Recent Advancements, Trends and Future Paradigms in Structural Design of Reinforced Concrete (RC) Tall Buildings

Naveed Anwar, PhD
Why new paradigms and needed?
How long do we have before the building will collapse in this fire?

- Asks the Fire Chief from the structural engineer / (Architect)

1974
The Towering Inferno (1974)

https://www.youtube.com/watch?v=FagbC09BO2o
The Challenges

• Architectural Design and Structural Engineering
  • Bigger, taller, complex forms, **but**
    Lighter, smaller, thinner structural elements
  • High performance, **but** Lower cost

• Architects and Structural Engineers
  • Apparent lack of innovativeness
  • Difficulties in collaborative working
Percentage of Urbanized World

World’s Population Urban-to-Rural Ratio

(www.un.org)
Urbanization → Growing Needs for built-up space
The Case of London
Advise to my fellow Engineers

1. Design is a team effort, and Architect is the lead

2. Everything is possible, don’t say no!
   • but it needs innovation, knowledge, skills, tools and,
   • of course resources

3. - - -
Conceptualizing a Solution

• Design a Rectangular Water Tank of 3mx4mx2m
  – Most engineers will readily calculate the wall thickness and required rebars and the cost

• Design the most efficient and cost effective water tank to hold 24 cuM of water
  – Many designs are possible
  – Most engineers will not know how to start?
A tussle between Heuristic and the Rational

Should design be based on
“Engineering Judgment” and intuition,
Or
controlled by explicit computations
and, restrictive limits and rational approaches
It is by logic we prove, but by intuition we discover.
Intuitive/Artistic Creations – Need no codes
Structural systems: Meeting new architectural demands
Conventional Systems

Evolution of Structural Systems

- Type I: Shear Frames
- Type II: Interacting Systems
- Type III: Partial Tubular Systems
- Type IV: Tubular Systems

Chart showing the evolution of structural systems with a scale of floors from 10 to 110.
## Development of Basic Structural Systems

<table>
<thead>
<tr>
<th>No.</th>
<th>System</th>
<th>Number of stories</th>
<th>Ultra-tall buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Flat slab and columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Hat slab and shear walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Hat slab, shear walls and columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Coupled shear walls and beams</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Rigid frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Widely spaced perimeter tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Rigid frame with haunch girders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Core supported structures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Shear wall—frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Shear wall—Haunch girder frame</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Closely spaced perimeter tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Perimeter tube and interior core walls</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Exterior diagonal tube</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Modular tubes, and spine wall systems with outrigger and belt walls</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Intuitive design, verification, application

Félix Candela
Intuitive forms and designs

Pier Luigi Nervi
The Diagrid System
BRB Based Systems (Braces that Don’t Buckle)
Innovative Systems

Doha Tower, Qatar
CTBUH best Tall Building Award 2012

KfW Westarkade, Frankfurt
CTBUH best Tall Building Award 2011
Burj Khalifa, Dubai

Mercury City Tower in Moscow – The Tallest building of Europe

Sky City (Changsha, China)
Innovative Systems

Linked Hybrid, Beijing
CTBUH best Tall Building Award 2009

Shanghai World Financial Center, China
CTBUH Award 2008

The Beetham Hilton Tower,
Manchester, UK, CTBUH Award 2007
Construction Innovations: Pre-Fabrication
Construction Innovations: Slip Forming
Construction Innovations: Top Down Construction
Construction Innovations: Modular Construction – 30 story in 15 days - China
Construction Innovations: Concrete Printing
Construction Innovations: Contour Crafting
The Growing Computational Requirements: Progressive Collapse

- A new and major concern for structural safety

- Structure should not collapse completely if one or two elements are “destroyed”

- Backup systems, alternate load paths, additional redundancy
Analysing for Construction Sequence

• Structure is normally analysed as if it is already fully built
  • Make the model, and apply loads

• Step-wise construction sequence analysis is essential for better and correct understating and design
  • Make the model, as it is built
  • Apply loads as they are applied
  • Consider temporary shoring etc
  • Consider in-construction corrections
  • Consider the aging effects
Without and With Construction Sequence
Innovative Solutions

• Connecting two buildings or parts of structure in the right way can lead to innovative solutions

