Design Guidelines for Earthquake Resistant RC Buildings based on Inelastic Displacement Concept

Damage and seismic code in Japan

1891 Nohbi EQ
1923 Kanyto EQ M7.9 approx. 140,000 deaths
- 1924 Revision of Building Standard Law
- 1933 "Standard for calculation of reinforced concrete structures" (AIJ)
  ➔ allowable stress design

1948 Fukui EQ M7.3 3895 deaths
- 1950 New Building Standard Law

1964 Niigata EQ M7.5 26 deaths
1968 Tokachi-oki EQ M7.9 52 deaths
shear failure of columns in RC buildings

Damage and seismic code in Japan

- 1971 Revision of seismic code
  - enforcement of requirement for hoop in column

1975 Ohita Chubu EQ M6.4 No death
- 1977 Seismic Evaluation Standard

1978 Miyagi-ken-oki EQ M7.4 28 deaths
- 1981 Revision of seismic code
  - Ultimate strength design

1983 Nihon-kai Chubu EQ M7.7 104 deaths(tsunami)
1993 Kushiro-oki EQ M7.8 2 deaths
1993 Hokkaido-nansei-oki EQ M7.8 230 deaths (tsunami)
1994 Hokkaido-toho-oki EQ M8.1 No death
1994 Sanriku Far-off EQ M7.5 3 deaths

Damage and seismic code in Japan

- 1990 Guideline for Seismic Design based on Ultimate Strength Concept

1995 Kobe EQ M7.2 over 6000 deaths
✓ More damage to buildings design by old seismic code
- 1995 Law for Promotion of Seismic Retrofit
  - Seismic retrofit of existing buildings
- 1997 Guideline for Design of Earthquake Resistant Building (AIJ, Architectural Institute of Japan)
- 1999 Revision of seismic code
  - Performance –based design
- 2004 Guideline for Performance Evaluation (AIJ)

Guideline based on Ultimate Strength (1990)

- Total collapse mechanism of beam yielding type
  - Lateral strength and inelastic deformation
    - ✓ductility（Ds=0.25）
  - Collapse mechanism and failure mode
- Shear strength based on plastic theory
- Design for bond splitting failure
- Design for beam-column joint

Guideline for EQ Resistant Building (1997)

- Target performance (limit states)
- Performance-based design
- Bi-directional input

Scope
- Regular frame and/or shear wall structure
- Total collapse mechanism

Contents

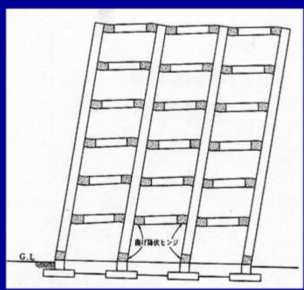
Structural plan

- Total collapse mechanism
- Categories for structural member
  - Plastic hinge
  - Potential plastic hinge (may yield at ultimate limit state)
  - Elastic region
- Irregularity
  - Prevention of torsion in plain and concentration of story deformation

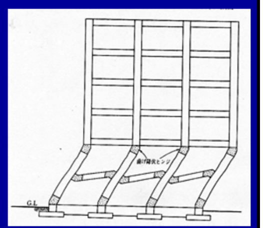
Example of story collapse

Collapse mechanism of frame structure

○ total collapse with beam yielding

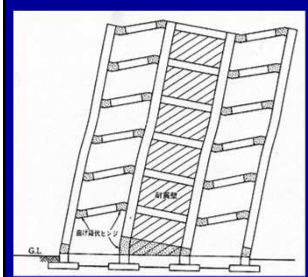


× story collapse

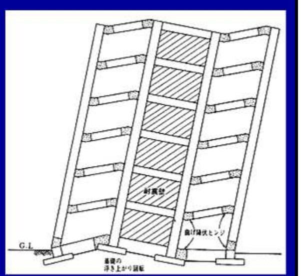


Collapse mechanism of wall frame structure

○yielding of wall



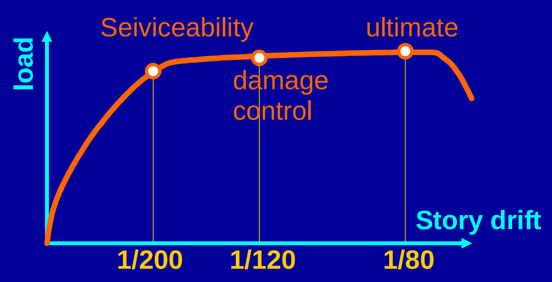
○ rotation of foundation



Target performance and limit state

- load ←→ target performance (Limit State)
  - Serviceability →seriviceability L. S.
  - Repairability →design (damage control) L.S.
  - Safety →ultimate L.S.

