## A Lecture of Hokkaido University

北海道地区自然災害科学資料センター　20130329

# 耐震設計の変遷と長大橋の現状

北海道大学大学院工学研究院北方圏環境政策部門
構造デザイン工学研究室　教授　林 川 俊 郎

## A Lecture of Hokkaido University

（1） Suspension Bridges in Japan

（2） Cable-stayed Bridges in Japan

（3） Future Plan of Strait-crossing Bridges

（4） Seismic Performance of Cable-stayed Bridge Towers under Great Earthquakes

## Suspension Bridges in the World

| No. | Name | Span Length | Location | Year |
|---|---|---|---|---|
| 1 | Akasi-Kaikyo | 1991 | Japan | 1998 |
| 2 | Great Belt East | 1624 | Denmark | 1998 |
| 3 | Hamber | 1410 | U.Kingdom | 1981 |
| 4 | Jiangyin Yangtze River | 1385 | China | 1999 |
| 5 | Tsing Ma | 1377 | China | 1997 |
| 6 | Verrazano-Narrows | 1298 | U.S.A | 1964 |
| 7 | Golden-Gate | 1280 | U.S.A | 1937 |
| 8 | High Coast | 1210 | Sweden | 1997 |
| 9 | Mackinac | 1158 | U.S.A | 1957 |
| 10 | Minami-Bisan-Seto | 1100 | Japan | 1988 |

## Cable-stayed Bridges in the World

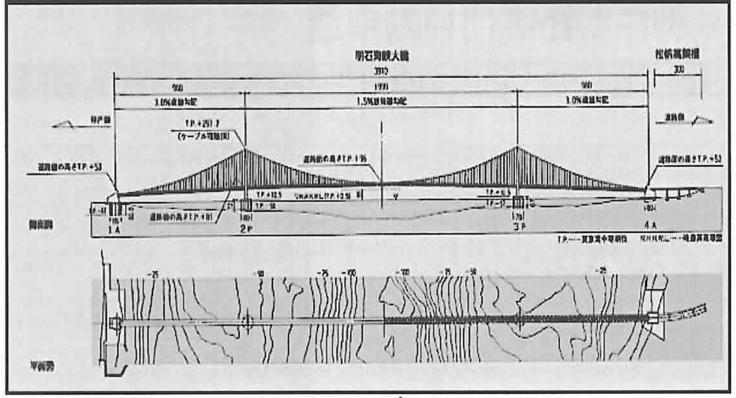
| No. | Name | Span Length | Location | Year |
|---|---|---|---|---|
| 1 | Tatara | 890 | Japan | 1999 |
| 2 | Normandy | 856 | France | 1995 |
| 3 | Second Nanging | 628 | China | 2001 |
| 4 | Third Wuhan | 618 | China | 2000 |
| 5 | Qingzhou Minjiang | 605 | China | 2000 |
| 6 | Yangpu | 602 | China | 1993 |
| 7 | Meico-Chuoh | 590 | Japan | 1998 |
| 8 | Xupu | 590 | China | 1996 |
| 9 | Rion-Antirion | 560 | Greece | 2004 |
| 10 | Skarnsundet | 530 | Norway | 1991 |

## Three Routes of Honshu-Shikoku Bridge Project

Kobe-Naruto Route, Kojima-Sakaide Route and Onomichi-Imabari Route


## Akashi Kaikyo Suspension Bridge

## Akashi Kaikyo Suspension Bridge (L=1,991m)



## Akashi Kaikyo Suspension Bridge

**Table 1 Main Steel Products Used in Superstructures of Akashi Kaikyo Bridge**

(tons)

| Structure | Materials and weight | | | | | Total weight |
|---|---|---|---|---|---|---|
| Towers | SM570Q | SM490 | SS400 | SS400 | Others | |
| | 38,500 | 2,700 | 800 | 2,500 | 4,800 | 49,300 |
| Cables | PWS 1,800 MPa class | PWS 1,600 MPa class | SCW480 | S450N | Others | |
| | 50,500 | 2,000 | 2,200 | 400 | 3,700 | 58,800 |
| Stiffening girders | HT780 | HT690 | SM570 | SM490Y | SS400 etc. | |
| | 4,900 | 2,800 | 2,800 | 10,400 | 64,300 | 85,200 |
| Total | | | | | | 193,300 |

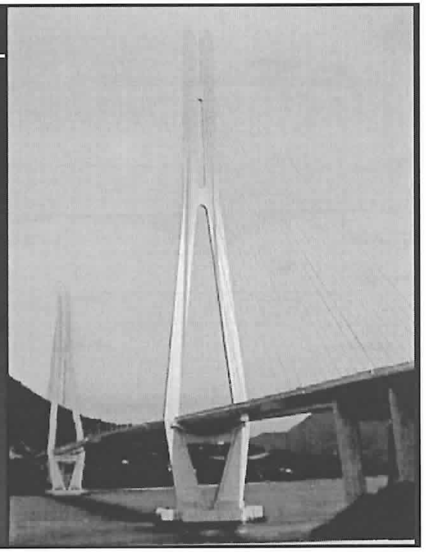
SS, SM, etc.: Steel materials specified in the Japanese Industrial Standards (JIS)
PWS: Parallel wire strands
HT: High-strength steel
Source: Excerption from *History of Highways in Japan*

