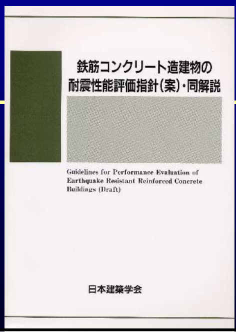
Guidelines for Performance Evaluation of Earthquake Resistant Reinforced Concrete Buildings



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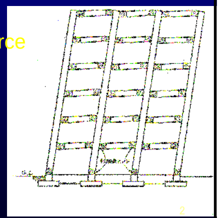
Design Guidelines based on Inelastic Displacement Concept(1988)

- Design based on ultimate strength
- Total collapse mechanism with beam yielding type
  - Upper bound strength, dynamic amplification, bi-directional seismic force
- Macro model for shear design
  - Classification of hinge and non-hinge region, ductility design
- Design method of beam-column joints and non-structural elements



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Lessons from damage by 1995 Kobe EQ

- Seismic motion from inner-land earthquake
- Intensity of seismic motion for structural safety
- Target performance for serviceability & repairability
- Explanation of performance to owners and users
- Minimum requirement for target performance
- Performance-based design based on reliability

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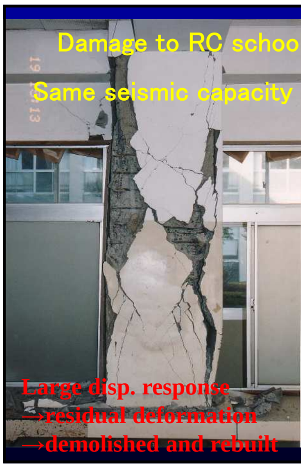
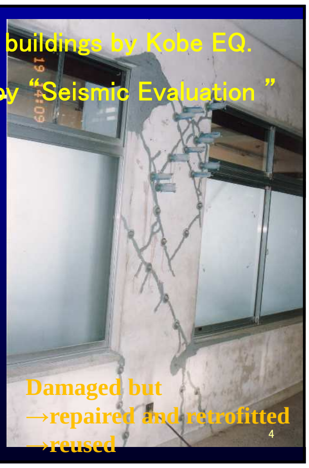
Damage to RC school buildings by Kobe EQ.

Same seismic capacity by "Seismic Evaluation"





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Design Guidelines based on Inelastic Displacement Concept (1997)

- Requirement-based → performance-based
- Target performance, limit state (L.S.)
  - Serviceability, design, ultimate L.S.
  - Flexural hinge location & collapse mechanism
  - Design against bi-directional seismic force
  - Non-linear push-over analysis
- Performance evaluation of members
  - Axial load, lateral reinforcement, bond, openin

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Target performance

Guidelines based on Inelastic Displacement Concept

	Target	Limit state	Damage level
serviceability	Functional	Serviceability (elastic)	Elastic bars, cracks in concrete
repairability	Escape economic loss	Damage control	Beam yielding total collapse mechanism
safety	Save human lives	Ultimate (collapse)	Prevent brittle failure & sustain vertical load

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General concept of seismic capacity

EQ	Seismic motion	Limit state	Damage level
M6 20km S.I. V	15 kine 100gal	Story drift ≦1/200 elastic	functional crack width slight damage
M8 40km S.I. VI	50 kine 300gal	Overall drift≦1/100 Total collapse mechanism	repairable damage control miner to moderate damage
M7 S.I. VII	70 kine 600gal	Overall drift≦1/67 structural member≦ 1/30 Sustain vertical load	Human safety Prevent collapse

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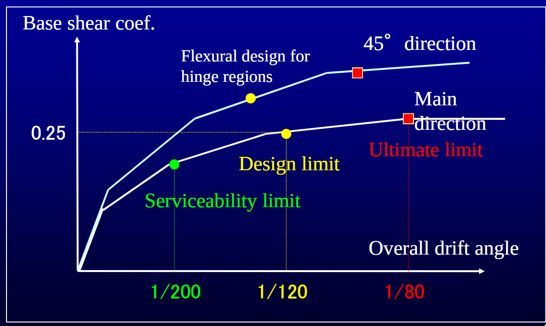
Limit state and response disp.

