Progression of Structural Design Approaches

Naveed Anwar, PhD
How long do we have before the building will collapse in this fire?

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

1974
Formalization of built environment

15th and 16th centuries: The visual appearance, sense of space and function became a distinct concern.

17th Century Onwards: Thinking about the load-bearing aspects of structures

Late 17th and 18th centuries: Thinking separately about the role of individual materials following Galileo's work.

Late 19th and 20th Century: Aesthetics should be given proper importance independent of load-bearing characteristics of the structure.

Architects and Engineers
The beginning of Structural Engineering

recognition of the loads,

and fact that loads have an effect on members and materials

and that there is a resistance within materials to resist the loads effects

and that there is some relationship between them
Basic Design Approaches
Evolution of our Understanding of Structures

- Limits on the allowable stresses to achieve in-direct 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.
- Risk integrated based design, and a more and holistic approach towards consequence based engineering.
- Performance based design and more explicit linkage between demand and performance.

Naveed Anwar, AIT
“Structural Design is the process of proportioning the structure to safely resist the applied forces in the most cost effective and friendly manner”

A systematic investigation of the stability, strength and rigidity of structures

Where Safety is a prime concern
Ensuring Safety through Factor of Safety!

Capacity > Demand

\[
\frac{C}{FoS} = D \quad \frac{C}{D} = FoS \quad C = D \times FoS
\]

\[
\frac{C}{FoS_1} = D \times FoS_2
\]
Approach 1: Working Stress Design

\[ \frac{C}{F_{oS}} = D \]
The “Real Behavior”

FORCE (F)

Strain Hardening

First yield

Initial Stiffness

Ultimate Strength

Ductile limit

Strength loss

Residual Strength

DEFORMATION (D)
The Strain becomes the primary concern,
Full “Strengths” of the materials at “ultimate” strains are utilized with appropriate “other” factors
The Stress Strain Models

\[ f = f \left[ \frac{2e}{e_y} \right] \left( \frac{2e}{e_y} \right)^2 \]

\[ f = \frac{2\varepsilon(\varepsilon/\varepsilon_0)}{1 + (\varepsilon/\varepsilon_0)^2} \]

\[ \varepsilon = 1.8f/y \]

\[ \varepsilon = 0.38 \]

Naveed Anwar, AIT
Considering Interaction of Actions

The realization that “Envelop Results” can not be used for design

- Shear-Torsion Interaction
- Shear – Flexure interaction
- Torsion-Flexure Interaction
- Shear-Torsion-Flexure Interaction
The Strut and Tie Approaches - Post Crack Strength

A Real Truss

An RC Beam and “Hidden” Truss
The Strut and Tie Approaches

- Extensively used for
  - “D” regions of all members
  - Shear Design
  - Torsion Design
  - “Deep” Beams
  - Brackets
  - Corbels
  - Joints
  - Pipecaps
  - Shear walls
  - Transfer girders
  - ...

Tension

Compression
Approach 3 - Limit State Design

- Limit State Design concept is an advancement over both Working Stress and Ultimate Strength design approaches.
- Attempts to ensure safety at ultimate loads and serviceability at working loads.
- The basic idea involves the identification of all potential modes of failure (i.e. identify significant limit states and determination of acceptable levels of safety against occurrence of each limit state).
- This philosophy uses more than one safety factor attempting to provide adequate safety.
## Limit State Design

<table>
<thead>
<tr>
<th>Types of Limit State</th>
<th>Description</th>
</tr>
</thead>
</table>
| Ultimate Limit states          | • Loss of equilibrium  
                                 | • Rupture  
                                 | • Progressive Collapse  
                                 | • Formation of plastic mechanism  
                                 | • Instability  
                                 | • Fatigue                                        |
| Serviceability limit states    | • Excessive deflections  
                                 | • Excessive crack width  
                                 | • Undesirable Vibration                                        |
| Special limit states           | Due to abnormal conditions and abnormal loading such as  
                                 | • Damage or collapse in extreme earthquakes  
                                 | • Structural effects of fire, explosion  
                                 | • Corrosion or deterioration                              |
Partial Factors of Safety

