

SEISMIC DESIGN, RESPONSE  
MODIFICATION, AND RETROFIT  
OF BRIDGES

Kazuhiko Kawashima  
Department of Civil Engineering  
Tokyo Institute of Technology

## PREFACE

This is a lecture note for “Seismic Design, Response Modification and Retrofit of Bridges” at the Graduate Course of the Department of Civil Engineering, Tokyo Institute of Technology, Japan. The scientific and engineering knowledge on the earthquake engineering is described in this note with an emphasis on the application to bridges. Since the contents includes a broad senses on the structural engineering, the structural dynamics, the concrete engineering, the soil mechanics, foundation engineering, the engineering seismology, and the construction engineering, students are required to take those courses before studying this class.

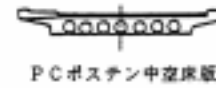
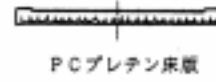
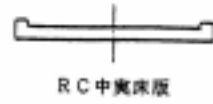
Bridges are unique structures in their structural responses compared to other structures. They are longitudinally lengthy. There are various types of superstructures, substructures, and foundations as shown in Figs. P-1, P-2, P-3, and P-4 (Road Maintenance Technology Center 1996), with complex geometries and dynamic response characteristics. However, bridges have a lower degree of static indeterminacy than buildings. Hence failure of a part of structural element such as columns or foundations likely results in a collapse of the entire bridge system. Effect of the soil-structure interaction and the spatial variation of ground motions are significant in bridges than buildings. Since bridges are a vital component of transportation system, bridges should have sufficient seismic safety in an earthquake.

The 1989 Loma Prieta, the 1994 Northridge, the 1995 Kobe, the 1999 Taiwan and the Turkey earthquakes caused significant damage to bridges and these events together with the research triggered as a consequence of past earthquakes has led to significant advances in seismic engineering of bridges.

This lecture note shows the recent technologies for seismic design, seismic response modification, and seismic retrofit of bridges. Past seismic damage of bridges, characterizations of ground motion, dynamic response analysis methods, seismic response characteristics of bridges, and strength and ductility of reinforced concrete columns are also described.

Kazuhiko Kawashima  
Professor, Department of Civil Engineering  
Tokyo Institute of Technology  
Meguro, Tokyo, Japan  
e-mail: [kawasima@cv.titech.ac.jp](mailto:kawasima@cv.titech.ac.jp)

①床版橋



②桁橋

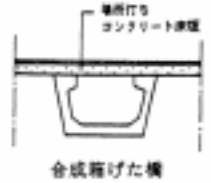
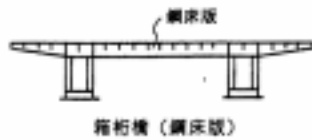
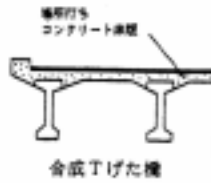
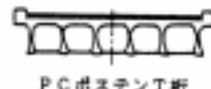
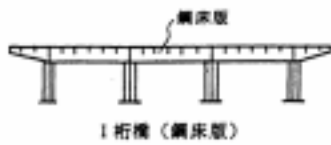
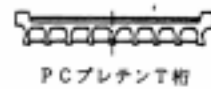
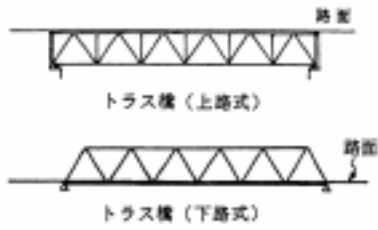
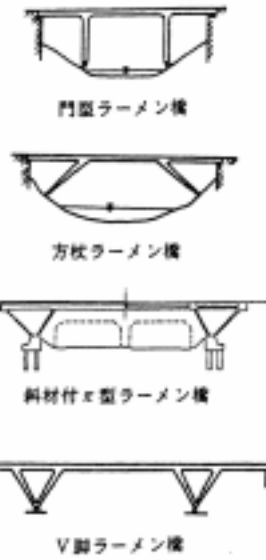


Fig. P-1 Types of Superstructure (1/2)