  • Rigidly connected
  • Fully free to move
  • Flexible connections
  • Elasto-Plastic Connections
  • Fuses
Design approaches: Looking beyond Life Safety
Evolution of our Understanding of Structures

- Limits on the allowable stresses to achieve indirect FOS
- Explicit consideration of partial FOS
- Formulation of limit state design principles
- Formulation of ultimate strength
- The introduction of capacity based design approaches
- The recognition of the difference between brittle and ductile failure
- Performance based design and more explicit linkage between demand and performance
- Risk integrated based design, and a more and holistic approach towards consequence based engineering
Seismic Design Approaches

- Code Based Design
- Performance Based Seismic Design
- Consequences and Risk Based Design
- Resilience Based Design
The First Building Code: Code of Hammurabi (1792 BC to 1750 BC)

Clause 229:

If a builder builds a house for someone, and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be put to death.
“In case you build a new house, you must also make a parapet for your roof, that you may not place bloodguilt upon your house because someone falling might fall from it”.

- The Bible, Book of Deuteronomy, Chapter 22, Verse 8
Development of Buildings Codes

- "Rebuilding of London Act" after the “Great Fire of London” in 1666 AD.
- In 1680 AD, "The Laws of the Indies" Spanish Crown
- In USA, the City of Baltimore first building code in 1859.
- In 1904, a Handbook of the Baltimore City
- In 1908, a formal building code was drafted and adopted.
- The International Building Code (IBC) by (ICC).
- European Union, the Eurocodes.
The Modern Codes

7.2.3 — Inside diameter of bend in welded wire reinforcement for stirrups and ties shall not be less than $4d_b$ for deformed wire larger than MD40 and $2d_b$ for all other wires. Bends with inside diameter of less than $8d_b$ shall not be less than $4d_b$ from nearest welded intersection.

(ACI 318 – 11)

a) A beam shall be deemed to be a deep beam when

the ratio of effective span to overall depth, $\frac{l}{D}$

is less than:

1) 2.0 for a simply supported beam; and
2) 2.5 for a continuous beam.

b) A deep beam complying with the requirements of 29.2 and 29.3 shall be deemed to satisfy the provisions for shear.

(IS 456-2000)
The General Code Families

- UBC, IBC
- ACI, PCI, CRSI, ASCE, AISI, AASHTO
- British, CP and BS
- Euro-codes
- China, USSR, Japan
Are All Buildings Codes Correct?

• If they differ, can all of them be correct?

• Did we inform the structures to follow which code when earthquake strikes?

• Codes change every 3 or 5 years, should we upgrade our structures every 3 or 5 years to conform?
Prescriptive Codes – A Shelter

• Public:
  • *Is my structure safe?*

• Structural Engineer:
  • *Not sure, but I did follow the “Code”*

As long as engineers follow the code, they can be sheltered by its provisions.
Shortcomings of Code Based Design

• Traditional codes govern design of general, normal buildings
  – Over 95% buildings are covered, which are less than about 50 m

• Not specifically developed for tall buildings > 50 m tall

• Prescriptive in nature, no explicit check on outcome

• Permit a limited number of structural systems

• Do not include framing systems appropriate for high-rise

• Based on elastic methods of analysis

• Enforce uniform detailing rules on all members

• Enforce unreasonable demand distribution rules

• Do not take advantage of recent computing tools
Design for Seismic Resistance and Extreme Events

- Force/stress based design
  - Assume reduced forces, limit the stresses

- Displacement based design
  - Allow force D/C to exceed, as long as displacements can be limited

- Capacity based design
  - Put “fuses” in the structure limit the force capacity, hence the demand

- Energy based design
  - Total energy input is collectively resisted by kinetic energy, the elastic strain energy and energy dissipated through plastic deformations and damping
Implicit Intent of Code Based Design

• Resist small shocks through stiffness and no damage

• Resist moderate earthquakes through strength with some damage

• Respond to strong earthquakes through damping, ductility and energy dissipation without collapse, but significant damage
Progression of Seismic Resistance Design

**Historical Approach:**
Earthquake forces proportional to building mass ($V_{des} = 5 - 10\%$ of $Wt$),

- Lack of Knowledge on Earthquake Demand and Building Capacity
- Linear Elastic Building Response