『Guidelines based on Inelastic Displacement Concept』



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Scope of guidelines

- Requirement-based➔performance-based
- Performance index
  - understandable by users
  - based on intensity of seismic motion
- Standard and regional seismic motion
- Non-linear seismic response
- Limit state and damage index
- Probabilistic approach

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Target performance

『Guidelines for Performance Evaluation』

Limit state	Target	Damage class	Damage level
Serviceability (elastic)	Serviceability Functional	I	Elastic bars, crack width < 0.2mm
Repairability I	Repairable with reasonable cost	II	No damage to cover concrete crack width < 1.0mm
Reparability II	Possible to repair	III	No damage to core concrete crack width < 1.0mm
Ultimate (collapse)	Save human lives	IV	Sustain lateral resistance and vertical load

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Procedure for performance evaluation

- Calculation of standard seismic motion
- Modeling of restoring force characteristics
  - Limit state and deformation limit
- Prediction of displacement response
  - Equivalent linearization method, etc
- Evaluation of seismic capacity index
  - Ratio of limit seismic motion to standard one
- Probability of exceedance of limit state
  - Regional seismic motion at construction site

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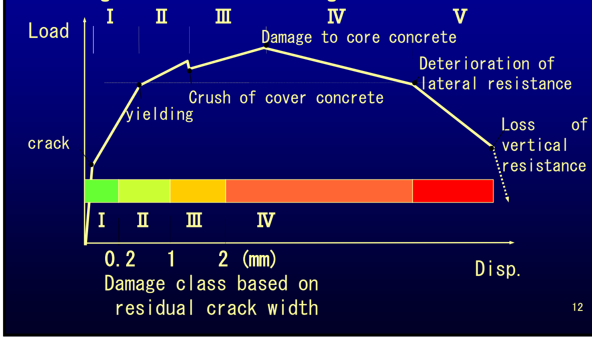
Damage class and limit state



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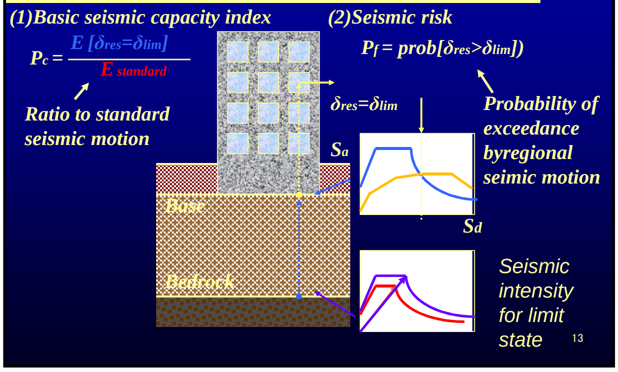
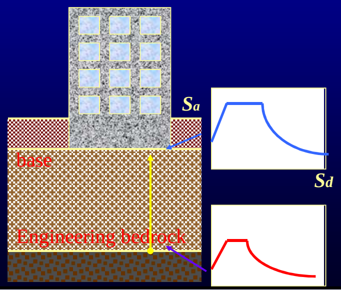
Seismic capacity index



Standard seismic motion

- Response spectrum at the open engineering bedrock is amplified considering ground surface condition



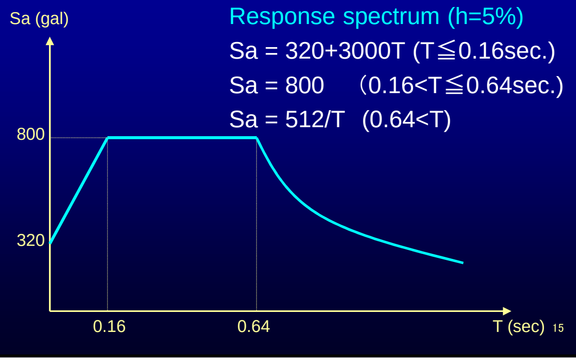
Response spectrum at the base

Response spectrum (h=5%)

Sa = 320+3000T (T≦0.16sec.)

Sa = 800　(0.16<T≦0.64sec.)

