Strength and Ductility of Reinforced Concrete Highway Bridge Pier

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Introduction

Highway bridges are the most common and critical civil infrastructure components of a transportation network as they play important role in

- evacuation and emergency routes for rescues,
- first-aid,
- firefighting,
- medical services and
- transporting disaster commodities

during and after the earthquake

Introduction (contd…)

The recent earthquakes, such as

- the 1994 Northridge earthquake,
- the 1995 Great Hanshin earthquake ,
- the 1999 Chi-Chi earthquake,
- the 2008 Sichuan earthquake,
- the 2010 Chile earthquake, and
- the 2010 Haiti earthquake,

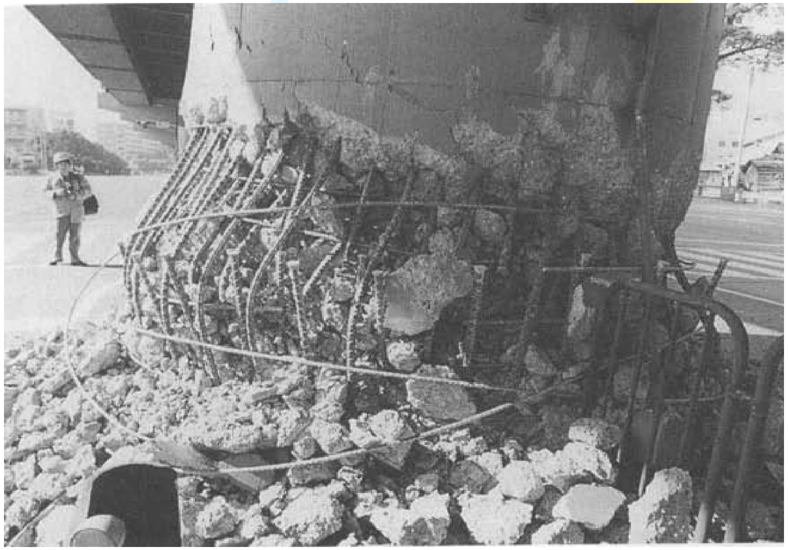
have shown the inadequacy of strength of the existing structures against earthquake effects

Damage Scenario

Flexural failure at the base of bridge pier of the Hanshin expressway in the 1995 Kobe earthquake

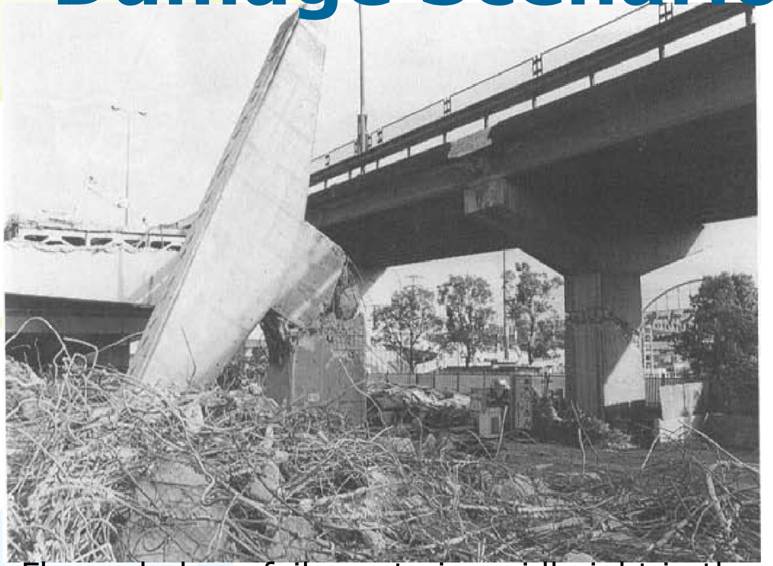
Shear Failure of flared column in the 1994 Northridge earthquake

Unseating of simply supported link span in the 1995 Kobe earthquake

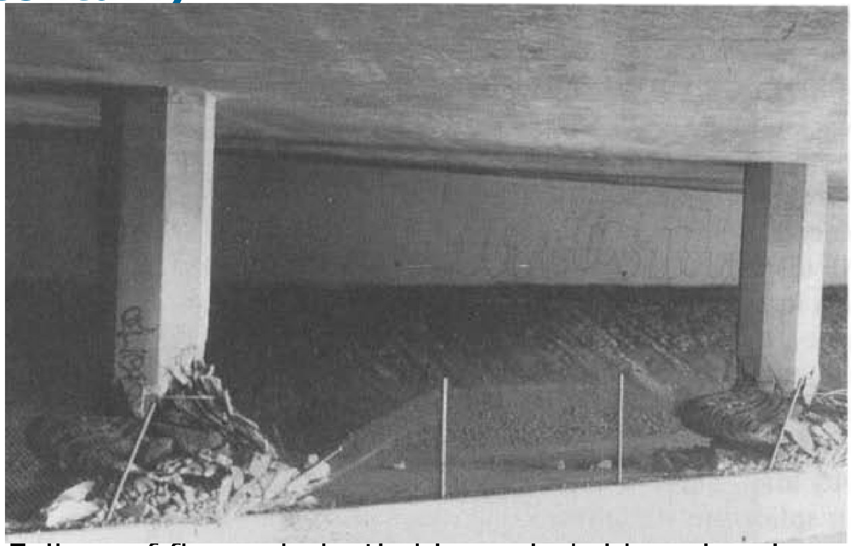


Bond failure of lap slices of bridge pier in the Loma Prieta earthquake in 1989

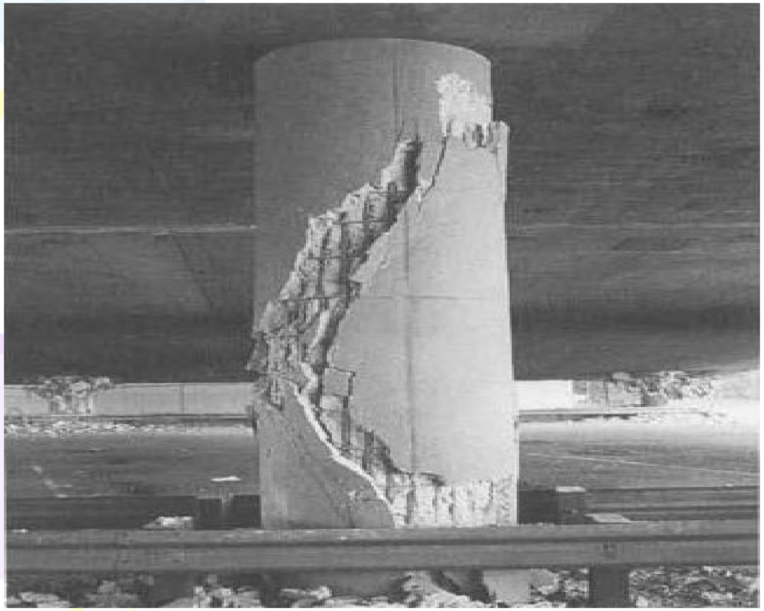
Damage Scenario (contd…)



Flexural-shear failure at pier midheight in the 1995 Kobe earthquake



Failure of flexural plastic hinges in bridge piers in the 1994 Northridge earthquake



Shear Failure of flared column in the 1994 Northridge earthquake

Collapse of the Hanshin expressway in the 1995 Kobe earthquake

Damage Scenario: at a glance

- flexural failure of piers of the Hanshin Expressway in the Kobe earthquake in 1995

- bond failure at the base of a RC columns attributable to lap slice in the Loma Prieta earthquake in 1989

- the flexure-shear failure of bridge piers initiated at bar cutoff locations around the pier mid-height level in the 1995 Kobe earthquake

- shear failure of columns in the 1994 Northridge earthquake

Philosophy of Seismic Design of RC Bridges

Basic concept of design philosophy and seismic performance criteria are more or less similar among seismic codes in Japan, the USA, the EU and New Zealand and some other countries that

- for small-to-moderate earthquakes, bridges should be resisted within the elastic range of structural components without significant **damage**,

- bridges exposed to moderate to strong earthquakes should not **collapse**

Development of Seismic Design Specification of Highway Bridge

1926 Design Specification:

- The first seismic provisions for highway bridges were introduced in 1926 after destructive damage of the 1923 Great Kanto earthquake
- It only specified a seismic lateral force of 20% of the gravity force; no other seismic-design-related provisions were given in this specification

Development of Seismic Design Specification of Highway Bridge (contd.)