**Traditional Codes:**
Elastic earthquake forces reduced for linear design ($V_{des} = V_{max}/R$)

- Elastic Forces reduced for Design by $R$
- Inelastic Response
- Yield
- Max
Current Seismic Design Approach

Current Trend:

a) Inelastic earthquake demand based on, inelastic capacity of building
b) Resolution of demand vs. capacity generates Performance Point
c) Design based on displacement, $\Delta_{des}$
Ductile link Analogy for Capacity based design

Original Chain

Ductile Link

Brittle Links

Loaded Chain

Ductile Link stretches by yielding before breaking

Brittle Links do not yield

C. V. R. Murty, 2002
Seismic Design Approaches

- Code Based Design
- Performance Based Seismic Design
- Consequences and Risk Based Design
- Resilience Based Design
Performance Based Design (PBD)

• An approach in which structural design criteria are expressed in terms of achieving a set of performance objectives or levels.

• Ensures structures reaches specified demands level in both service and strength design levels.

• Why it was needed?
  • Traditional codes not suitable/adequate
  • Explicit verification not specified or required in most codes
  • Public does not care about the code, or theories or procedures, they care about “safety” and ‘performance’
## Prescriptive Vs Performance

<table>
<thead>
<tr>
<th>Approach</th>
<th>Procedure</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prescriptive (emphasis on procedures)</td>
<td>Specify “what, and how to do”</td>
<td>Implicit Expectation</td>
</tr>
<tr>
<td></td>
<td>Make Concrete: 1:2:4</td>
<td>(a strength of 21 MPA is expected)</td>
</tr>
<tr>
<td>Performance Based Approach (emphasis on KPI)</td>
<td>What ever it takes</td>
<td>Explicit Performance</td>
</tr>
<tr>
<td></td>
<td>(within certain bounds)</td>
<td>Concrete less than 21 MPA is rejected</td>
</tr>
</tbody>
</table>
Define Performance Levels

Operational (O)  Immediate Occupancy (IO)  Life Safety (LS)  Collapse Prevention (CP)

Based on FEMA 451 B
Link the Damage to Performance Levels

- Hazard
- Loading Severity
- Vulnerability
- Structural Displacement
- Consequences
Link Performance other Indicators

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Lowest</th>
<th>Highest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational (O)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Immediate Occupancy (IO)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life Safety (LS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collapse Prevention (CP)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage or Loss</td>
<td>0 %</td>
<td>99 %</td>
</tr>
<tr>
<td>Casualties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downtime for Rehab</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rehab Cost to Restore after event</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retrofit Cost to Minimize Consequences</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ref: FEMA 451 B
How to Work with PBD

Requires:
- Detailed modeling
- Nonlinear-dynamic analysis
- Appropriate computing tools, knowledge, skills and lots of patience
Performance Based Design Process

- Analyzing Linear Elastic Model for Code Based Design Loading
- Formulation & Analysis of Nonlinear Model of Real Building
- Results Extractions and Processing
- Interpretation of Results for Decision Making
AIT’s Focus on PBD

- Considerable research, development focus on PBD
- Specially targeted to Tall Buildings and retrofitting of exiting structures
Beyond PBD

- For public, the performance criteria still does reduce the effects of the events
- Insurance companies want to have greater reliability of assessment of risk and damages
Seismic Design Approaches

- Code Based Design
- Performance Based Seismic Design
- Consequences and Risk Based Design
- Resilience Based Design
Questions still un answered

• What if the chance that performance level is not achieved?

• What is the risk?

• What are the consequences?

• What if the performance levels are not sufficient?

Code based was implicit, with not confirmation of response

PBD is explicit, can help to confirm the response and performance level
Is this acceptable?
Even though it satisfies CBD and PBD
Why do we need to go Beyond PBD

- For public and society, the performance criteria still does reduce the effects of the events
- The non structural damage is not acceptable
- The disruption and loss goes much beyond the building
- Insurance companies want to have greater reliability of assessment of risk and damages
Consequence Based Engineering

• It is not enough to say “Cracking and non-structural damage is acceptable, as long as structure does not collapse”

• A natural extension of the performance-based design approach

• Structural consequences can be defined in terms of repair costs, casualties and loss of use duration (dollars, deaths and downtime) (Porter, 2003).

