in frequency range similar to that of local soil formations
- Extremely high local amplifications

• Based on experience from 1957: PGA ≈ 0.06g

• Microzonation:
  I  Firm ground
  II Transition zone, $H_s < 20m$
  III Soft soil, $H_s > 20m$

• Types of structures:
  1. Unbraced RC or SS ductile frames, $Q = 6.0$
  2. RC or SS frames; limited contribution of shear walls or bracing elements, $Q = 4.0$
  3. Other RC, SS, wood, confined plain masonry, $Q = 3.0$
  4. Confined or reinforced hollow masonry, $Q = 1.5$
  5. Other systems, $Q = 1.0$
MEXICO CITY, Zone III
SEISMIC DESIGN CODE, 1976-1985

\[
a = a_0 + (c - a) \frac{T}{T_a} \quad \text{for } T < T_a
\]
\[
a = c
\]
\[
a = c \left( \frac{T_2}{T} \right)^r \quad \text{for } T > T_b
\]

Wide plateau: intended to cover uncertainties in \( T_{\text{soil}} \) and \( T_{\text{system}} \)

\[c = 0.24\]
\[T_a = 0.8s\]
\[T_b = 3.3s\]
MEXICO CITY, 1985
Average response spectra

Return intervals:
100-125 years

Seed et al
THE 1985 EARTHQUAKE AND GUERRERO SEISMIC GAP

$M_s = 8.1$

$R \sim 360\text{km}$

Lives: 10,000 (?)

Homeless: 50,000

Collapsed buildings: 200

Monetary loss: $6 \cdot 10^9$ DIs

Aftershock $M_s = 7.5$, 36 hours later
NON-APPLICABLE INTENSITY-ATTENUATION FUNCTIONS: Firm ground site in Mexico City

\[ f = 0.5 \text{ Hz}, \text{All Earthquakes} \]

Ordaz and Singh, 1992
OBSERVED vs PREDICTED FOURIER AMPLITUDE SPECTRA: MEXICO CITY, 1985
MEXICO CITY, 1985
Lessons about structural response

- Discrepancies between observations and nonlinear response estimates in up-to-date design practice
  - Irregular variation of strength and stiffness along building height
  - Soft stories
- Survival of apparently weak systems
  - Contribution of non-structural elements to lateral strength and energy dissipation capacity
IMPERFECT SEISMO-TECTONIC KNOWLEDGE AND MODELS

- NORTHridge, USA, 1994
- HANSHIN (KOBE), JAPAN, 1995
- NISHQUALLY, USA, 2001
NORTHRIDGE, 1994

From EERI photo gallery
NORTHRIDGE, 1994

- $M_s = 6.8$

- Source: deep thrust ramp beneath San Fernando Valley, California

  A surprise for seismologists: It did not match any previously known surface-geology feature

- Occurrence: consistent with high activity rate in L.A. area, during the previous 20 years

Seismic hazard associated with concealed faults: recognized since 1987 Whittier Narrows earthquake
NORTHRIDGE, 1994

- Shock generation and propagation: directional effects
  - High velocity pulses
  - Significant recent advances in models of fault rupture and wave propagation!

- Brittle failure of welded connections in steel structures
  - Stress concentrations
  - Influence of very fast loading rate
  - ...

Are we paying enough attention to the influence of damage accumulation in life-cycle system reliability?
NORTHRIDGE, 1994: More lessons

- Significant economic losses and disruption of functionality associated with equipment, content and essential facilities
  - They might have been easily prevented at very low cost!
- Satisfactory performance of
  - Base isolated structures
  - Bridges retrofitted after San Fernando, 1971
- But: failure of cable restraint units and collapse of girders after sliding off their supports
HANSHIN (KOBE), 1995

From EQE Summary Report
KOBE, 1995

- Most damaging earthquake in Japan since Kanto (1923)
  - $M_s = 7.2$
  - Strike-slip fault rupture directly into downtown Kobe
  - Last previous large-magnitude earthquake: 1948

Previous extended belief: seismic hazard assumed to be determined by larger-magnitude, deeper-focus earthquakes generated at interface between Pacific plate and Philippine sea plate.
KOBE, 1995