1971 Design Specification:

- The first comprehensive seismic design provisions were issued by the Ministry of Construction in 1971 in the form of the *Guide Specification for Seismic Design of Highway Bridges*

- It was specified in the 1971 Specification that the lateral force shall be determined depending on **seismic zone**, **importance** and **ground condition**

Development of Seismic Design Specification of Highway Bridge (contd…)

1980 Design Specification

- The 1971 Guide Specification for Seismic Design were revised in 1980 to become the Design Specification for Highway Bridges

Development of Seismic Design Specification of Highway Bridge (contd…)

1990 Design Specification:

- The 1980 Design Specification was revised in 1990
- Various major revisions were included in the revised version by incorporating the **ductility method** as a checking tool

Development of Seismic Design Specification of Highway Bridge (contd…)

1995 Design Specification

- Forty days after the Hyogo-ken nanbu (H-k-n) earthquake, the Japan Ministry of Construction issued the Guide Specification for reconstruction and repair of highway bridges which suffered damage in the (H-k-n) earthquake (1995 Specification) for use in the reconstruction of the damaged bridges

Development of Seismic Design Specification of Highway Bridge (contd…)

1996 Design Specification:

- Although the 1995 and 1996 Specifications are essentially the same in concept, modifications and upgrading were included in the 1996 Specification, most importantly, **the check on the Ductility was upgraded to the Ductility Design method**

Development of Seismic Design Specification of Highway Bridge (contd…)

2002 Design Specification

- Because of the unsatisfactory performance of bridges in the 1995 Kobe earthquake, the Japanese Design Specifications of Highway Bridges was revised in 1996.

- The code was further revised in 2002 based on the **Performance-based design** concept for the purpose to respond the international harmonization of design codes and the flexible employment of new structures and new construction methods

Performance Based Design

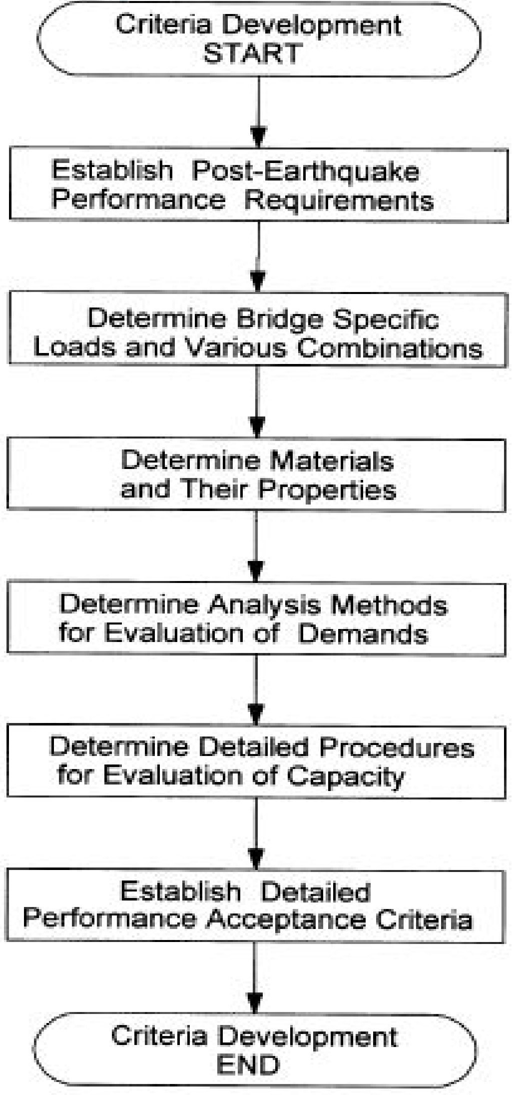
- Design for seismic resistance has been undergoing a critical reappraisal in recent years, with the emphasis changing from “**strength**” to “**performance**”.

- For most of the past 70 years – the period over which specific design calculations for seismic resistance have been required by codes – **strength and performance** have been considered to be synonymous.

- However, over the past 25 years there has been a gradual shift from this position with the realization that **increasing strength** may not enhance safety, nor **necessarily reduce damage**.

Performance Based Design (contd.)

The performance-based design concept is that the necessary **performance requirements** and the **verification policies** are to be clearly specified


Criteria Development START

Establish Post-Earthquake Performance Requirements

Determine Bridge Specific Loads and Various Combinations

Determine Materials and Their Properties

Determine Analysis Methods for Evaluation of Demands

Determine Detailed Procedures for Evaluation of Capacity

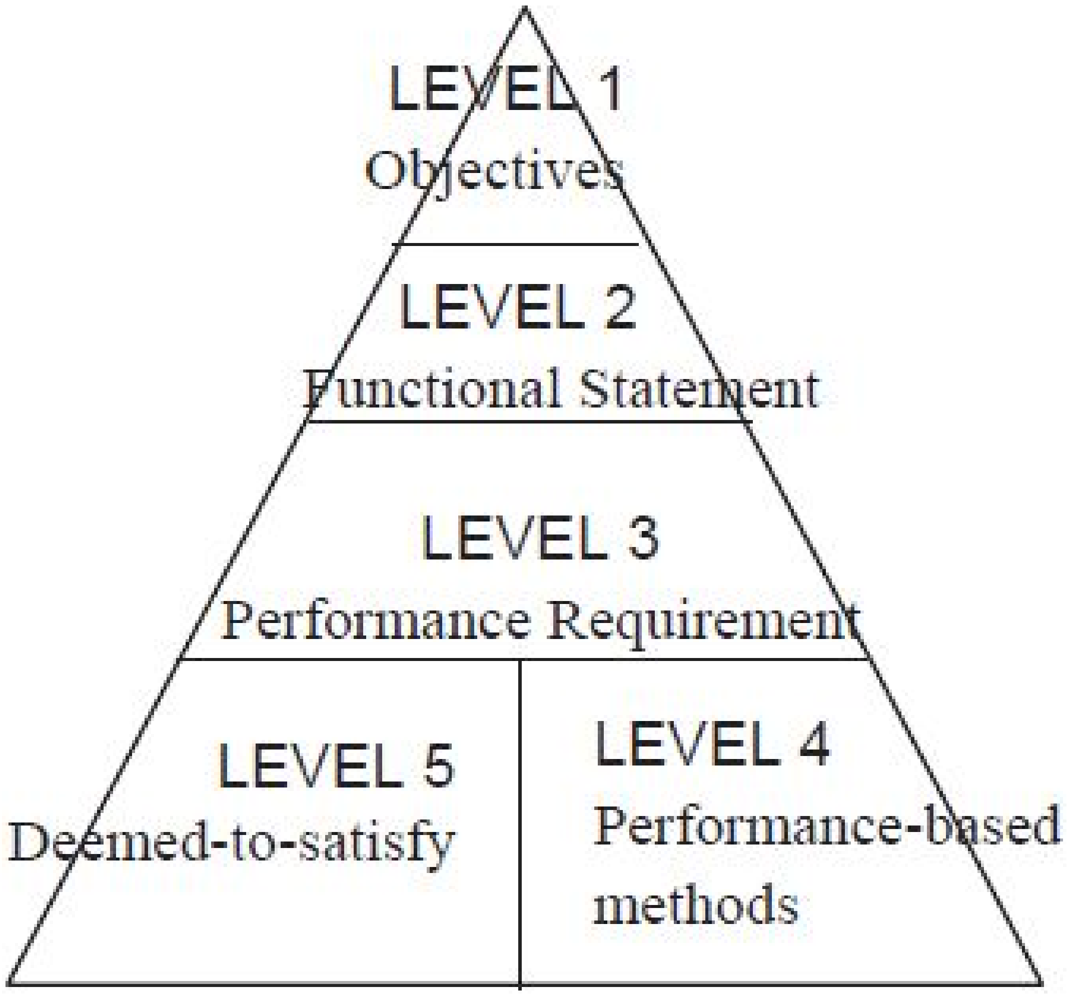
Establish Detailed Performance Acceptance Criteria

Criteria Development END

Performance Based Design (contd.)