• Other types of consequences which result from the inherent function of a structure, are addressed using importance factors for various occupancy categories in design codes (Yuxian 2013).
Consequence Based Engineering

• “Structural consequence and non-structural effects” determined entirely from the analysis of structural member as well as overall system behavior.

• The consequence-based structural design approach proceeds through the analysis of expected system consequences, irrespective of the event triggering these consequences.

• This philosophy requires the structural members to be designed for variable reliability levels, depending upon their contribution in causing adverse system consequences.
Risk Based Design Process

- Safety Studies (Probability and Consequence Analysis)
- Risk Quantification
- Safety Critical Element
- Design Accidental Load
- Structure Design
Parameters of Risk Based Seismic Assessment

- Site Seismic Hazard
- Consequence of Failure
- Likelihood of Failure (Structure Vulnerability)

Risk Plot (High and Low Priorities)

- Probability of Hazard
- Expected Consequences
- Acceptable Risk Limit
- Higher Priority
- Lower Priority

- Increasing Risk
Special Purposes Guidelines from USA

- Applied Technology Council (ATC)
- Federal Emergency Management Agency (FEMA) and
- National Earthquake Hazards Reduction Program (NEHRP)
- PEER Guidelines for Tall Buildings
- Tall Buildings Initiatives (TBI)
- CTBUH Guidelines
Seismic Design Approaches

- Code Based Design
- Performance Based Seismic Design
- Consequences and Risk Based Design
- Resilience Based Design
Resilience Based Earthquake Design

• A holistic approach which seeks to identify all earthquake-induced risks (including those outside the building envelope) and mitigate them using integrated multi-disciplinary design and contingency planning to achieve swift recovery objectives in the aftermath of a major earthquake.

• The key principle in resilience-based earthquake design is to limit expected damage to structural and architectural components and egress systems (elevators, stairs, and doors)

Economic Loses

Loss of Quality of Life

Loss of Community and Culture

Go Beyond Life Safety
Green Buildings

Resilient Buildings

Resilience-based Earthquake Design Initiative (REDi) Rating System for the Next Generation of Buildings

Main authors: Arup
Supported by USRC and many others
Enhancement of Structural Design

- Code Minimum Requirements
- Design Demands
- Vertical Earthquakes
- Minimum Structural Damage
- Minimize Residual Drift
- Expose Structural Elements
- Symmetric Design

Source: REDi™ Rating System
Tools: How to design efficiently?
The Role of Computers and Software

- Initially, computers were used to program the procedure we had

- Now, we develop procedures that are suited for computing
Design Approaches evolved to match computing revolution
Some Tools of the Trade

By Computers and Structures Inc. USA

**CSI BRIDGE**
Integrated 3D Bridge Design Software

**SAP 2000**
Integrated Software for Structural Analysis and Design

**ETABS**
Integrated Analysis, Design and Drafting of Building Systems

**SAFE**
Integrated Design of Flat Slabs, Foundation Mats and Spread Footings

**PERFORM3D**
Nonlinear Analysis and Performance Assessment for 3D Structures

**CSI COL**
Design of Simple and Complex Reinforced Concrete Columns
Decisions Support Systems

- Explicit learning from experience
- Combination of Rational and Heuristic thinking
- Encapsulating natural thinking process into formal decision systems
A Swing Towards the AI

- Rich Pictures
- Analytical Hierarchy Process (AHP)
- Artificial Neural Networks (ANN)
- Genetic Algorithms (GA)
- Expert Systems (ES)
- Fuzzy Logic
- Deep Thinking
- Big Data and Data Mining
Rich Picture for Choosing Structural System
ANN for Tall Buildings

- Number of story
- Length, Width, Height
- Grid spacing
- ... 

- Column size
- Shear wall size
- Rebar quantities

- Natural period
- Drift ratio
- Base shear

To make design preliminary decisions *without* explicit calculations
Mobile computing might change how we design
Can we make it safe?
Control: Making structures smarter
Smart Everything!

- Smart Phone
- Smart Car
- Smart TV
- Smart Home
- Smart City

Smart Cities, Smart Buildings, Smart Structures, Smart Devices, Smart Materials
Why smart structures?