Image of limit state



Serviceability limit state

- Load:
  - Vertical load (long term)
  - Moderate EQ (return period of several decades)
    - ✓Ground motion of 80-100gal, C_0=0.2
    - ✓60% Provability of exceedance in 50 years
- Performance:
  - Operational after EQ (slight or no damage)

Serviceability limit state

- Response remains within elastic.
  - Flexural reliable strength
    - ➔prevent residual deformation and crack
  - Shear cracking strength
    - ➔prevent wide shear
  - Drift angle＜1/200
    - ➔prevent large deformation

Design (damage control) limit state

- Load:
  - Large EQ (return period of several centuriess)
    - ✓Ground motion of 300-500gal, C_0=1.0(elastic) C_0=0.25 (frame), 0.30 (wall frame)
    - ✓20% Provability of exceedance in 50 years
- Performance:
  - Repairable with economical cost after EQ (modrate or minor damage)

Design (damage control) limit state

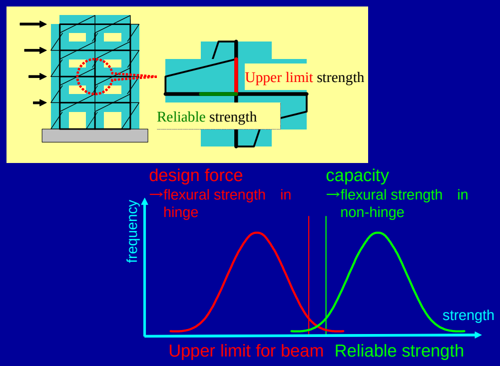
- Inelastic deformation
- Assurance of designed collapse mechanism
  - No yielding except for designed plastic hinges
  - Proof of deformation capacity
    - ➔prevent shear and bond splitting failure
- Design limit displacement
  - Drift angle＜1/120 (frame)
1/150 (wall frame)

Assurance of mechanism

Margin for design stress in non-plastic hinge region

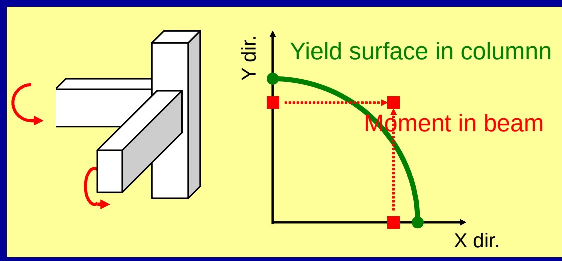
- Variation of member strength
  - ➔upper limit and reliable strength
- Bi-directional input
  - ➔bi-directional bending from beam in column
- Dynamic effect
  - ➔amplification of static seismic load

Upper limit and reliable strength



Bi-directional bending

- Single direction column > beam
- Bi-direction column > beam



Ultimate limit state

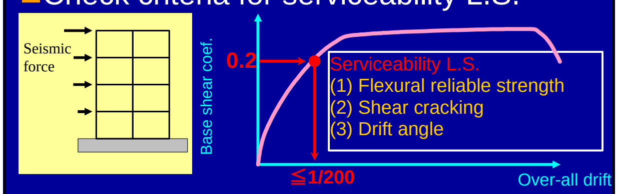
- Load:
  - Large EQ (return period of thouthand years)
    - ✓3-5% Provability of exceedance in 50 years
- Performance:
  - Security of human lives
  - Prevent collapse (maintain vertical load) EQ (severe damage but no collpse)

Ultimate limit state

- Ductility of plastic hinge regions
  - >1/50rad.(beam), 1/67(column), 1/75(shear wall), etc
- Prevention of brittle failure
- Vertical load carryng capacity
- Prevention of story collapse
  - Allow for yielding of potential hinge column
- Ultimate limit displacement
  - Drift angle <1/80rad.(frame), 1/100(wall frame)

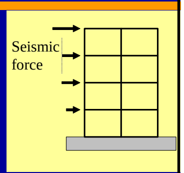
Flow of design (1)

- Initial design (dimension and reinforcing arrangement of members)
- Push-over analysis
- Check criteria for serviceability L.S.

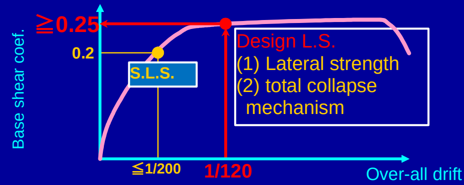


Flow of design (2)

- Check criteria for design L.S.