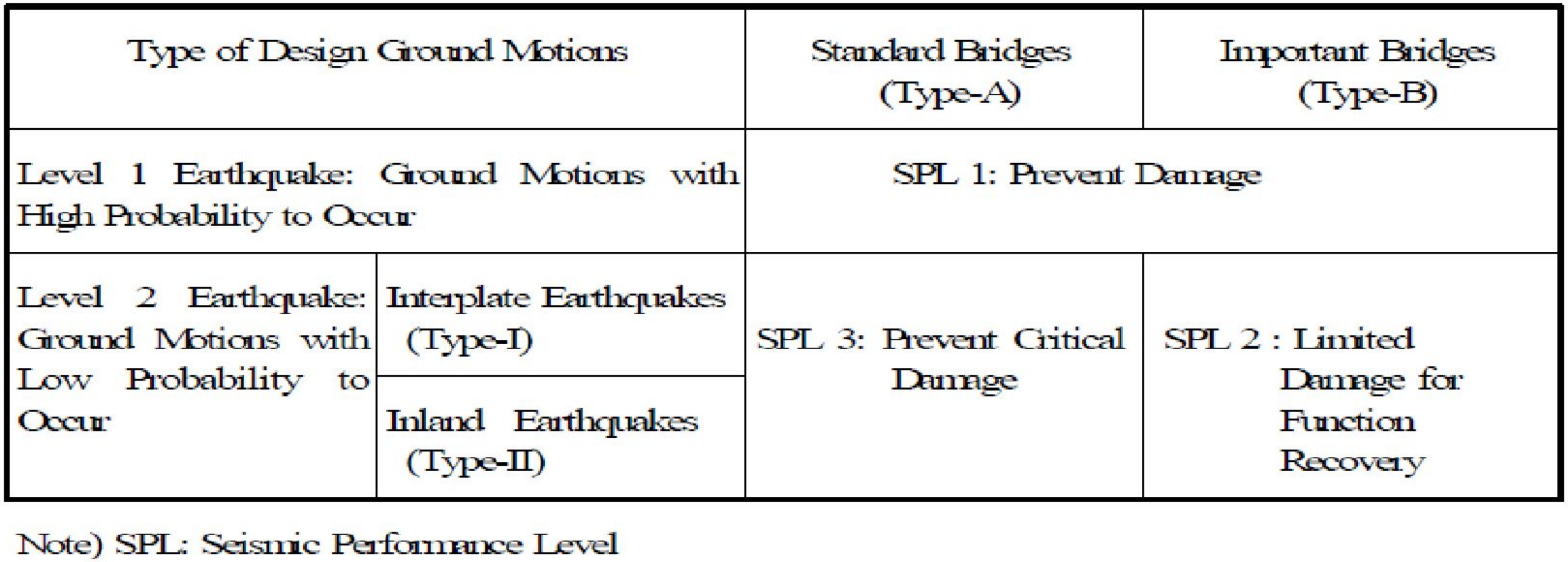
- The performance-based design distinguishes itself from the conventional design approach by specifying
- **Objectives (or Goals)** and **Functional Requirements (Functional Statements),** which are qualitative, and
- specifying or referencing **Performance Requirements (or Criteria)**
- can be used to assess whether or not the **Objectives** have been met

Performance Based Design (contd.)



Hierarchy of performance-based design

Seismic Performance Criteria (JRA, 2002)



Type of Design Ground Motions		Standard Bridges (Type-A)	Important Bridges (Type-B)
Level 1 Earthquake: Ground Motions with High Probability to Occur		SPL 1: Prevent Damage	
Level 2 Earthquake: Ground Motions with Low Probability to Occur	Interplate Earthquakes (Type-I)	SPL 3: Prevent Critical Damage	SPL 2 : Limited Damage for Function Recovery
	Inland Earthquakes (Type-II)		

Note) SPL: Seismic Performance Level

- the Level 1 earthquake is the moderate ground motion with high probability of occurrence and
- the Level 2 Earthquake is strong ground motion with low probability to occur
- Type I earthquake: the Kanto earthquake
- Type II earthquake: the Kobe earthquake

Seismic Performance Criteria (ATC 32)

Ground Motion (GM)	Service level		Damage level	
	Ordinary Bridges	Important Bridges	Ordinary Bridges	Important Bridges
Functional evaluation GM	Immediate	Immediate	Repairable Damage	Minimum damage
Safety evaluation GM	Limited	Immediate	Significant damage	Repairable damage

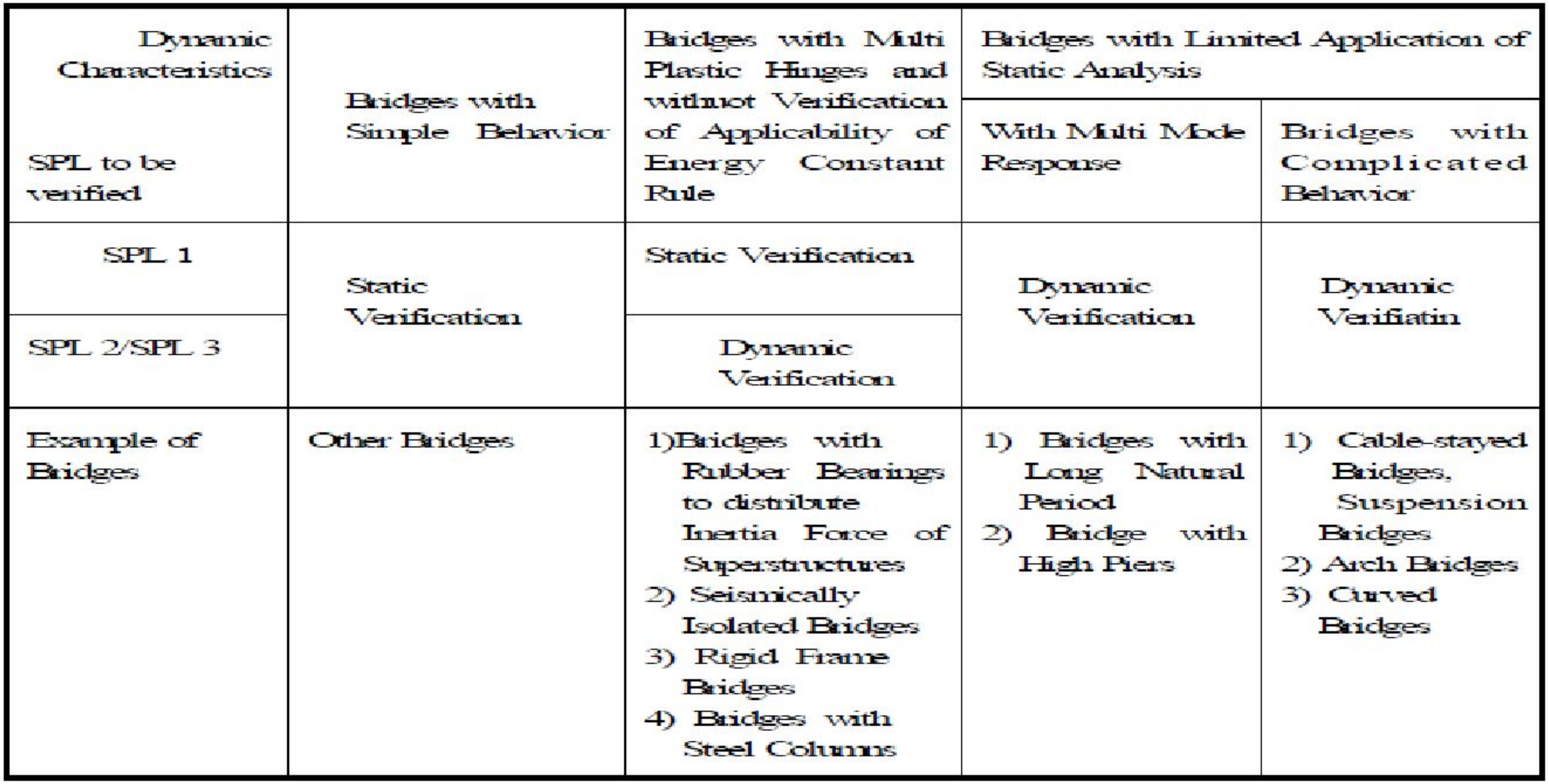
In service level, “immediate” implies full access to normal traffic almost immediately following the earthquake, and

“limited” implies that limited access (reduced lanes, and light emergency traffic) is possible within days of the earthquake, and that full service is restorable within months.

- Specifications for highway bridge; seismic design: part V, Japan Road Association, 2002
- Applied Technology Council (ATC-32), 1996

Verification Methods of Seismic Performance

It is the fundamental policy of the verification of seismic performance that **the response of the bridge structures** against design earthquake ground motions **does not exceed the determined limit states**.



Dynamic Characteristics SPL to be verified	Bridges with Simple Behavior	Bridges with Multi Plastic Hinges and without Verification of Applicability of Energy Constant Rule	Bridges with Limited Application of Static Analysis	
			With Multi Mode Response	Bridges with Complicated Behavior
SPL 1	Static Verification	Static Verification	Dynamic Verification	Dynamic Verifiatin
SPL 2/SPL 3		Dynamic Verification		
Example of Bridges	Other Bridges	1)Bridges with Rubber Bearings to distribute Inertia Force of Superstructures 2) Seismically Isolated Bridges 3) Rigid Frame Bridges 4) Bridges with Steel Columns	1) Bridges with Long Natural Period 2) Bridge with High Piers	1) Cable-stayed Bridges, Suspension Bridges 2) Arch Bridges 3) Curved Bridges

Structural Deformation Capacity (AASHTO-LRFD)