- Seismic code revisions: 1971, 1981
- Observed damage depended significantly on the design code used
  - Foundation failure, liquefaction
  - Column failure produced by vertical ground accelerations
  - Reinforced concrete joints, shear failure in columns
  - Pancake failures at midheight stories of multistory buildings
  - Large viaduct structures
NISHQUALLY, 2001

- $M_s = 6.8$, focal depth = 52 km
- Intra-slab earthquake under Anderson Island, Puget Sound, near US-Canada border
- Cascadia zone, along Western coast of North America, associated with one of the world’s quietest subduction zones

- Potential source of large magnitude ($M > 8.0$) earthquake: Energy accumulation process at subduction zone of Juan de Fuca plate under North American plate
SEISMIC PERFORMANCE OF URBAN CONSTRUCTIONS:
LESSONS LEARNED WORLDWIDE
MEXICO CITY, 1985
PRONOUNCED
ASYMMETRY IN
STIFFNESS

Corner building
MEXICO CITY, 1985:
WEAK GROUND-STORY BUILDINGS
MEXICO CITY, 1985:
WEAK GROUND-STORY WITH ELEVATOR CORE
L’ACQUILA, 209

GUJARAT, 2001
SHEAR FAILURE OF MASONRY WALL PANELS

Structural shear walls, Gujarat, 2001

Infill elements, Mexico City, 1985
BRITTLE FAILURE OF SHORT COLUMNS

Mexico City, 1985

Concepción, Chile, 2010
BRITTLE FAILURE OF SHORT COLUMNS
BINGÖL, TURKEY, 2009
EXCESSIVE GRAVITATIONAL LOADS
(CHANGE OF USE) MEXICO CITY, 1985
IMPACT BETWEEN ADJACENT BUILDINGS
MEXICO CITY, 1985
FOUNDATION FAILURES, MEXICO CITY, 1985

Bearing failure

Bond failure of friction piles
FOUNDATION FAILURES, MEXICO CITY, 1985

Excessive residual tilting
DEFICIENT SLAB-TO-COLUMN CONNECTIONS
MEXICO CITY, 1985
UPPER STORY FAILURES

MEXICO CITY, 1985
OUT-OF-PLANE COLLAPSE OF MASONRY PANELS
GANDHIDHAM, GUJARAT, 2001

Murty et al, 2002
BRITTLE FAILURE OF STEEL BEAM-TO-COLUMN CONNECTION

NORTH RIDGE, 1994

Maison et al., 2004
DEFICIENT REINFORCEMENT DETAILS

Bingöl, Turkey, 2003
Gur et al, 2009

Adana-Ceyhan, Turkey, 1999
Bachmann, 2003
BUILDING WITH DISCONTINUED STRUCTURAL WALL AT ONE CORNER CONCEPCIÓN, CHILE, 2010

Elnasahi et al, 2010
PERFORMANCE-BASED EARTHQUAKE ENGINEERING

CURRENT CHALLENGES AND TRENDS
QUANTITATIVE PERFORMANCE INDICATORS

Deierlein, 2004

Base Shear

IO  LS  CP

FEMA 273/356 Performance Levels

$ % replacement
Casualty rate
Downtime, days

25%  50%  100%

0.0001  0.001  0.01  0.25

1  7  30  180
EXPECTED PERFORMANCE vs SEISMIC EXPOSURE

Earthquake Performance Level

- Fully operational
- Operational
- Life Safe
- Near Collapse

Earthquake Design Level

- Frequent
- Occasional
- Rare
- Very Rare

Calvi, 2010
CURRENT CHALLENGES AND TRENDS OF EARTHQUAKE ENGINEERING: AN OVERVIEW

• Life-cycle performance targets

• Performance-based targets for given intensities, instead of compliance with lateral strength and stiffness requirements

• Estimating expected performance targets for given intensities
  - response analysis: static, dynamic; linear, non linear
  - aleatory and epistemic uncertainties

• Capacity-design criteria  ➔ ductile behavior
SEISMIC HAZARD AND RISK ASSESSMENT

