Reinforced Concrete Structures

Outline

- Basics of Reinforced Concrete
- Types of Reinforced Concrete Structures
- Deficiencies
- Rehabilitation Strategies

Hyatt, Baguio, Philippine Islands, 1991
Properties of Concrete

- **Mixture of:**
  - **paste**
    - cement & water
  - **coarse aggregate**
    - crushed rock
  - **fine aggregate**
    - sand

- **Strong in Compression**

Concrete Compressive Strength

- **Characterized by 28 day compressive strength -** $f'_c$
  - based on test of standard cylinder specimens
  - $\sigma$  $f'_c$  $\varepsilon$
  - 0.003  0.004
Concrete Compressive Strength

- Early concrete $f'_c$  
  ~2,000 psi

- Modern concrete
  - western U.S.: 3,000 psi < $f'_c$ < 6,000 psi
  - eastern U.S.: $f_c$ ranges to 20,000 psi

- Increasing compressive strength generally corresponds to more brittle behavior

Concrete Compressive Behavior

- More ductile behavior can be obtained by:
  - delaying onset of large negative stiffness in concrete
  - achieved by confinement
    - can increase compressive strength
    - can increase ultimate compressive strain ~0.015

Effect of confinement
Tensile Properties of Concrete

- Concrete is weak in tension
  - cracks
  - pulls apart

✓ Modulus of rupture typically taken as $7.5 \sqrt{f'}$ for normal weight concrete
  $5 \sqrt{f'}$ for light weight concrete

Reinforcing Steel

- Steel has good tension strength
- Provides reinforced concrete with stiffness and strength in tension

- Prevents cracks from opening and helps concrete retain its strength
Reinforcing Steel

For the reinforcing to be effective, tension must transfer from concrete to steel.

This mechanism is known as bond.

Modern steel has deformations to increase bond older steel (pre-1930 did not).

Reinforcing for Concrete Compression

Concrete is strong in compression.

Under extreme loads:
- split
- spall
- crush
Confinement Steel

- Binds concrete together
- Prevents vertical splitting under compression
  - effectively decreases onset of negative stiffness
- Delays crushing

Confinement Steel

- Confinement is achieved through Poisson effects
  - as concrete compresses, it grows in the transverse direction
  - hoop steel confining the inner core must also grow
  - hoops develop tension as they grow
  - induces compression as secondary principal stress
Confinement Steel

Most efficient form of confinement steel is a continuous round hoop

This is approximated by spiral reinforcement

Confinement Steel

Confinement can be approximated by rectangular ties

Cross ties improve effectiveness of rectangular ties
Confinement Steel

To be effective, confinement steel must be
- closely spaced (~4”)
- developed for tension inside the confined core of the member
  - 135 degree minimum hooks

Confined core

Flexure

Combined influence of compression and tension on different faces of member
- Cracks tensile face
- Yields or debonds tensile steel
- Crushes compressive face
- Buckles compressive steel
Flexure

Ductile behavior can be achieved by:

- confining compressive zone and providing lateral restraint for compressive steel
- assuring adequate development of tensile steel
  - lap splices perform poorly
  - mechanical and welded splices can perform better

Lap Splice Behavior

Confinement steel around lap splices holds bars into confined core and facilitates stress transfer
Strain, Curvature and Flexural Ductility

Yield Condition

\[ T = A_f F_y = C = 0.85 f_c^' (\beta_y c) b \]

Yield Curvature

\[ \phi_y = \frac{0.003}{\epsilon_c} \]

Failure Curvature

\[ \phi_u = \frac{\epsilon_{cu}}{c} \]

Elastic regime

- curvature \( \phi = \frac{M}{E_i_{cr}} \)
- \( I_{cr} \) = “cracked section” property often taken as 50% of gross section property
- “cracked section” property should not be calculated as equivalent section comprised of steel and compressive zone

\[ \Delta_y = \frac{P_y L^3}{3EI_{cr}} \]
Cracked section properties

- Equivalent section, consisting of steel area in tension and concrete compressive zone exists only, locally at cracks
- In between cracks, more of concrete is effective, both in tension and compression, resulting in more rigid section
- Appropriate cracked section properties must account for the “average” section properties considering cracked and uncracked zones