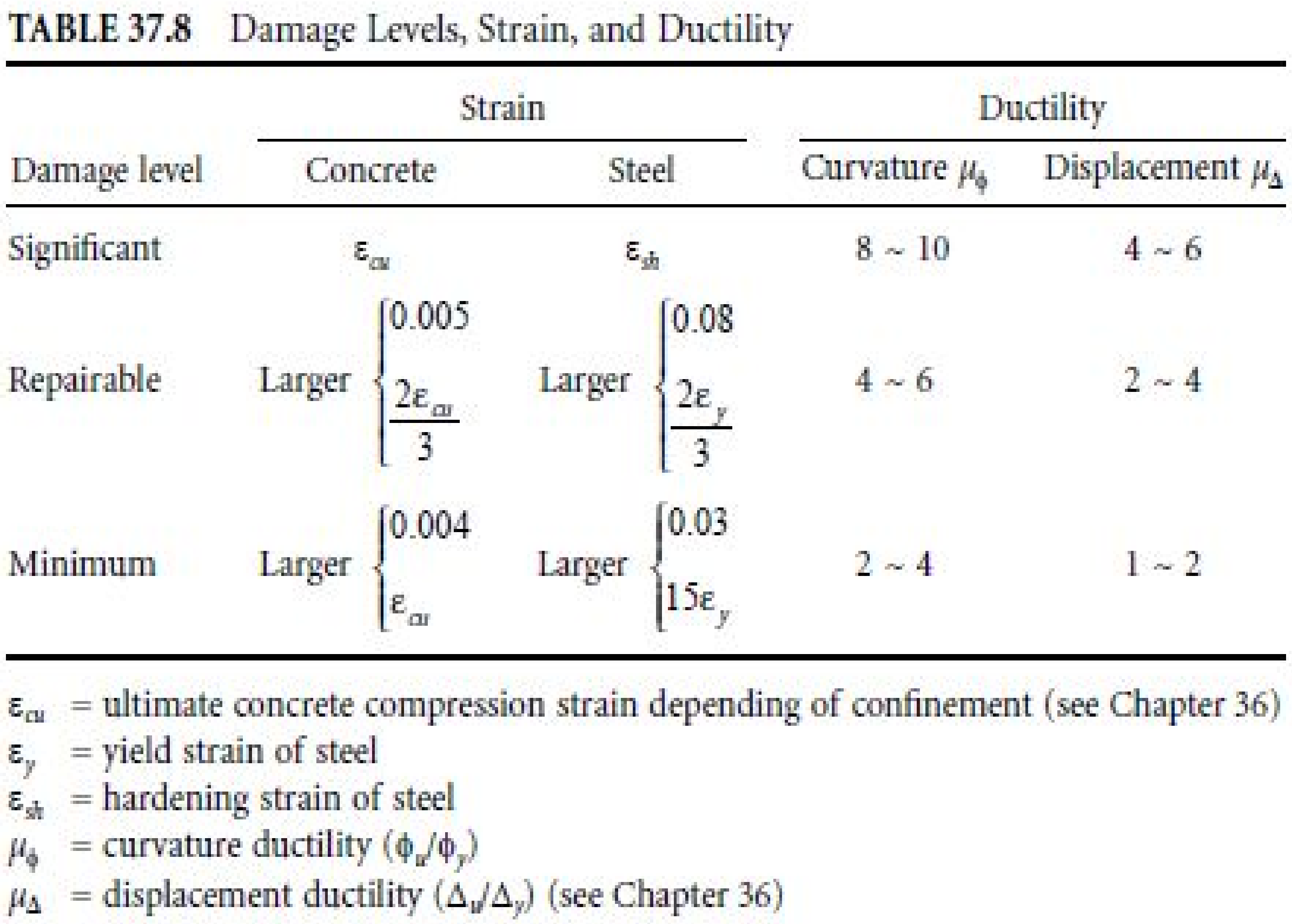


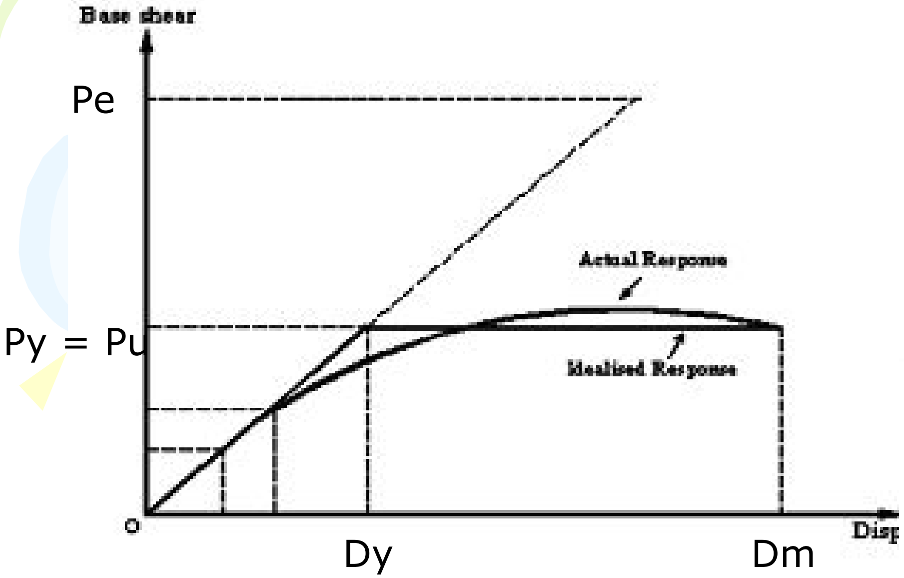
TABLE 37.8 Damage Levels, Strain, and Ductility

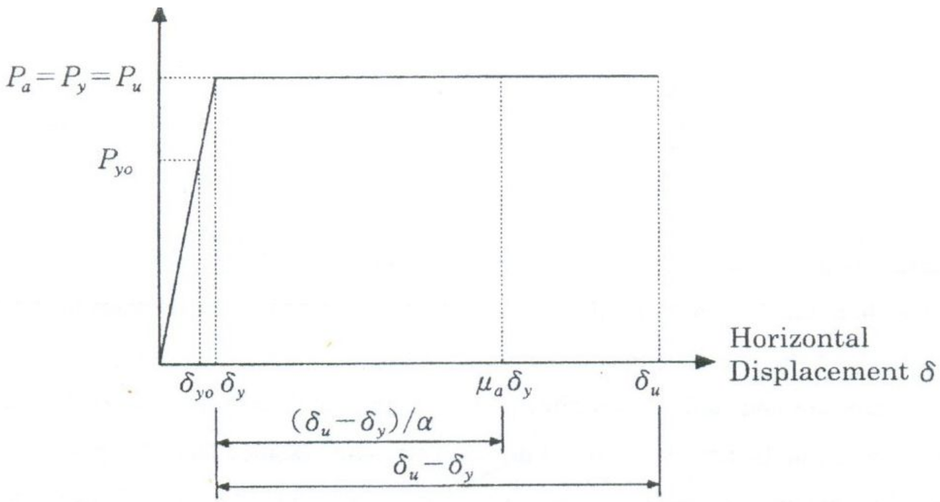
	Strain		Ductility	
Damage level	Concrete	Steel	Curvature μ_ϕ	Displacement μ_Δ
Significant	ε_{cu}	ε_{sh}	8 ~ 10	4 ~ 6
Repairable	Larger $\begin{cases} 0.005 \\ \frac{2\varepsilon_{cu}}{3} \end{cases}$	Larger $\begin{cases} 0.08 \\ \frac{2\varepsilon_y}{3} \end{cases}$	4 ~ 6	2 ~ 4
Minimum	Larger $\begin{cases} 0.004 \\ \varepsilon_{cu} \end{cases}$	Larger $\begin{cases} 0.03 \\ 15\varepsilon_y \end{cases}$	2 ~ 4	1 ~ 2

ε_{cu} = ultimate concrete compression strain depending of confinement (see Chapter 36)
ε_y = yield strain of steel
ε_{sh} = hardening strain of steel
μ_ϕ = curvature ductility (ϕ_u/ϕ_y)
μ_Δ = displacement ductility (Δ_u/Δ_y) (see Chapter 36)

Failure mode, lateral strength and ductility capacity of a bridge pier

- The pier strength and the design ductility factor of pier can be determined based on the failure mode





$^P u$ □ $^P s$: flexural failure

$^P u$ □ $^P s$ □ $^P s0$: shear failure after flexural yielding

$^P s0$ □ $^P u$: shear failure

$^P s$ □ $^V c$ □ $^V s$

V_c □ $k_c.k_e.k_{pt}.v_c.b.h$;

V_s □ A_w.□$_{sy}$.d.□sin□ □cos□□/□1.15.a□

Failure mode, lateral strength and ductility capacity of a bridge pier (contd..)