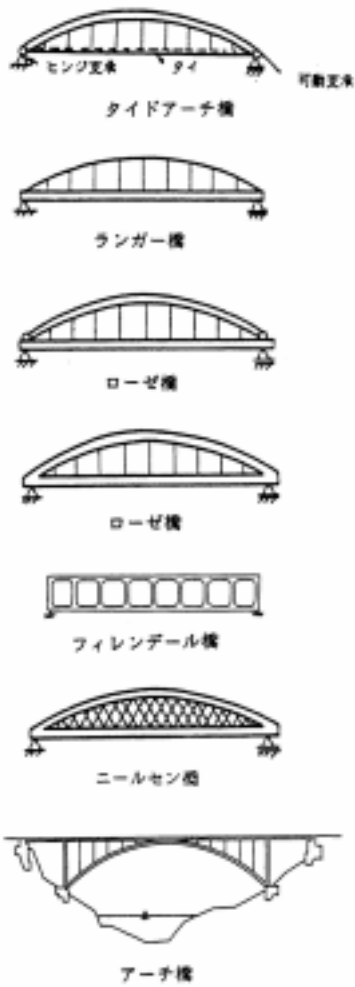
③トラス橋



⑤ラーメン橋



④アーチ系橋



⑥斜張橋



⑦吊橋

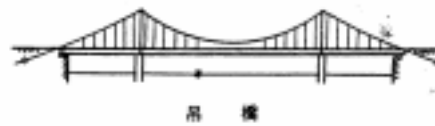


Fig. P-1 Types of Superstructure (2/2)

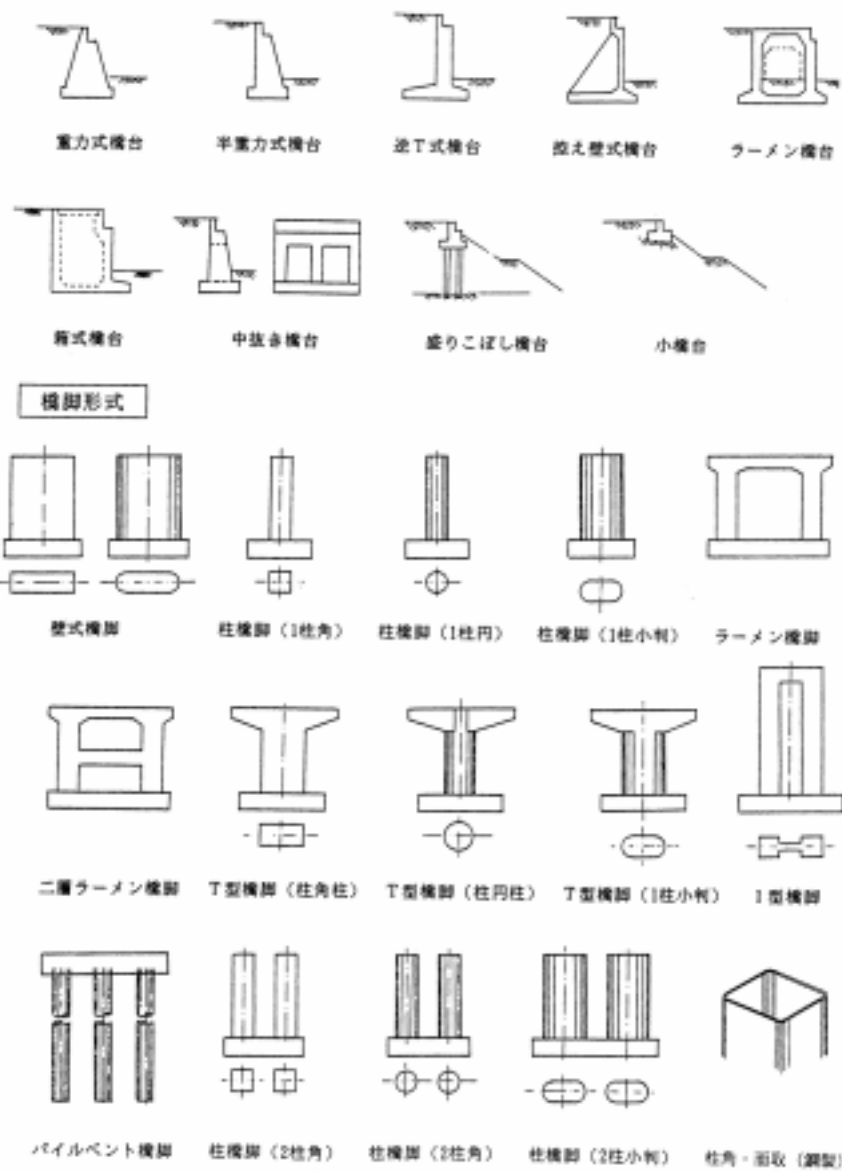


Fig. P-3 Types of Substructure (1/2)