Strain, Curvature and Flexural Ductility

- Plastic regime
  - all plastic curvature is assumed to be accommodated within a discrete zone around the yield area known as the “hinge zone”
  - hinge zone typically assumed to have a length ranging from $d/2$ to $d$

  \[
  \Delta_p = \phi_p \left( L - \frac{L_p}{2} \right) \\
  \Delta_T = \Delta_y + \Delta_p \\
  \mu = \frac{\Delta_T}{\Delta_p}
  \]
Stress Strain Relationships: Steel

\[ f_s = \frac{E_s \varepsilon_s}{1 + \left( \frac{E_s \varepsilon_s}{f_y} \right)^{0.03}} + \left( 1 + \frac{\text{sign}(\varepsilon_y - \varepsilon_{sh})}{2} \right) \left( f_{su} - f_y \right) \left( 1 - \frac{\varepsilon_{su} - \varepsilon_s}{\varepsilon_{su} - \varepsilon_{sh}} \right) \]

\[ p = E_{sh} \frac{\varepsilon_{su} - \varepsilon_{sh}}{f_{su} - f_y} \]

Various Grades of Reinforcement
Concrete Stress Strain Relation:

Mander et al. (1989)

Steel Stress Strain Relation:

Conservative estimate of ultimate strain governed by hoop fracture (Priestley et al.)

\[ \varepsilon_{cu} = 0.004 + \frac{1.4\rho f_y \varepsilon_{cu}}{f'_{cc}} \]
Confinement of Circular Columns

Confinement Effectiveness Coeff

\[ k_e = \frac{A_e}{A_{cc}} \]

Area of Core Concrete

\[ A_{cc} = \frac{\pi}{4} d_s^2 \left(1 - \rho_{cc}\right) \]

Effectively Confined Core

\[ A_e = \frac{\pi}{4} d_s^2 \left(1 - \frac{s'}{2d_s}\right)^\alpha \]

\( \alpha = 2 \) for circular hoops; 1 for spirals

From free body diagram

\[ 2A_{sp} f_y = f'_{l}s d_s \times k_e \]

\[ 2t_{jacket} \times 1 f_{yj} = f'_{l} \times 1 d_s \]

Define volumetric ratio of lateral steel:

\[ \rho_s = \frac{Vol. \ of \ Steel}{Vol. \ of \ Concrete} = \frac{A_{sp} \pi d_s}{s \pi / 4 d_s^2} = \frac{4 A_{sp}}{s d_s} \]

Therefore,

\[ f'_{l} = \frac{1}{2} k_e \rho_s f_y = \frac{2t_{jacket}}{d_s} f_{yj} \]
Confinement of Rectangular Sections

\[
A_e = \left( b \cdot d - \sum_{j=1}^{n} \frac{W_j^2}{6} \right) \left( 1 - \frac{s'}{2b} \right) \left( 1 - \frac{s'}{2d} \right)
\]

\[
A_{cc} = b \cdot d \left( 1 - \rho_{cc} \right)
\]

\[
k_e = \left( 1 - \sum_{j=1}^{n} \frac{W_j^2}{6b d} \right) \left( 1 - \frac{s'}{2b} \right) \left( 1 - \frac{s'}{2d} \right) (1 - \rho_c)
\]

\[
f_{lx}' = k_e \cdot \frac{A_{sx}}{sd_e} f_{yh} = k_e \rho_x f_{yh}
\]

\[
f_{ly}' = k_e \cdot \frac{A_{sy}}{sb_c} f_{yh} = k_e \rho_y f_{yh}
\]

Evaluation of Confinement

For Circular Columns & Square Sections with \( \rho_x = \rho_y \)

\[
f_{c}' = f_e' \left( -1.254 + 2.254 \sqrt{1 + \frac{7.94 f_e'}{f_y' - 2 f_e'}} \right)
\]