The allowable lateral capacity $^{P}\, a$ is provided as

$$P_a \square \begin{array}{l} \square \\ \square P_y \square \dfrac{P_u \square P_y}{\square} \\ \square \\ \square \quad P_i \end{array}$$

flexural failure + shear failure after flexural damage

shear failure

The allowable displacement ductility $\square\ a$ is provided as

$$\square_a \square \begin{array}{l} \square \\ \square 1 \square \dfrac{\square_u \square\square_y}{\square \cdot \square_y} \\ \square \\ \square \quad 1 \end{array}$$

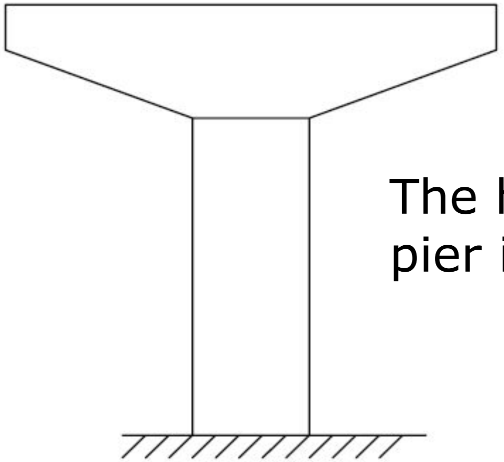
flexural failure

shear failure after flexural damage and shear failure

□ is safety factor depending upon bridge importance and type of earthquake ground motion ,

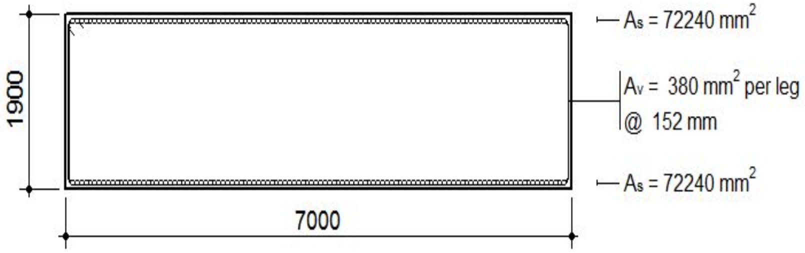
$\square\ y$ and $\square\ u$ are yield and ultimate displacement of the bridge pier under earthquake ground motion

Evaluation of Lateral Strength and Ductility of RC Bridge Pier



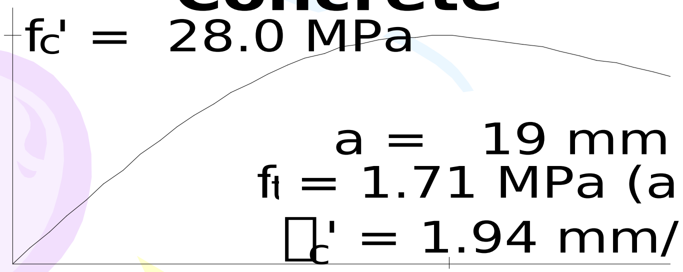
The cross-section of the pier is 7 m ×1.9 m

The height of the pier is 11.5 m



The weight of the superstructure and pier are, respectively, 990 tonf and 347 tonf .

Concrete



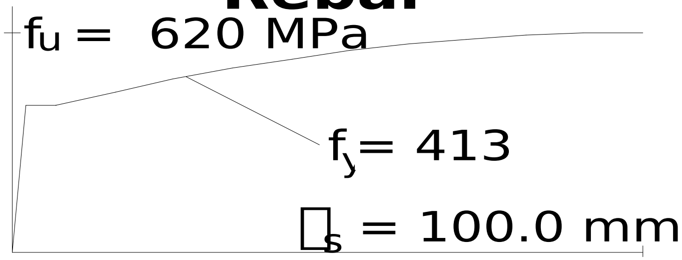
f_c' = 28.0 MPa

a = 19 mm

f_t = 1.71 MPa (auto)

$\square_c'$ = 1.94 mm/m

Rebar

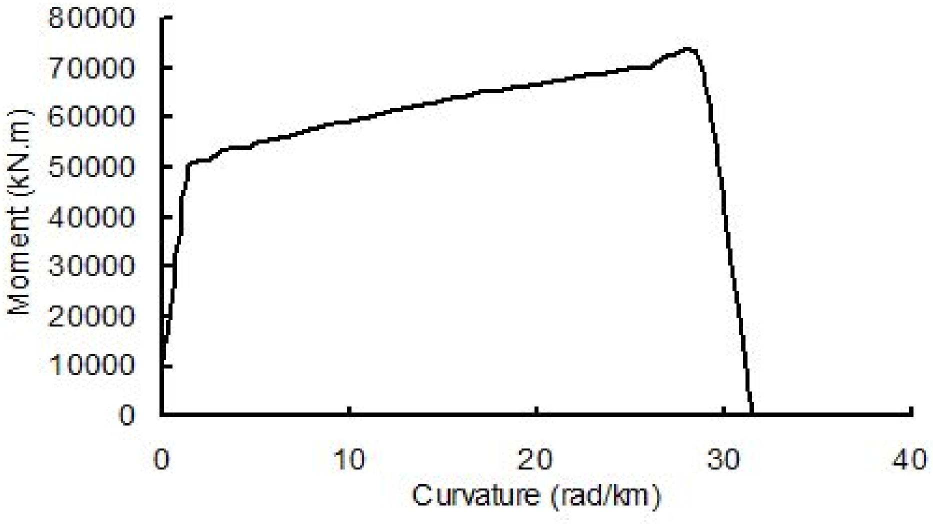


f_u = 620 MPa

f_y = 413

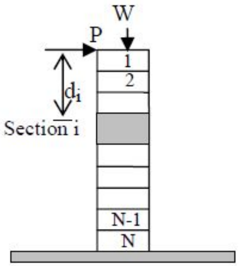
$\square_s$ = 100.0 mm/m

Evaluation of Lateral Strength and Ductility of RC Bridge Pier (contd…)



Using the moment-curvature plot shown in Figure (left) and the Equation presented below, the top displacement of the bridge pier can be obtained

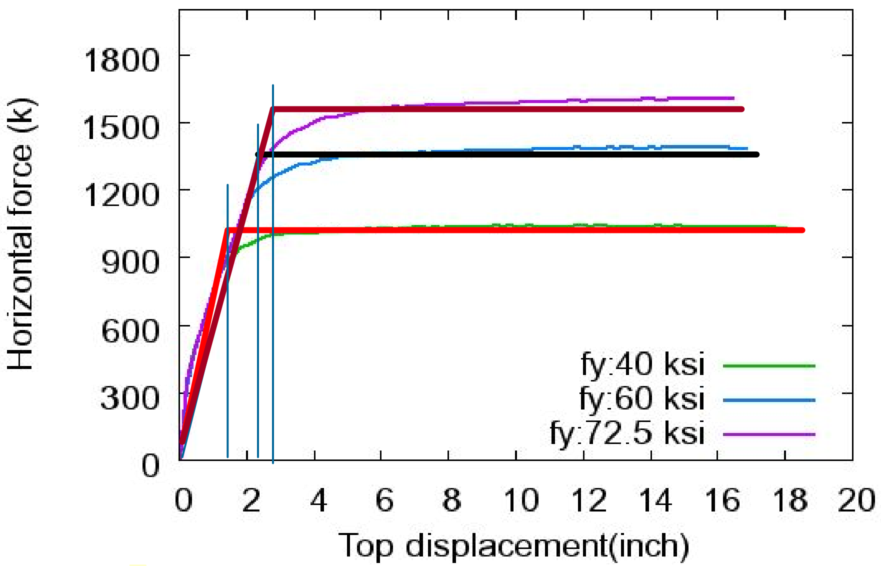
$$\Delta = \sum_{i=1}^{50} \left(\phi_i \times dy \times d_i \right)$$

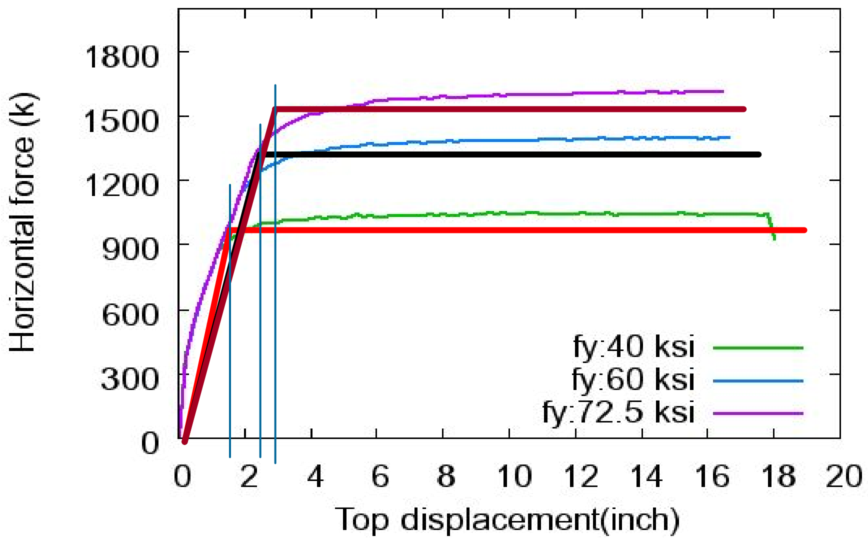


Finally, the force-displacement relationship at top of the bridge can be obtained from which the lateral strength and ductility capacity of the bridge pier can be evaluated.