• Activity of potential seismic sources near a site of Interest

• Near-to-source intensity attenuation functions and response spectra

• Ground motion models, including simple and multiple components
ACTIVITY OF POTENTIAL SEISMIC SOURCES NEAR A SITE OF INTEREST

• Local seismicity functions: annual rates of occurrence of earthquakes with magnitudes greater than given values
• Insufficient statistical samples: Need to use information from similar sources: Bayesian statistical analysis
• Unidentified seismic sources: use geotectonic information

Account for epistemic uncertainties in seismic hazard estimates
NEAR-TO-SOURCE INTENSITY ATTENUATION FUNCTIONS AND RESPONSE SPECTRA

- Derive intensity-attenuation functions applicable to sites located in the immediate vicinity of the seismic source.
- Obtain sufficient samples of actual or artificial near-to-source ground motion records with adequate frequency-content and duration.
- Use these records to derive design-oriented reduction factors of linear response spectra, to account for nonlinear ductile behavior and energy-dissipation capacity.
MULTIPLE-COMPONENT GROUND MOTION MODELS

• Random relation between ground motion intensities in two horizontal orthogonal directions

• Intensity $I$, characterized by quadratic mean of intensities in two horizontal orthogonal components

$$I_M = \sqrt{\left(\frac{I_X^2}{I_Y^2}\right)/2}$$

• Random relation between intensity in vertical direction ($I_Z$) and $I_M$
SPECIFIC ENGINEERING CHALLENGES II

SEISMIC VULNERABILITY FUNCTIONS AND RELIABILITY-BASED DESIGN

- Reliability measures
- Capacity design
- Global and local performance indicators
- Irregular systems
- Systems with asymmetric shear-distortion functions
- Development and calibration of consistent-reliability, practically applicable, seismic analysis and design criteria
- Damage accumulation and life-cycle reliability analysis
SEISMIC-RISK-REDUCTION PROGRAMS

• Seismic vulnerability and risk assessment of existing constructions

• Ensuring code compliance and quality control

• Non-engineered constructions
CAPACITY DESIGN

• OBJECTIVE: Avoiding occurrence of brittle failure modes
• METHOD:
  - Pre-select yielding elements
  - Design them for an adequate safety factor
  - Design other members for sufficiently higher safety factors, in order to “ensure” predominance of ductile failure mechanisms
• IMPORTANT CONSIDERATIONS:
  - Account for uncertainties about mechanical properties
  - Improve ductile capacity of members that provide a significant portion of lateral strength
GLOBAL AND LOCAL PERFORMANCE INDICATORS IN MULTISTORY BUILDINGS

• GLOBAL INDICATORS
  - Overall and story drift ratios: $\psi/\psi_c$, depending on type of structural arrangement
  - About $\psi_c$: typical values or pushover analysis

• LOCAL INDICATORS
  - Easy to assess in bracing members, ...
  - Difficult for bending member ends, plastic hinges,...
  - Their evaluation may require step-by-step dynamic response analysis
  - Simplified methods of analysis: must lead to sufficiently low probabilities of exceedance of local deformation capacities
IRREGULAR SYSTEMS

- **Type I: Vertically irregular**
  - along-height significant variations of
    - floor masses
    - story strength and stiffness properties
    - safety factors with respect to story shear associated with linear response.

- **Type II: In-plan irregular**
  - significant eccentricities of story shear-forces determined by linear dynamic response analysis with respect to centres of lateral strength and stiffness.

- **Type III: Slender systems**
  - height/width ratios greater than 2.5

- **Others:** in-plan openings, recessed and salient areas, non-rigid floor diaphragms, large length/width ratio...
CONSISTENT-RELIABILITY, PRACTICALLY APPLICABLE, SEISMIC ANALYSIS AND DESIGN CRITERIA: DEVELOPMENT AND CALIBRATION

ALTERNATIVE APPROACHES
(FEMA 356, 2000)

- Linear static
- Linear dynamic (response spectra)
- Nonlinear static (pushover)
- Nonlinear dynamic (step-by-step)

CONCEPTS TO BE CONSIDERED

- Uncertainties affecting response and performance predictions:
  - *aleatoric*: cannot be eliminated
  - *epistemic*: depend on response analysis method, among other concepts

*These uncertainties should be clearly recognized in comments to normative documents*

- Need for simple, practically applicable, consistent-reliability criteria and methods for seismic analysis and design
DAMAGE ACCUMULATION AND LIFE-CYCLE RELIABILITY ANALYSIS

- Damage accumulates in structural members under the action of moderate- and high-intensity earthquakes.