- Excitation fluctuates so Demand fluctuates

- But Capacity is constant

- Therefore level of safety is not consistent

- Typically capacity is designed based on “Peak” estimated demand

- What if peak demand never comes > Un-economical

- What if demand exceeds estimated peak > Un-safe
What a smart structure does?

1. Ability to sense any change in external actions
2. Diagnose any problem at critical locations
3. Measure and process data
4. Take appropriate actions to improve system performance while preserving structural integrity, safety, and serviceability
Smart structures use smart devices and materials to add some intelligence to adapt, react, adjust, respond and handle multiple demands, and levels as and when needed.

Help to make the structures safer, specially for earthquakes and strong winds.
Smart Structure Devices

- Energy Dissipating Systems
- Active or Passive Control Systems
- Health Monitoring Systems
- Data Acquisition System
Applications for Smart Structure Devices

1. Structures subjected to extraordinary vibrations

2. Important structures with critical functionality and high safety requirements

3. Flexible structures with high serviceability requirements
Research Areas in Smart Structure Technology

• Analytical or numerical modeling of control systems.

• Experimental investigation of control systems

• Properties of smart materials and their applications

• Applicability and Full-scale implementation

• Development of guidelines and standards for design of smart systems
Damping Devices and Systems

Seismic force-resisting system (SFRS)

Damping system (DS)

Internal damping device sharing column with SFRS

Internal damping device with common elements of SFRS

External damping device

Damping devices and systems applied to a lateral load-resisting system
Damping Devices and Systems

- Passive Control Systems
- Semi-active Control Systems
- Active Control Systems
- Hybrid Systems
Passive Control Systems

- Use various mechanical devices which react to structural vibrations resulting in dissipating a portion of their kinetic energy.

- Requires no external power source and are capable of generating large damping forces with increasing structural response
Tuned Mass Dampers (TMD)

Tuned Liquid Dampers (TLD)

Friction Devices

Metallic Yielding Devices
Tuned Mass Dampers (TMD)

Tuned Liquid Dampers (TLD)
Viscoelastic Dampers

Fluid Viscous Dampers
## Common Semi-active Control Systems

<table>
<thead>
<tr>
<th>Semi-active Tuned Mass Dampers</th>
<th>Semi-active Tuned Liquid Dampers</th>
<th>Semi-active Friction Dampers</th>
<th>Semi-active Vibration Absorbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrorheological Dampers</td>
<td>Semi-active Stiffness Control Devices</td>
<td>Magnetorheological Dampers</td>
<td>Semi-active Viscous Fluid Damper</td>
</tr>
</tbody>
</table>
Active Control Systems

Use electrohydraulic actuators which generate optimum amount of control force based on actual measured response of main structure

Advantages

- Effective Control on Structure Response
- Adaptability to Ground Motion Characteristics
- Suitability to Use for any Control Objectives
- Ability to Suppress Responses Against Wide Range of Frequencies
Active Mass Dampers (AMD)

Comparison of Smart Structures with AMD and TMD

Model & Free Body Diagram for Structures with AMD
Active Mass Dampers (AMD)

Active Tendon System

Active Bracing System with Hydraulic Actuator
Common Hybrid Systems

Hybrid Mass Damper

Hybrid system with base isolation and actuators

Hybrid Damper Actuator Bracing Control
Intelligent Hybrid Control Systems

Working Mechanism of Three Stage Intelligent Hybrid System

Ground Motion

Stage 1
Structure
Damper
Response
> 1st Threshold
No
Yes

Stage 2
Structure
Damper
Actuator
Response
> 2nd Threshold
No
Yes
Will Adjusted feedback gain

Stage 3
Structure
Damper
Actuator
Base Isolation Systems for Seismic Response Control

Tend to reduce the energy transfer from ground acceleration to structure.
Common Types of Bearing

- **Elastomeric Bearings**
  - Steel shims
  - Thick steel plate connected to column
  - Lead core
  - Natural rubber

- **Lead-Plug Bearings**
  - Thick steel plate connected to foundation

- **Typical Plot Type Bearing**
  - Top Plate with Stainless Surface
  - Piston with Teflon-Coated Surface at the top
  - Elastomer
  - Base Pot
  - Seal
Types of Bearing

Friction Pendulum Bearing

Friction Pendulum Bearing with Double Concave
Sensing and Data Acquisition Systems

Components of Data Acquisition and Digital Control Systems
Thank you