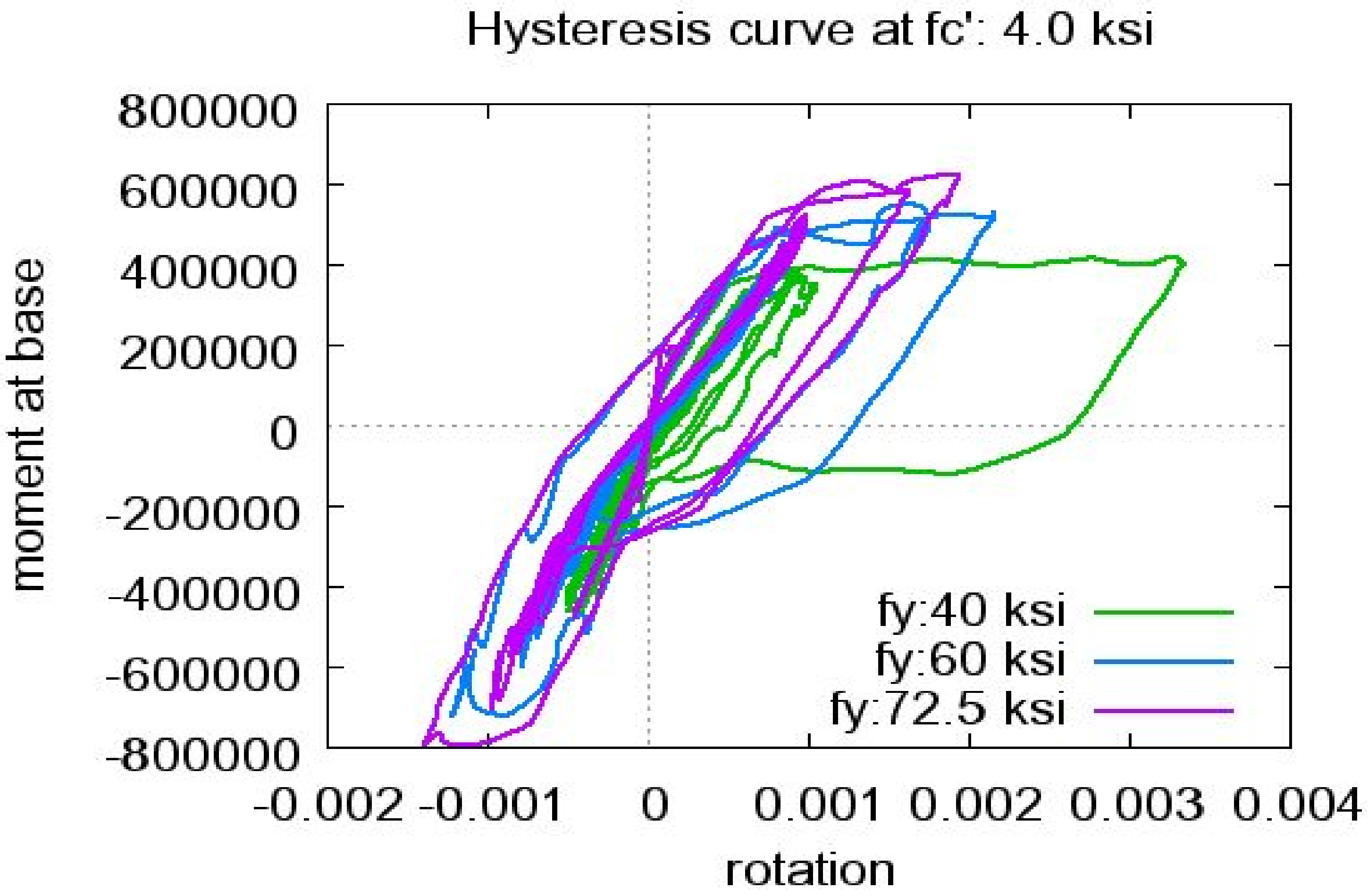
Evaluation of Lateral Strength and Ductility of RC Bridge Pier (contd…)

Moreover, a professional software (for example, Seismostruct 2011) can be used to derive the force-displacement relationship at top of the bridge pier by conducting **push-over analysis**


Force-displacement curve at fc': 3.0 ksi


Force-displacement curve at fc': 4.0 ksi

Seismic Performance of a reinforced concrete bridge pier under strong seismic event

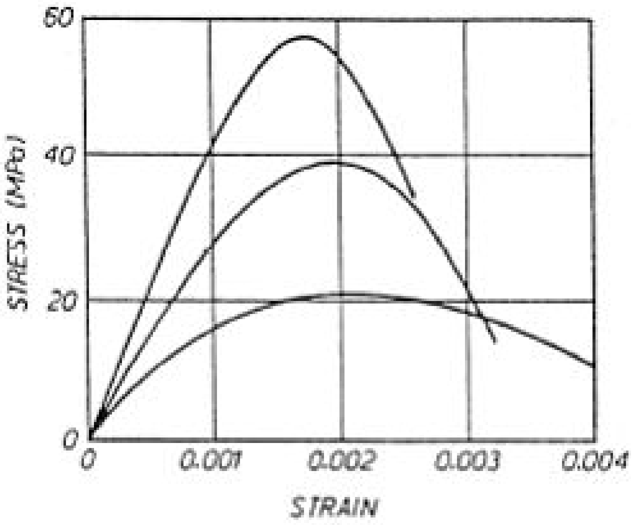


Ductility of RC Structures

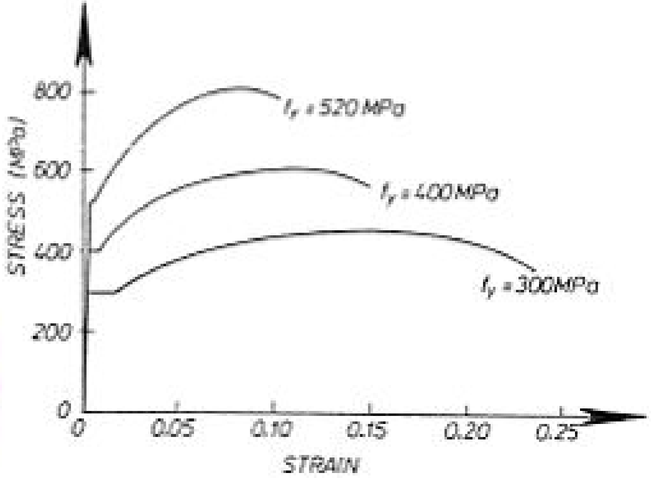
- Material Ductility
- Curvature (section) Ductility
- Element Ductility
- Structural Ductility

Material Ductility

- **Unconfined concrete:**
  - Negligible tensile strength
  - Higher compressive strength (f_{ck}) ⇒ lower ductility
  - Ultimate strain ε_{cu}=0.0035 (EC 2)

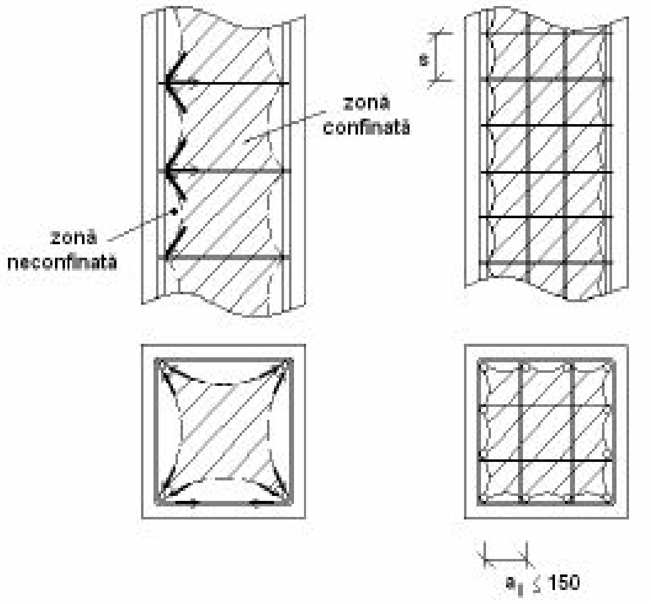


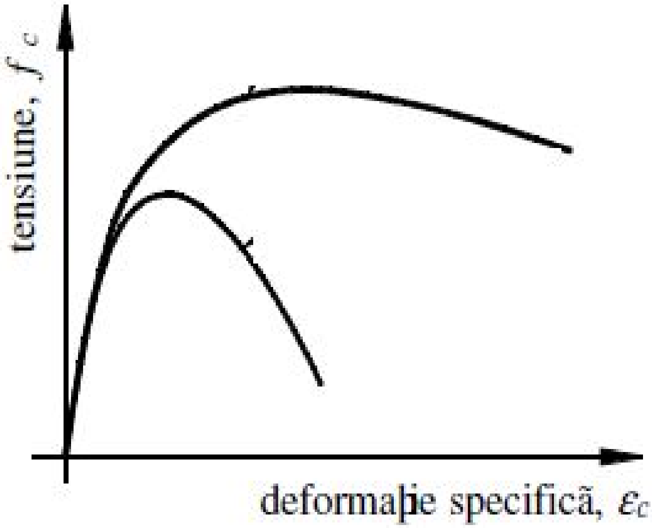
- **Reinforcing steel:**
  - Higher strength ⇒ lower ductility
  - Elongation at maximum force: $\varepsilon_{uk}\geq$0.075 for DCH (EC2 & P100-1/2006) $\varepsilon_{uk}\geq$0.050 for DCM (EC2 & P100-1/2006)