Characteristic value of material basic strength

Characteristic value of Load

Design Strength

Design load

Design member capacity

Material safety Factor

Member Factor

Structure Factor

Verification

The value of Safety Factor tells how much confidence we have on our knowledge.
# Improving Factors of Safety

<table>
<thead>
<tr>
<th>Factors</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure Level</td>
<td>Importance Factors (1.0 to 1.5)</td>
</tr>
<tr>
<td></td>
<td>Structure type “R” factors</td>
</tr>
<tr>
<td>Member Level</td>
<td>Over strength Factors</td>
</tr>
<tr>
<td>Action Level</td>
<td>Different “fi” factors for flexure, shear, ...</td>
</tr>
<tr>
<td>Material Level</td>
<td>Different gamma factors for concrete and steel</td>
</tr>
<tr>
<td>Load Factors</td>
<td>Different for different loads, based on probability of variance</td>
</tr>
<tr>
<td>Load Combination Factors</td>
<td>Deferent for various probability of simultaneous occurrence</td>
</tr>
</tbody>
</table>
The Development and Role of Building Codes
The First Building Code: Code of Hammurabi

• The earliest known written building code was the Babylonian law of ancient Mesopotamia.
• Also known as the code of King Hammurabi (who ruled Babylon from 1792 BC to 1750 BC).
• Found in 1901 in Khuzestan, Iran.
• Contains detailed accounts of laws pertaining to builders as well as construction conflicts.
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

London Building Act of 1844.

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)

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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
- Eurocodes
- 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 be upgrade our structures every 3 or 5 years to conform?
Is my Structure safe?

What level of Richter earthquake my structure sustain?
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
Newer Design Approaches

Primarily geared towards Earthquakes and Extreme Events
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
Progression of Seismic Resistance Design

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

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

• Explicitly link the performance with earthquake hazard

• 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 (a strength of 21 MPA is expected)</td>
</tr>
<tr>
<td></td>
<td>Make Concrete: 1:2:4</td>
<td></td>
</tr>
<tr>
<td>Performance Based Approach (emphasis on KPI)</td>
<td>What ever it takes (within certain bounds)</td>
<td>Explicit Performance</td>
</tr>
<tr>
<td></td>
<td></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)

Ref: FEMA 451 B
Link the Damage to Performance Levels

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

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

<table>
<thead>
<tr>
<th>Damage or Loss</th>
<th>0 %</th>
<th>99 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casualties</td>
<td>Lowest</td>
<td>Highest</td>
</tr>
<tr>
<td>Downtime for Rehab</td>
<td>Lowest</td>
<td>Highest</td>
</tr>
<tr>
<td>Rehab Cost to Restore after event</td>
<td>Lowest</td>
<td>Highest</td>
</tr>
<tr>
<td>Retrofit Cost to Minimize Consequences</td>
<td>Highest</td>
<td>Lowest</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
AIT’s Focus on PBD

• Considerable research, development focus on PBD

• Specially targeted to Tall Buildings and retrofitting of existing structures
Demand to Capacity Ratio - An Important indicator

- This could apply to
  - Forces, actions (Moment, shear, etc)
  - Ductility
  - Deformations (drift, deflection)

- Indicates the “safety”, “acceptability” as well as “efficiency” of design

\[
\begin{align*}
D/C &> 1 \quad \text{Not acceptable, in many cases} \\
D/C &< 1 \quad \text{Acceptable in most cases} \\
D/C &= 1 \quad \text{Ideal design, not practical} \\
0.5 &< D/C < 0.9 \quad \text{Efficient design}
\end{align*}
\]
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
Risk Based Design

- 

Naveed Anwar, AIT
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.
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
Intuitive Or Rational Design
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 design, verification, application
Intuitive forms and designs

Pier Luigi Nervi
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

- Partial Differential Equations
- Closed Form with Approximations
- Full 3D Nonlinear, Inelastic Dynamic FEA
- 2D/3D Linear Static FEA/Matrix
- Equations, Charts, Tables, Rules, Limits
- Rigorous Analysis
- Semi Analytical
- Regorous Numerical
- Simplified Numerical
- Specified Procedures
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

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

**CSI COL**
Design of Simple and Complex Reinforced Concrete Columns
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
Mobile computing might change how we design
Can we make it safe?
Thank you