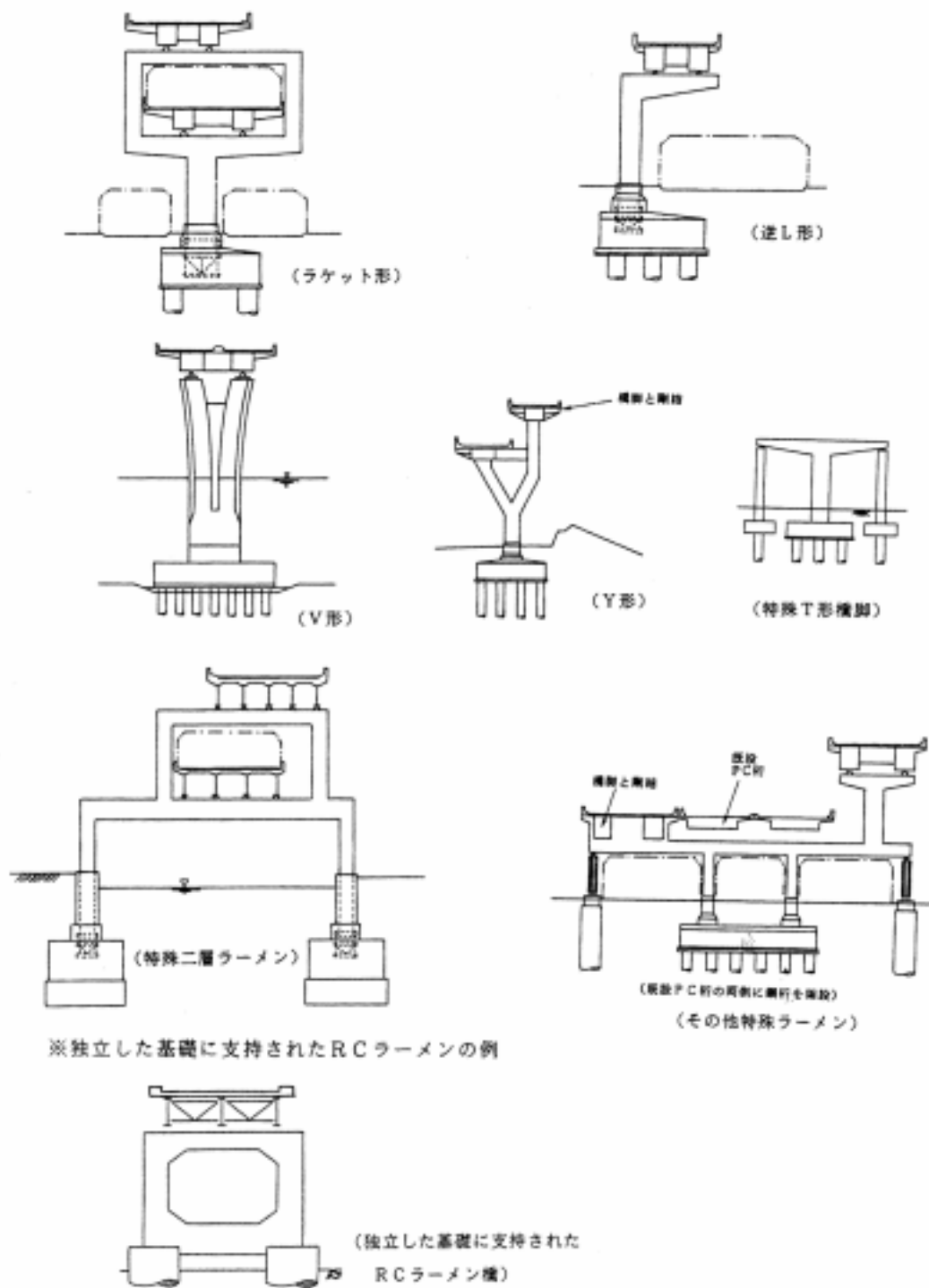


Fig. P-4 Types of Substructure (2/2)