Material Ductility

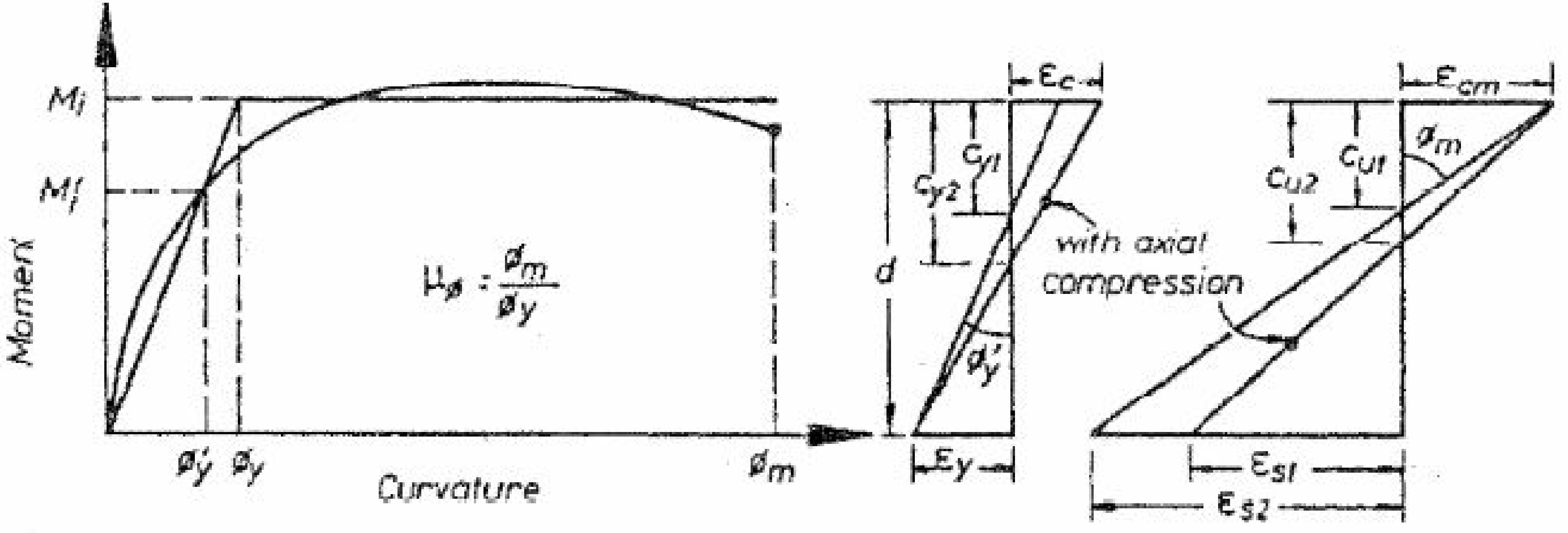
- Concrete compressive stress levels approaching crushing strength ⇒ high lateral tensile strains
- Lateral restrain provided by transverse (together with longitudinal) reinforcement ⇒ confinement
- Effect of confinement:
  - higher compressive strength
  - higher ductility (of the order ε_{cu}=0.005)





Curvature Ductility

- Rotation in plastic hinges - the most desirable source of inelastic deformations
- Curvature - rotation per unit length under bending moment
- Yield curvature: yielding of reinforcement or attainment of high concrete strains (ε_c=0.0015)