For all others

Note that for rectangular sections:

\[
\rho_s = \rho_x + \rho_y
\]
Moment Curvature Analysis

- Shows variation of sectional moment against increasing curvature
- Useful for evaluating ductility capacity of a section
- **M-φ analysis is for a constant axial load only**
- Maximum moments from M-φ analyses for various P's can be used to generate overstrength P-M interaction curve

M-φ Analysis using fiber elements

- Given: Section, f'c, steel properties and P
- Start with a given φ and calculate corresponding M
Assumptions of M-Φ Analysis

- Plane sections remain plain before and after bending
- When compression strain exceeds spalling strain strain, cover is lost and stress in cover = 0.
- Concrete does not have strength in tension
- Bond slip ignored
- Transverse steel prevents bar buckling & so compression capacity of steel is maintained

M-Φ Analysis; Steps

- Step 1: For a given Φ assume a neutral axis depth c
- Step 2: Create the strain diagram and find the strains at the various steel locations and center of the compression fibers
- Step 3: Integrate the stresses to find the axial load

\[ P = C_c + \left( C_s - T_s \right) \]

\[ P = \sum_{i=1}^{nc} f_{ci} A_{ci} + \sum_{i=1}^{nc} f_{cci} A_{cci} + \sum_{j=1}^{ns} f_{sj} A_{sj} \]
M-f Analysis; Steps

1. Step 4: Check $P (= P_{calc})$ against given $P$.
   If $P - P_{calc} > \text{tolerance}$ go back to step 1 and start with a new “c”. However, if $P - P_{calc} \leq \text{tolerance}$, go to step 5.

2. Step 5: Calculate moment $M$

   $$M = \sum_{i=1}^{nc} f_{ci} A_{ci} y_{ci} + \sum_{i=1}^{nc} f_{cci} A_{cci} y_{ci} + \sum_{j=1}^{ns} f_{sj} A_{sj} y_{sj}$$

3. Step 6: Choose next $\phi$ and repeat

Effect of Confinement on $M$-$\phi$
**Effect of Axial Load on M-φ**

![Graph showing the effect of axial load on M-φ](image)

**Axial Load Moment Interaction**

![Diagram illustrating axial load moment interaction](image)
Shear

- Results from non-aligned, equal but opposite forces
- Tends to push elements “out of square”
- Is a natural by-product of non-uniform flexure in a structural member

Effects of Shear

- Results in diagonal crack patterns in walls
- Results in cracks inclined at 45° in beams and columns
Effects of Shear

- Shear forces must always be in equilibrium
- Diagonal between “effective” point of application of these balanced shear forces defines the principal stress planes
  - Principal Compression Stress
  - Principal Tensile Stress

Effects of Shear

- Classical diagonal “shear” crack is really a principal tensile stress crack
- Shear behavior can be conceived as a diagonal compressive behavior, rather than a pure “shear” behavior
Shear Reinforcing in Walls

- Curtains of vertical and horizontal reinforcing
- Intended to cross the crack diagonals and hold the faces together

Shear Reinforcing in Beams and Columns

- Horizontal hoops spaced around longitudinal reinforcing
- Hold concrete together across diagonal cracks
Shear Reinforcing - Strut and Tie Models

- Concrete transfers shear through inclined diagonal compression fields or “struts”
- Shear reinforcing steel act as “tie” elements to complete a “truss” type member

Shear Failure Modes

- **Diagonal cracking**
  - results in loss of stiffness
  - loss of strength as aggregate interlock is lost
- **Shear steel anchorage failure**
  - results in rapid and total loss of strength
- **Compressive crushing**
  at toes of compressive strut zones
Shear Strength of Beam-Columns

\[ V_n = V_c + V_s + V_p \]

\[ V_c = k \sqrt{f'_c A_e} \rightarrow A_e = 0.8 A_{\text{gross}} \]

\[ V_p = P \tan \alpha \]

\[ V_s = \frac{\pi A_e f_{y h} D'}{2} \cot \theta \rightarrow \text{Circular} \]

\[ V_s = \frac{A_e f_{y h} D'}{s} \cot \theta \rightarrow \text{Rectangular} \]

\[ \theta \text{ typically ranges between 30 to 35 degrees} \]