## Table of Contents

### 1. Engineering Characterization of Ground Motion

1.1 Ground Motions

1.2 Peak Ground Motions

1.3 Duration of Ground Accelerations

1.4 Response Spectra

1) Horizontal Component

2) Vertical Component

1.5 Acceleration Response Spectrum Taking Number of Response Cycle into Account

1.6 Force Reduction Factor Resulting from Nonlinear Response

1.7 Relative Displacement Response Spectrum

1.8 Residual Displacement Response Spectrum

1.9 Multiple Excitation Response Spectrum

### 2. Dynamic Response Analysis of Bridges

2.1 Introduction

2.2 Analytical Modeling of Bridges

1) Structural System

2) Stiffness Idealization

3) Mass Idealization

4) Damping Idealization

2.3 Dynamic Analysis for Seismic Response of Bridges

1) Equations of Motion

2) Linear Analysis Procedure

3) Single Mode Spectral Analysis

4) Nonlinear Analysis

5) Evaluation of Computed Solution

### 3. Seismic Damage in the Past Earthquakes

3.1 Loma Prieta and Northridge, USA, Earthquakes (Not yet included)

3.2 Pre-Kobe and Kobe, Japan, Earthquakes

1) Pre-Kobe Earthquakes

2) 1995 Kobe Earthquake

3.3 Kocaeli and Duzce, Turkey, Earthquakes

- 1) Kocaeli Earthquake
- 2) Duzce Earthquake
- 3.4 Chi Chi, Taiwan, Earthquake

#### 4. Strength and Ductility of Reinforced Concrete Members

##### 4.1 Strength and Ductility

##### 4.2 Lateral Confinement of Concrete by Ties

- 1) Lateral Confinement Effect
  - a) Hysteresis for repeated full unloading and reloading
  - b) Hysteresis for partial unloading and full reloading
  - c) Hysteresis for full unloading and partial reloading
- 2) Lateral Confinement of Concrete by Carbon Fiber Sheets
  - a) Lateral confinement of concrete by CFS
  - b) Lateral confinement of concrete by both CFS and Ties

##### 4.3 Loading Tests

- 1) Test Methods
- 2) Yield and Ultimate
- 3) Equivalent stiffness and energy dissipation

##### 4.4 Effect of Various Factors on Strength and Ductility Capacities of Reinforced Concrete Columns

- 1) Effect of Loading Hysteresis
- 2) Effect of Varying Axial Force
- 3) Effect of Bilateral Loading
- 4) Hybrid Loading Tests
- 5) Verification of Seismic Performance using Plot-size Models

##### 4.5 Reinforced Concrete Columns with Enhanced Ductility

- 1) Interlocking Columns with Large Cross Sections
- 2) Unbonding of Longitudinal Bars at the Plastic Hinge
- 3) Prestressed concrete columns
- 4) Isolator built-in column

##### 4.6 Seismic Performance of C-Bent Columns

#### 5. Seismic Response of Bridges

##### 5.1 Seismic Response Characteristics of Standard Bridges

##### 5.2 Seismic Response Analysis of Kaihoku Bridge

##### 5.3 Effect of Multiple Excitation

#### 5.4 Effect of Pounding of Decks

- 1) Importance of Pounding
- 2) Idealization of Longitudinal Collisions of Two Elastic Bars using Impact Spring
- 3) Analysis of Seismic Response of a Straight Model Bridge with Pounding Effect

#### 5.5 Seismic Response of a Curved Bridge with Poundings

- 1) Structural Response of Curved Bridges
- 2) Analytical Model of Expansion Joints
- 3) Analytical Prediction of Seismic Response

#### 5.6 Seismic Response of Skewed Bridges

#### 5.7 Seismic Response of Bridges Supported by Pile Foundations

#### 5.8 Seismic Response of Bridges Supported by Spread Foundations

#### 5.9 Response of Pile Foundations for Fault Dislocation

#### 5.10 Seismic Response of Arch Bridges

#### 5.11 Seismic Response of Cable Stayed Bridges

- 1) Dynamic Characteristics of Cable Stayed Bridges based on Forced Excitation Tests
  - a) Onomichi Bridge
  - b) Suehiro Bridge
  - c) Yamato-gawa Bridge
  - d) MEiko-nishi Bridge
- 2) Natural Periods and Mode Shapes of Cable Stayed Bridges
- 3) Damping Ratios of Cable Stayed Bridges
- 4) Analysis of Damping Ratios of a Cable Stayed Bridges based on Measured Records
  - a) Dynamic Characteristics of Suigo Bridge
  - b) Measured Records during Past Earthquakes
  - c) Dynamic Characteristics based on Measured Accelerations
  - d) Dynamic Response Analysis of Suigo Bridge
- 5) Damping Ratios Resulting from Energy Dissipation at Movable Bearings
- 6) Dependence of Damping Ratios on Mode Shapes
  - a) Experimental Tests
  - b) Effect of Cable Types on the Damping Ratios in the Longitudinal Direction
  - c) Effect of Cable Types on the Damping Ratios in the Vertical Direction
  - d) Evaluation of Damping Ratios of Cable Stayed Bridges
  - e) Evaluation of Energy Dissipation Functions for the Model Bridges
  - f) Evaluation of Damping Ratio of Model Bridges Based on Energy Dissipation