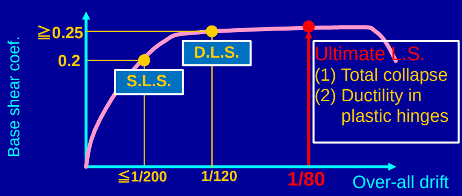


Reliable strength in non-hinge region ≧ Amplified design force



Flow of design (3)

- Check criteria for ultimate L.S.
  - Prevent story collapse
    limit of number and stress in potential hinge columns
  - Design for shear and bond of hinge members



Design for shear and bond in beam and column

- Serviceability L.S.
  - Shear cracking
- Ultimate L.S.
  - Prevent shear and bond failure
  - Assure deformation capacity

Shear cracking strength

$$V_c = \phi\kappa\left(\sqrt{\sigma_T^{\,2} + \sigma_T \cdot \sigma_0}\right)bD$$

ϕ : strength factor

κ : shape factor

σ_T : tensile strength of concrete

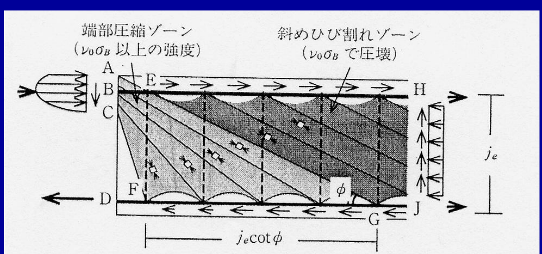
σ_0 : axial stress

Shear failure of column

Evaluation of shear strength

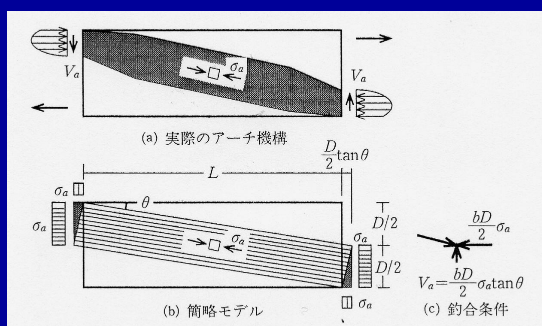
Formula based on plastic theory

- Truss mechanism



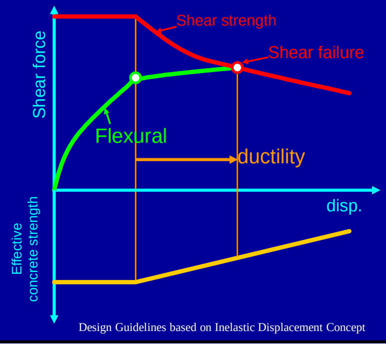
Evaluation of shear strength

- Arch mechanism



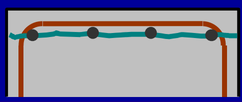
Evaluation of shear strength

- Plastic deformation capasity



Bond splitting failure

- Major parameters
  - space bet. bars
  - concrete cover
  - lateral reinforcement



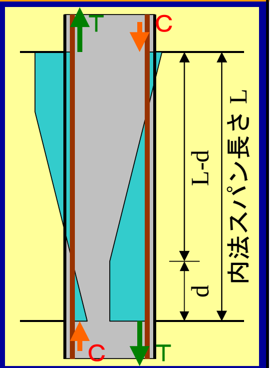
Side splitting failure

Design for bond of bars in beam and column

- Deterioration of bond induces
  - Pull-out of bars
  - Decrease of bar stress in compression

⬇

  - Decrease of flexural and shear strength
  - Pinching



Design of beam-column joint

- Design criteria:

  Until ultimate L.S.
  - No failure, stiffness degradation and pinching
- Check:
  - Shear strength of joint
  - Bond and anchorage of bars in joint

Example of joint failure

- Northridge EQ. (1994, USA)

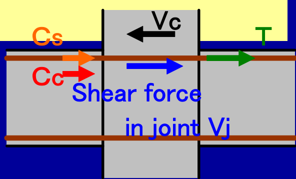
Shear strength of beam-column joint

$$V_{ju} = \kappa \phi F_j b_j D_j$$

κ : shapefactor (cross shape : 1.0, T-shape : 0.7, L-shape : 0.4)

ϕ : shape factor (transverse beams in both sides : 1.0, others : 0.85)

$F_j = 0.8 \times \sigma_B^{0.7} \, (N/mm^2)$



Vj＝T+Cs+Cc−Vc