Sa = 512/T　(0.64<T)



Evaluation of amplification characteristics for ground surface

- Equivalent linear seismic response analysis
- Ministry of Construction Notification #1458 of 2000
  - Seismic response analysis
  - Approximation by amplification factor, Gs
- A new method proposed in this guidelines based on recent researches

Amplification fac., Gs by ground surface

Ground of category 1

Gs = 1.5　(T≦0.576)

Gs = 0.864/T　(0.576<T≦0.64)

Gs = 1.35　(0.64<T)

Ground of category 2 & 3

Gs = 1.5　(T≦0.64)

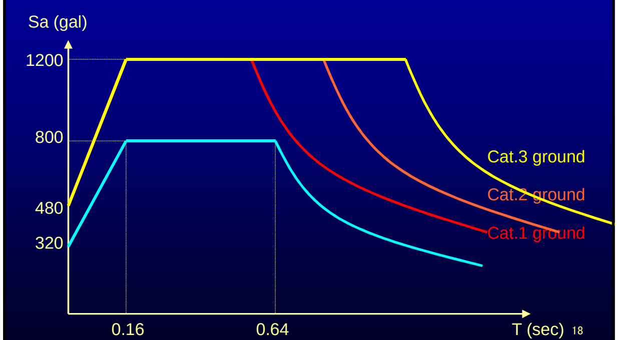
Gs = 1.5T/0.64　(0.64<T≦Tu)

Gs = gv　(Tu<T)

Tu = 0.64gv/1.5

gv = 2.025（cat.2）、2.7（cat.3）

Response spectrum



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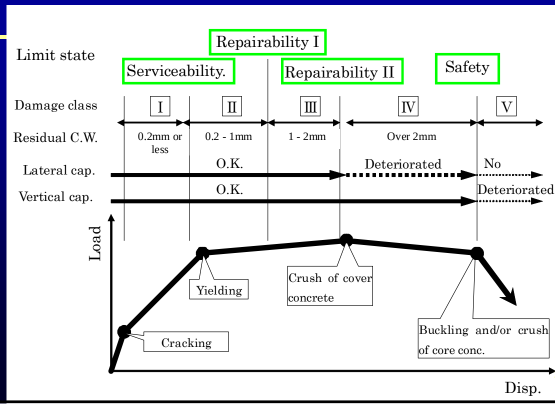
Damage class and limit state of members



Damage class III


Crack width of 2mm


No damage to core concrete and steel bars

Damage class III


No spalling nor crush of concrete.

Some cracks at boundary of wall but no deformation of bars.

Damage class IV



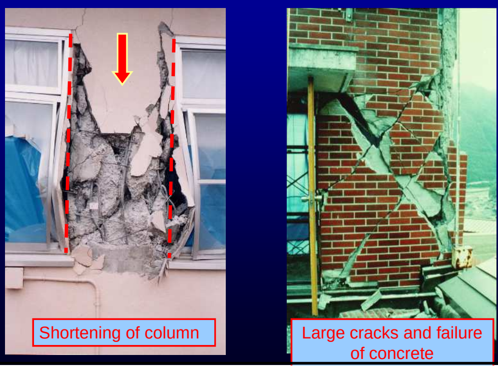
No buckling nor fracture of bars.

Damage class IV


Partial deformation of bars and local damage to concrete

No buckling nor fracture of steel bars. Column sustains vertical load.

Damage class V


Shortening of column
Large cracks and failure of concrete

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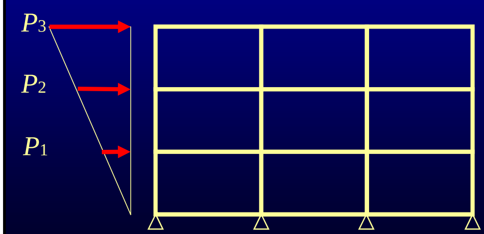
Evaluation of limit state

- Push-over analysis of a frame



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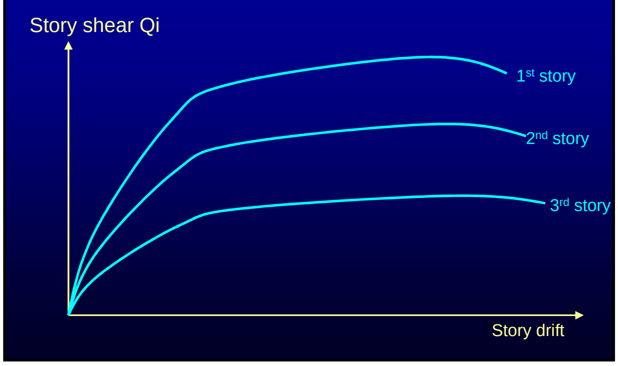
Story shear vs. inter-story drift