## Functions

### 7) Effect of Propagating Ground Motions for Cable Stayed Bridges

## 5.12 Seismic Performance of Long-span Bridges during the 1995 Kobe Earthquake

## 6. Seismic Design

### 6.1 Introduction

### 6.2 Practice of Seismic Design in Japan

- 1) Past History of Seismic Design
- 2) Seismic Performance Goals
- 3) Design Ground Motions
- 4) Design of Bridge System
- 5) Design of Reinforced Concrete Columns
  - a) Evaluation of Response Modification Factors
  - b) Evaluation of Strength and Ductility Capacity
  - c) Residual Displacement
  - d) Design Detailings
  - e) Comparison of Pre-Kobe and Post-Kobe Codes
- 6) Design of Foundations
- 7) Liquefaction and Liquefaction-Induced Ground Movement

### 6.3 Features of Recent Seismic Design Codes

- 1) Seismic Design Codes
- 2) Design Philosophy and Seismic Performance Criteria
- 3) Seismic Loads
- 4) Analytical Methods and Design Requirements
- 5) Response Modification Factors and Target Displacement Ductility Demand

## 7. Seismic Response Modification Design

### 7.1 Introduction

### 7.2 Seismic Response Modification using Viscous Damper Stoppers

### 7.3 Seismic Response Modification of Cable Stayed Bridges

### 7.4 Seismic Isolation

- 1) Principles
- 2) System Design
- 3) Design of Devices

### 7.5 Implementation of Seismic Isolation

- 1) Application to 29-span Continuous Viaduct

- a) Ohito Viaduct
- b) DEsign
- c) Detailings
- 2) Application of High Performance Stopper and Buffer System,
  - a) Wakayama Viaduct
  - b) Design
  - c) Cost Evaluation
- 3) Application to Reconstruction of a 19-span Continuous Viaduct
  - a) Benten Viaduct
  - b) Design
- 7.6 Technical Development for Seismic Isolation
  - 1) Evaluation of Seismic Response Based on a Measured Acceleration
  - 2) Development of Expansion Joints with Large Relative Displacement
  - 3) Shock Absorbers for Mitigation of Pounding Effect
  - 4) Effect of Pounding between Adjacent Decks
  - 5) Isolator and Column Interaction
- 7.7 New Seismic Response Control Technology
  - 1) Response Control by Variable Damper
  - 2) Response Control of MR-Damper

## 8. Seismic Assessment and Retrofit

### 8.1 Introduction

### 8.2 Assessment of Seismic Vulnerability

### 8.3 Seismic Retrofit of Columns

- 1) Steel Jacket for Single Reinforced Concrete Columns
- 2) Reinforced Concrete Jacket for Wall Piers
- 3) Precast Concrete Jacket
- 4) Composite-Materials Jackets
- 5) Retrofit of Steel Columns

### 8.4 Seismic Retrofit of Foundations

- 1) Seismic Retrofit of Foundations with Inadequate Soil Bearing Capacity
- 2) Seismic Retrofit of Pile Foundations by Enlarging Footing and Increasing Number of Piles
- 3) Seismic Retrofit of Reinforced Concrete Moment Resisting Piers
- 4) Seismic Retrofit of an 11-span Bridge Supported by Bent Piles in Liquefiable Sandy Soils

## 5) Retrofit of Abutments using Expanded Polystyrene

### 9 Restoration Technology

#### 9.1 Introduction

#### 9.2 Principles of Restoration after the 1995 Kobe Earthquake

#### 9.3 Restoration of Major Standard Bridges

- 1) 18-span Continuous Bridge, Fukae, Hanshin Expressway
- 2) Restoration using Seismic Isolation
- 3) Restoration of a Viaduct by Jacking-up of Decks
- 4) Restoration of Foundations against Lateral Spreading

#### 9.4 Restoration of Long-Span Bridges

- 1) Akashi Straight Bridge
- 2) Restoration of Higashi Kobe Bridge

#### 9.5 Advanced Technologies for Restoration

- 1) Damage Detection by Impact Loading Test
- 2) Damage Detection of Piles using Borehole Camera
- 3) Steel Jacketing for Reinforced Concrete Piers
- 4) New Composite Materials Jacketing and Precast Concrete Segment Jacketing