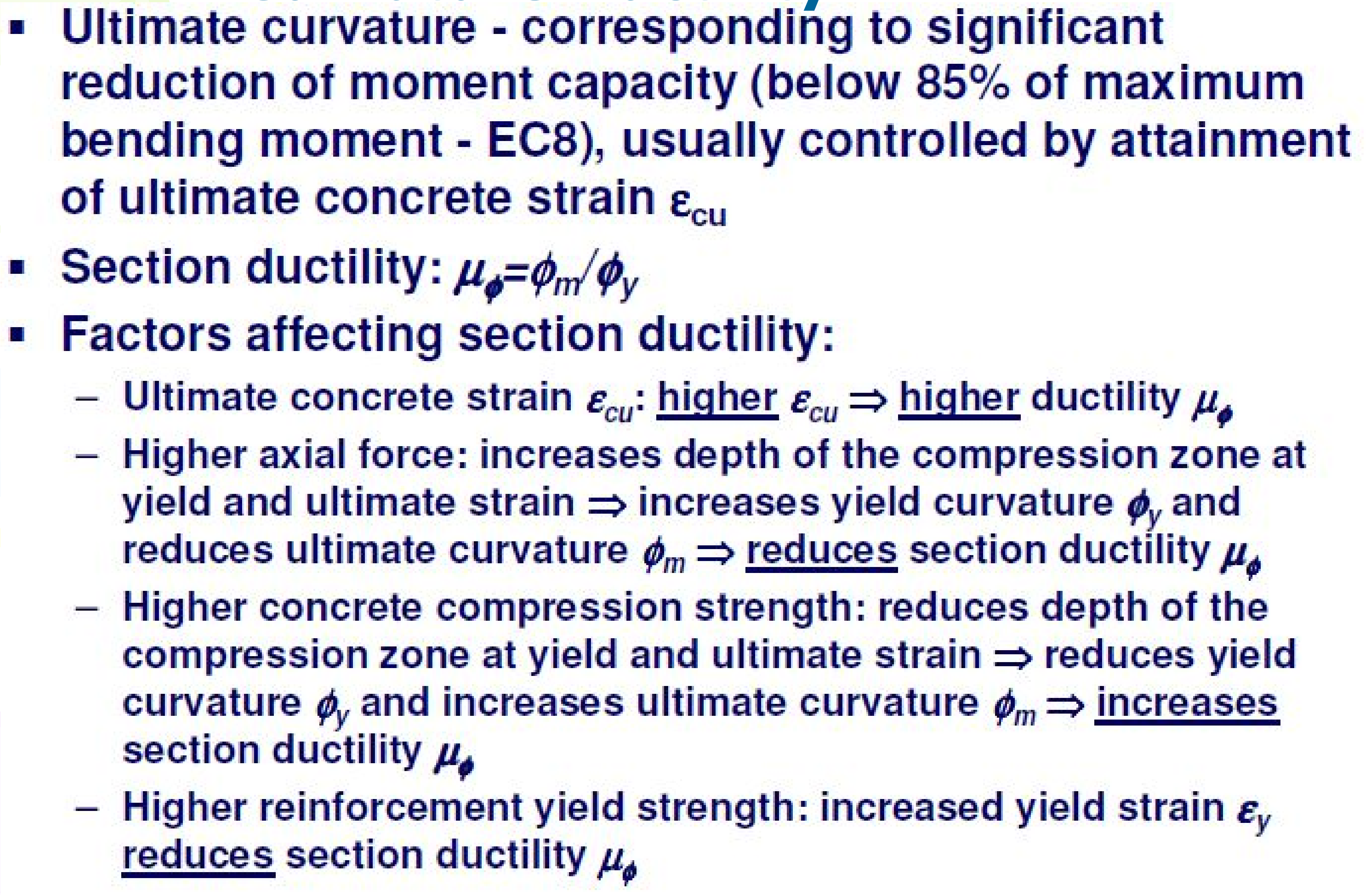


(a) Moment curvature relationship

(b) First-yield curvature

(c) 'Ultimate' curvature

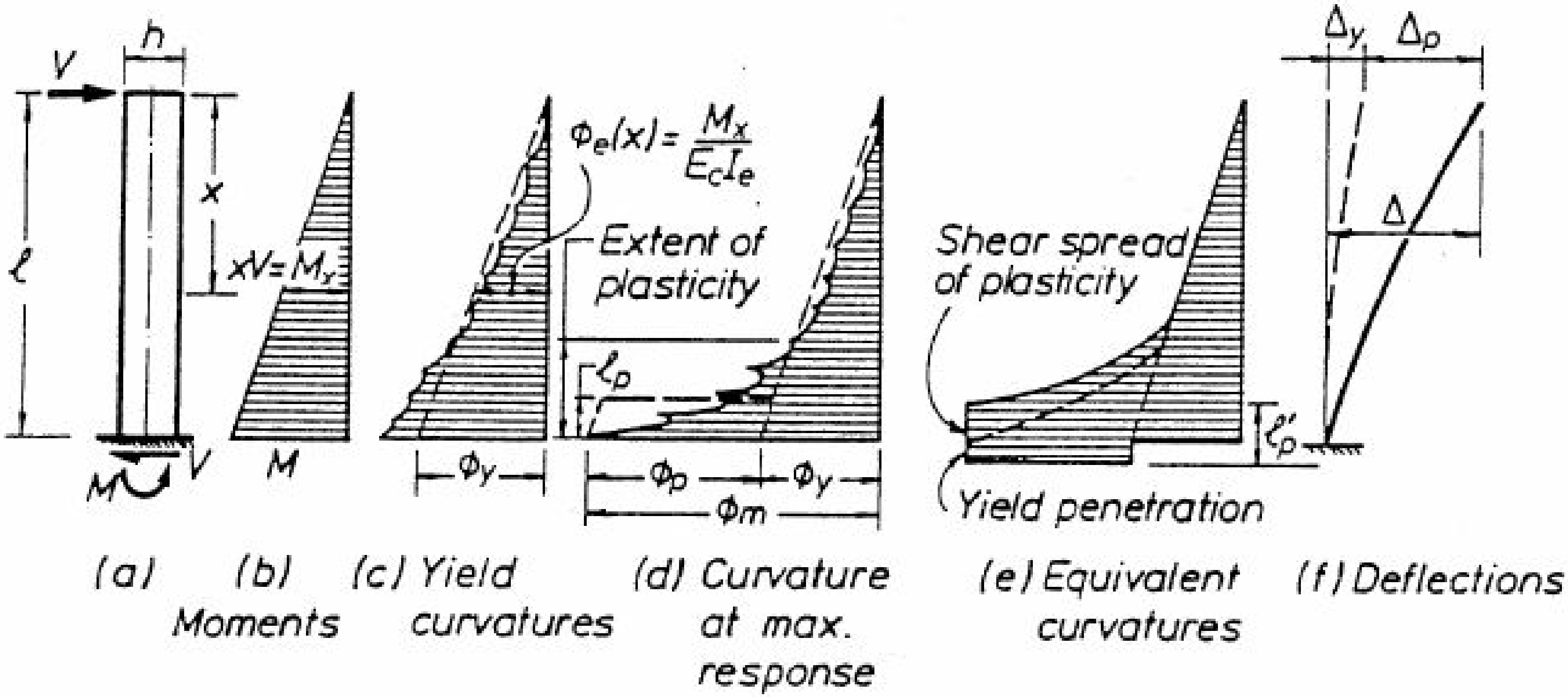
Curvature Ductility



- Ultimate curvature - corresponding to significant reduction of moment capacity (below 85% of maximum bending moment - EC8), usually controlled by attainment of ultimate concrete strain ε_{cu}
- Section ductility: $\mu_\phi = \phi_m / \phi_y$
- Factors affecting section ductility:
  - Ultimate concrete strain ε_{cu}: higher $\varepsilon_{cu} \Rightarrow$ higher ductility μ_ϕ
  - Higher axial force: increases depth of the compression zone at yield and ultimate strain $\Rightarrow$ increases yield curvature ϕ_y and reduces ultimate curvature $\phi_m \Rightarrow$ reduces section ductility μ_ϕ
  - Higher concrete compression strength: reduces depth of the compression zone at yield and ultimate strain $\Rightarrow$ reduces yield curvature ϕ_y and increases ultimate curvature $\phi_m \Rightarrow$ increases section ductility μ_ϕ
  - Higher reinforcement yield strength: increased yield strain ε_y reduces section ductility μ_ϕ

Element Ductility

- Rotations in plastic hinges - distributed over a finite length: plastic hinge length
- Element ductility: $\mu_\Delta = \Delta/\Delta_y$
- Displacements Δ_y and Δ can be obtained by integrating the curvature over its height

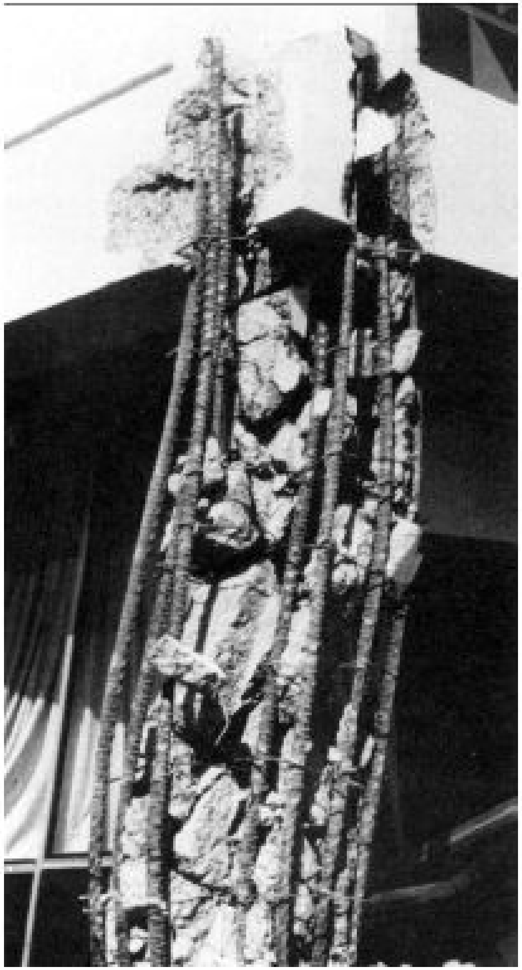


(a) (b) Moments (c) Yield curvatures (d) Curvature at max. response (e) Equivalent curvatures (f) Deflections

Element Ductility

- **Example: damage of columns of the same building (Olive View Hospital) during the San Fernando earthquake, California, USA, from February 9, 1971**

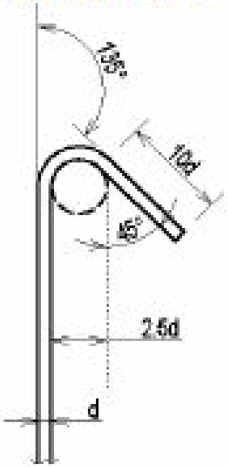
adequate
transverse
reinf.

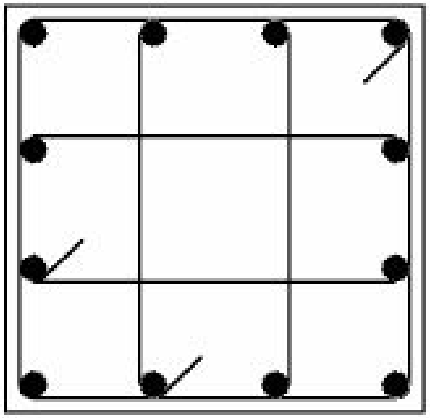


inadequate
transverse
reinf.

Element Ductility (Column)

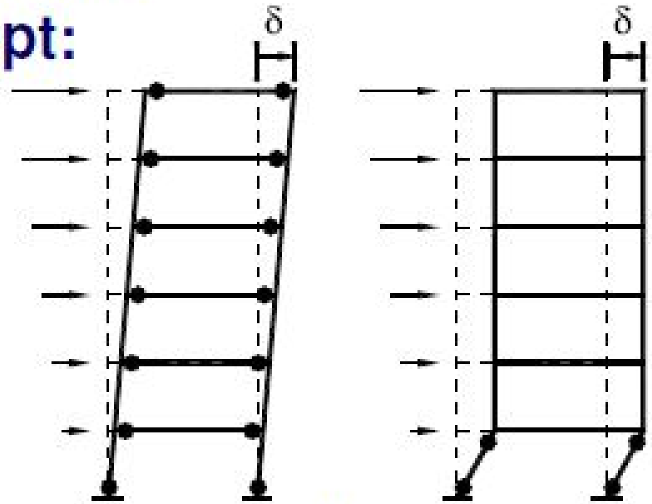
- Strong column - weak beam design philosophy
- However, plastic hinges in columns not precluded completely ⇒ columns should be detailed for ductile behaviour in potential plastic hinges (column ends)
- Columns: bending, shear force, axial force
- Ductility provided by:
  - – confinement by transverse and longitudinal reinforcement
    - intermediate longitudinal reinforcement
    - longitudinal bars fixed with stirrups and ties
    - 135° bent stirrups for good anchorage in confined concrete
    - closer spacing of transversal reinforcement
  - – prevention of shear failure
  - – avoiding of splices in potential plastic hinges





Structural Ductility (Frame)

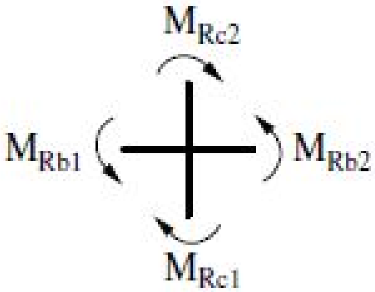
- Promote global plastic mechanism:
  - maximum possible number of plastic zones
  - uniform distribution of ductility demands in the structure
  - avoid plastic hinges in columns - elements more important for overall structural stability
- Strong column - weak beam concept:



$$\sum M_{Rc} \geq 1.3 \sum M_{Rb}$$

ΣM_{Rc} - sum moment resistances of columns framing into the joint. Account shall be taken of the axial force present in the column in the seismic design situation

ΣM_{Rb} - sum moment resistances of beams framing into the joint



ACI 318-02 special provisions for seismic design of RC structures

Goal:

- to ensure adequate ductility under inelastic displacement reversals brought on by earthquake loadings

How to achieve the goal?

- this goal can be achieved by providing **concrete confinement** and **inelastic rotation capacity** in RC structures

Use of seismic hook on stirrups, hoop and crossties, etc.

Maintain the minimum ratio of tensile strength to yield stress of reinforcing bars