- Reliability and expected performance analysis must be established within a life-cycle framework, including:
  - Differential settlements
  - Optimum repair and maintenance policies:
    - Select damage location and failure mechanisms: ductile, easy to identify and repair
  - Multi-risk analysis
SEISMIC RISK REDUCTION PROGRAMS: SOME SIGNIFICANT CHALLENGES

- SEISMIC VULNERABILITY AND RISK ASSESSMENT
- ENSURING CODE COMPLIANCE AT DESIGN, CONSTRUCTION AND QUALITY CONTROL STAGES
- NON-ENGINEERED CONSTRUCTIONS
SEISMIC VULNERABILITY AND RISK ASSESSMENT

- Implement seismic retrofit programs oriented to risk control in urban constructions
- Focus efforts on those presenting highest expected values of human, economic and social losses:
  - Schools, auditoriums, theaters: large congregations of persons
  - Hospitals, transportation terminals, firemen and police stations, tele-communication centers: operation essential during emergencies
  - Museums, public register offices: important, non-replaceable materials, works of art, cultural-heritage elements, ..
SEQUENTIAL PROCESS:

- Preliminary identification of high-risk constructions (sidewalk evaluation)

- Vulnerability and risk assessment with the aid of simplified models

- Refined vulnerability and risk analysis

ENSURING CODE-COMPLIANCE, SOUND CONSTRUCTION AND QUALITY CONTROL PRACTICES

- Counting with modern, advanced, practical and robust building codes and technical norms is not a guarantee of adequate reliability levels.

- A large number of cases of seismic mal-performance or collapse is associated with human errors or wrong attitudes such as careless design, faulty workmanship and deficient quality control: professional incompetence or limited risk consciousness

DAMAGE PREVENTION AND RISK CONTROL STRATEGIES:
• Continuous education, professional updating
• Peer-review of structural design documents and quality control processes of all essential facilities and randomly selected constructions of other types
NON-ENGINEERED CONSTRUCTIONS

Local materials and traditional structural arrangements
A large percentage of the human losses produced by past earthquakes has been associated with the collapse of non-engineered constructions.

Causes of their high vulnerability:
- well known
- extremely difficult to eliminate, because of socio-economic constraints

Reasonable levels of structural safety can be achieved by adopting appropriate design and construction details involving only small extra expenditure which should be within the reach of people in most countries (IAEE-NICEE, 2004).

Standing challenges:
- developing dissemination and training programs oriented to transmitting these techniques, together with the necessary risk awareness and risk-reduction attitudes, to the social groups that require them.
- making the essential economic and technical resources available to the least favoured members of society in many developing countries.
CONCLUDING REMARKS

- Evolution of Earthquake Engineering, based on:
  a) lessons learned from earthquakes
  b) conceptual engineering models.

- Many painful experiences would have been avoided if engineers, authorities and population of the zones exposed to earthquake hazard had joined forces to create awareness and enhance consciousness about
  a) the magnitude of the risk and
  b) the means and tools to mitigate it.
CONCLUDING REMARKS

- Spectacular development of Earthquake Engineering: high improvement in our understanding and handling of
  
  a) sources of seismic hazard, processes of earthquake generation and propagation
  b) cyclic behavior of structural members and systems that determine the dynamic response of complex nonlinear systems to high intensity seismic excitations;
  c) complex and powerful mathematical models and computational tools
Pending problems:

- Failures to identify in advance previously ignored potential sources of seismic hazard and risk,

- Significant efforts must be devoted to produce practically-applicable engineering design criteria and tools, aimed at attaining previously specified reliability and expected performance targets,

- Conscience must be created among the engineering community about the need to understand the uncertainties lying beyond the simplified methods ordinarily applied in the practice of earthquake engineering.
THANK YOU FOR YOUR KIND ATTENTION!