Concrete Shear Strength Vc

\[ V_c = k \sqrt{f'_c A_e} \]

Priestley et al. (1996)
Diagonal Strut Action $V_p$ 

![Diagram](image)

Shear Hysteretic Behavior

- Diagonal cracking
- Steel strain hardening
- Degradation due to steel bond loss or concrete crushing
Ductile Concrete Reinforcing

- Very effective
- Not specified by codes prior to 1967
- Not regularly provided in structures until 1976 or later
- Very difficult (often impossible) to put retroactively into existing structures

Types of Reinforced Concrete Structures

- Wall structures with wood floors/roofs
- Wall structures with cast concrete floors/roofs
- Wall structures with precast floors/roofs
- Frame structures
Wall structures with Wood Roofs and Floors

- Direct descendent of URM buildings
- Common industrial & commercial construction
- Many of the same problems
  - poor anchorage of walls
  - weak diaphragms
- If diaphragm and anchorage problems are addressed, nonductile behavior modes of shear wall for in-plane behavior can occur.

Wall Structures with Cast Concrete Floors

- Range in size from 1-20+ stories
- Common in:
  - industrial/warehouse
  - multi-family residential
  - institutional
  - government
- Generally treated as rigid diaphragm structures
- More realistically, diaphragms are semi-rigid
Elements of Wall Structures with Cast Floors/Roofs

- End Walls
- Side Walls
- Roof Diaphragm
- Floor Diaphragms
- Interior Columns

Vulnerability of Wall Structures

- Piers
- Slab punching shear
- Interior Columns
- Spandrels
Vulnerability of Wall Structures

- Although many of these behavioral modes are quite brittle, performance of these structures is highly dependent on induced deformation.
- Good behavior is obtained by ensuring that deformation induced by design earthquake does not exceed failure deformation for critical elements.

Wall Structures with Precast Diaphragms

- Common in industrial applications.
- Similar to other Wall structures, but has poor continuity and no formal diaphragms unless topping slab provided.
- If topping slab is present, behaves as rigid or semi-rigid diaphragm building.
Wall Structures with Precast Diaphragms

- Double “T” Precast floor units
- Post-tensioned precast girders

Wall Structures with Precast Diaphragms

- Hollow Core Floor Planks
- Post-tensioned precast girders
Concrete Frame

- Became popular in 1950s
- Used for many large structures in 1960s
- Common in office and institutional occupancies

Elements of Concrete Frames

- Exterior Columns
- Exterior Spandrels
- Floor and Roof Slabs
- Interior Columns
Vulnerability of Concrete Frames

- Soft/weak story columns
- Beam column joints
- Beams

Plastic Behavior of Frames

Beam-hinge mechanisms

- Ideal behavior is formation of beam-hinge mechanism
- Beam hinging protects columns from damage
- Beam hinging is a ductile behavioral mode
- Formation of full mechanism requires many plastic hinges to form
- Deformation is distributed over height of structure
- P-delta effects minimized
- Extensive energy dissipation possible
Plastic Behavior of Frames

Beam-column joint hinge mechanism

Less preferred behavior is formation of beam-column joint mechanism
- joint hinging protects columns from damage
- joint hinging is a less ductile behavioral mode
- formation of full mechanism requires fewer plastic hinges to form
- deformation is distributed over height of structure
- P-delta effects minimized
- moderate energy dissipation possible

Plastic Behavior of Frames

Single-story mechanism

Undesirable behavior is formation of single story column shear or hinge mechanism
- columns are subject to damage
- columns with heavy axial loads behave in non-ductile manner
- full mechanism requires few plastic hinges to form
- little energy dissipation
- deformation is concentrated in height of single story
- P-delta effects increased
Frame Behavioral Modes

Many older concrete frames are subject to single-story behavioral modes
- short column (shear sensitive columns)
  - inadequate horizontal reinforcing
  - presence of architectural elements that shorten effective span

Methods of Strengthening & Stiffening

• Shear Walls
  - Economical and effective (very stiff and strong)
  - May be placed on interior or exterior
  - Often have significant architectural impact
  - Can be blended with existing architecture
Shear Walls