## Tatara Bridge

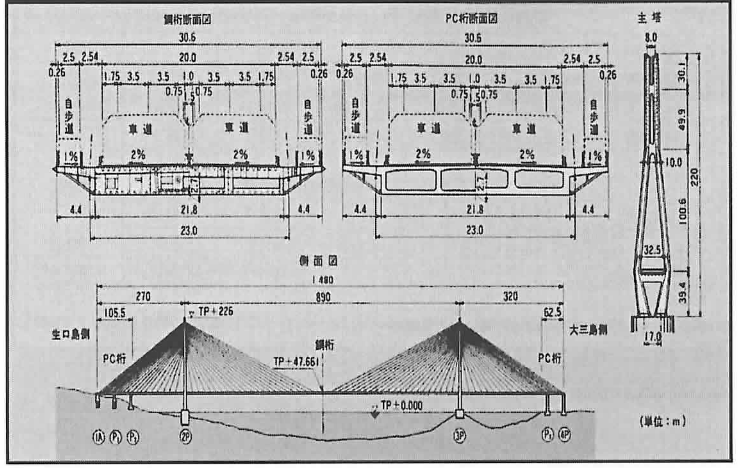
Cable-stayed Bridge

Main Span Length = 890m

Hybrid stiffening girders



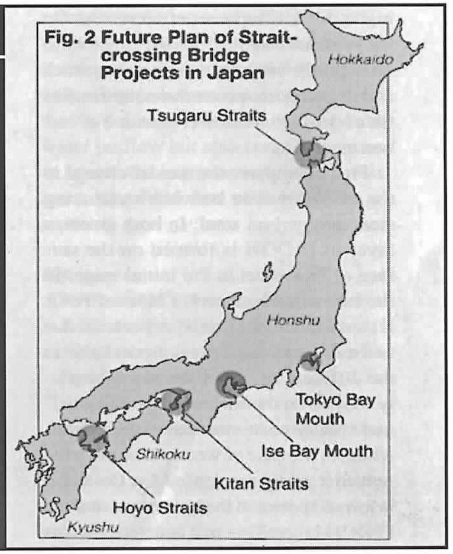
## General View of Tatara Cable-stayed Bridge (L=890m)




## Future of Large-Scale Bridge Building Projects

Second National Land Axis Concept

New Highway Network along the Pacific Coast




## Seismic Performance of Cable-stayed Bridge Towers

(1)Finite Element Model

(2)Vertical Ground Motion and Damping

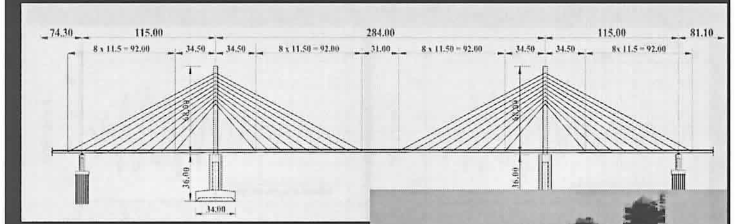
(3)Construction Initial Imperfections

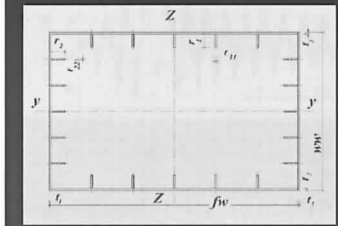
(4)Tower Model Shapes

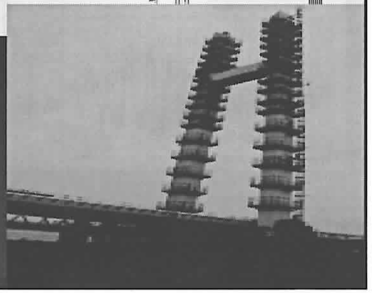
(5)Low Yield Material

(6)Passive Control Devices

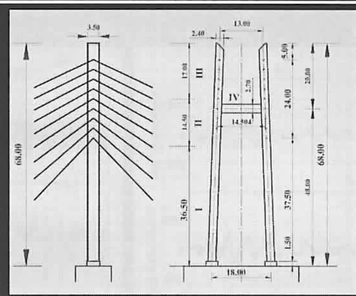
## Description of cable stayed bridge and Tower structure model