Percentage of damage classes and limit states of a story

damage class

Limit state	Ⅰ	Ⅱ	Ⅲ	Ⅳ	（Ⅴ）
serviceability	—	0%			
repairability Ⅰ	—	a(30)	b(20)	0%	
repairability Ⅱ	—	—	c(50)	0%	
safety	—	—	—	—	（0%）

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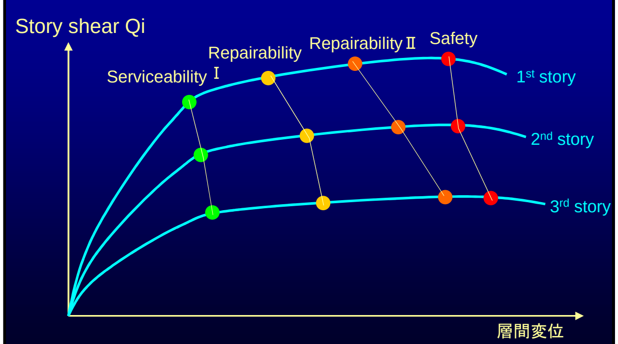
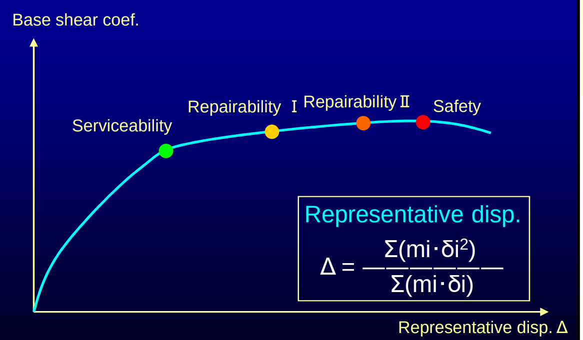
Story shear vs. inter-story drift and limit state



Reduction to an equivalent single-degree-of-freedom system



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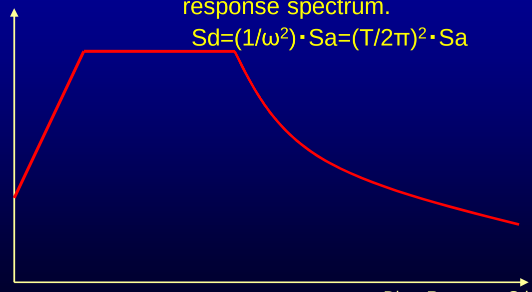
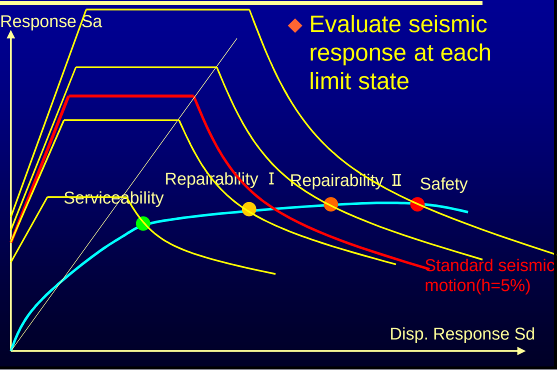
Prediction of response

- Sa-Sd curve is derived from response spectrum.
  $Sd=(1/\omega^2)\cdot Sa=(T/2\pi)^2\cdot Sa$



Sa−Sd curve

- Evaluate seismic response at each limit state



Evaluation of seismic motion at limit state

- Evaluate seismic motion at limit state considering response reduction by damping due to inelastic deformation

Reduction factor of response by damping

$$F_h = \frac{1.5}{1+10h}$$

Damping factor, h

$$h = 0.05+0.25(1-1/\sqrt{\mu})$$

μ : ductility factor

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Seismic capacity is basically given by "seismic capacity index"

$$\text{Seismic capacity index} = \frac{\text{Limit seismic motion}}{\text{Standard seismic motion}}$$

- Limit seismic motion: intensity of seismic motion at which building response reach to the limit states (serviceability, repairability I & II, safety L.S.)
- Standard seismic motion: intensity of seismic motion for return period of 100 yrs. (article 82, Enforcement Ordinance of Building Standard Law)

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