- Holes drilled in existing concrete
- Surface of concrete roughened
- New reinforcing placed
- Dowels epoxied into existing concrete
- New concrete cast or “shot” in place

Methods of Strengthening & Stiffening

- Braced frames
  - Moderate strength and stiffness
  - Less massive but significant architectural impact
Braced Frames

- Holes drilled in existing concrete
- Erect steel frame
  - Columns
  - Beams
  - Braces
- Bolt frame to concrete

Methods of Strengthening and Stiffening

4 Moment Frames

- Low stiffness and moderate strength
- Relatively expensive to construct
- Low impact on existing architecture
Moment Frames

- Holes drilled in existing concrete
- Surface of concrete roughened
- Dowels epoxied into existing concrete
- New reinforcing placed
- New concrete cast in place

Energy Dissipation

- Very effective upgrade for concrete frames
- Installed as part of a braced frame system
- More costly than standard braced frames
- Maintenance required over life
Energy Dissipation Devices

- **Fluid Viscous**
  - Visco Elastic

- **Friction**

- **Hysteretic**

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**Energy Dissipation Devices**

- Always installed as part of braced frame
- More expensive than braced frames
- Better performance than braced frames
- Can effectively reduce seismic response by 50%
Energy Dissipation Devices

- Fluid viscous dampers
- Friction dampers
- Hysteretic dampers
  - ADAS
  - Unbonded Braces
- Viscoelastic dampers

Seismic Isolation

Fixed - base structure  Isolated Structure
Seismic Isolation

- Laminated Rubber Bearings
  - lead core - rubber
  - high damping rubber

Seismic Isolation

- Friction Pendulum Systems
Seismic Isolation

Seismic Isolation System
- Designed to reduce seismic forces and displacements by energy dissipation.
- Provides wind resistance.
- Internal Rubber Layers: Provides lateral stability.
- Steel Reinforcing Plates: Provide vertical load capacity and confine load core.
- Top Mounting Plate: Not shown.

1. Select Isolation Plane at structure at isolation plane.
2. Cut structure at isolation plane.
3. Install Isolators.
4. Build new diaphragms to stabilize isolators.
5. Provide Temporary Support.
Seismic Isolation

- Expensive but highly effective technology
- Most applicable to structures with period less than 1 sec.
- For structures with moderate strength has low impact on architecture of superstructure
- Best overall seismic performance

Methods of Enhancing Ductility

- Removal (or replacement) of brittle components
- Providing shear heads at column slab interfaces
- Removal of short column conditions
- Provision of external reinforcement (Jacketing)
Removal/Replacement of Brittle Elements

Add supplemental supports

Removal of Short Column Conditions

Sawcut element restraining movement of columns
Composite Fabrics

- Serve same purpose as reinforcing, except on exterior rather than interior of elements

Common retrofit applications
- Supplemental shear reinforcing in walls
- Supplemental shear attachment of precast elements
- Confinement jacketing

Composite Fabrics

- Material comes in sheets - like wall paper
- Fibers aligned with sheet
- Tension strength provided only in fiber direction
- Carbon or Glass fibers embedded in epoxy resin matrix
- Glass fiber subject to chemical attach from concrete
- Epoxy resins photo sensitive
Composite Fabrics

Advantages
- economical
- applies easily
- minimal architectural impact

Disadvantages
- potential for degradation
- limited applications

Supplemental Wall Reinforcing

- Material applies in sheets (like wall paper)
- Reinforcing fibers are aligned along sheet
- Sheets must be placed in orthogonal directions to simulate reinforcing

- Surface preparation and bonding critical
- Over-reinforcement possible
Supplemental Attachment

Confinement

- Jacketing must completely and continuously encase elements, to form hoops of reinforcement
- Most effective on round members
- Rectangular corners must be rounded
Many (most?) concrete structures constructed prior to mid-1970s at significant risk. Many techniques are available to improve these structures. Upgrades usually consist of:

- modifying response of structure to reduce deformation induced by earthquake
  - strengthening and stiffening
  - adding damping
  - isolation (period shift)
- providing additional ductility for existing members to accommodate deformation