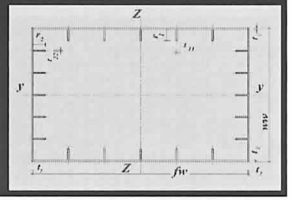



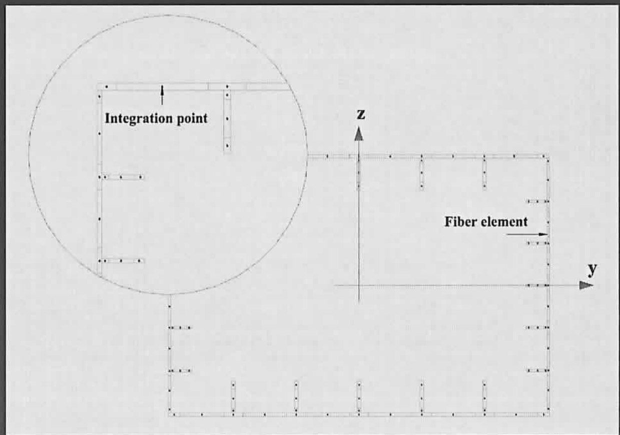
## Tower structure model



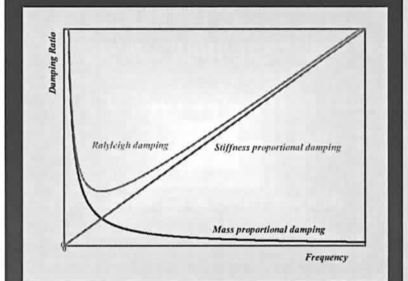

| Tower parts | Outer dimension | | | | Stiffener dimension | | | |
|---|---|---|---|---|---|---|---|---|
| | $fw$ | $ww$ | $t_1$ | $t_2$ | $r_1$ | $r_2$ | $t_{11}$ | $t_{22}$ |
| I | 350 | 240 | 2.2 | 3.2 | 25 | 22 | 3.6 | 3.0 |
| II | 350 | 240 | 2.2 | 3.2 | 22 | 20 | 3.2 | 2.8 |
| III | 350 | 240 | 2.2 | 2.8 | 20 | 20 | 2.8 | 2.2 |
| IV | 350 | 270 | 2.2 | 2.6 | 31 | 22 | 3.5 | 2.4 |



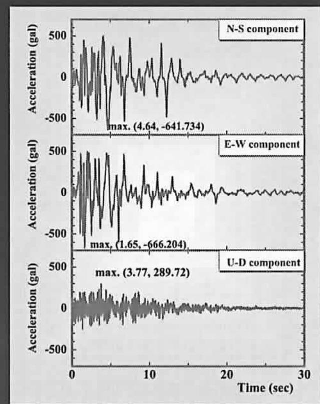

## Fiber model




## JR Takatori input earthquake & Damping scheme




(a) Damping scheme




(b) JR Takatori Input Earthquake

## Natural Vibration Analysis

| Mode order | Period *T* (sec) | Effective mass as a fraction of total mass | Viscous damping percent | Mode shape |
|---|---|---|---|---|
| 1 | 2.0723 | 33.195 | 2.00 | $H_1$ |
| 2 | 0.9335 | 30.330 | 2.00 | $L_1$ |
| 3 | 0.7726 | 0.000 | 2.18 | $T_1$ |
| 4 | 0.5235 | 0.034 | 2.81 | $V_1$ |
| 5 | 0.3751 | 1.735 | 3.68 | $L_2$ |
| 6 | 0.3625 | 0.080 | 3.79 | $H_2$ |
| 7 | 0.3296 | 0.000 | 4.12 | $T_2$ |
| 8 | 0.1559 | 34.079 | 8.35 | $V_2$ |
| Sum | -- | 99.423 | -- | -- |

**Depending on the relative amplitude of the mode shapes**

**Lateral dominant modes (right angle bridge axis, H and longitudinal bridge axis, L)**

**Torsional dominate modes, T.**

**Vertical dominate modes, V.**

## Seismic Performance of Cable-stayed Bridge Towers

(1)Finite Element Model

(2)Vertical Ground Motion and Damping

(3)Construction Initial Imperfections

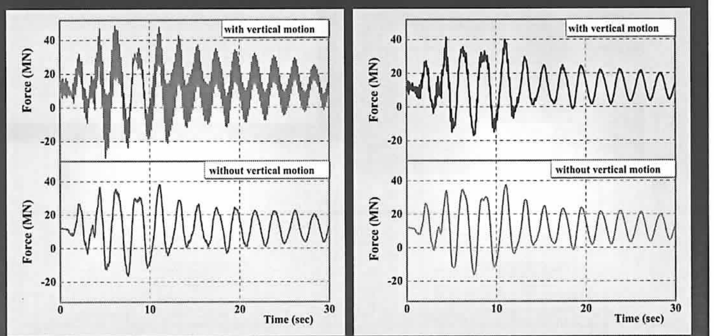
(4)Tower Model Shapes

(5)Low Yield Material

(6)Passive Control Devices

## Effects of Vertical Ground Motion and Damping

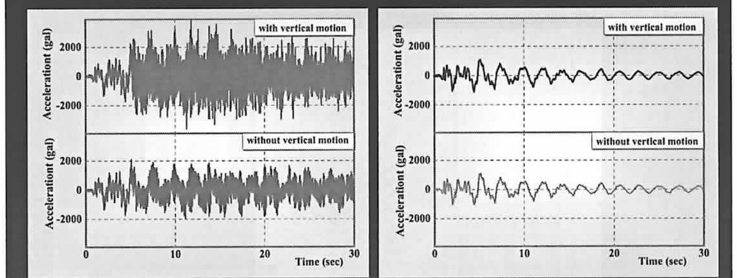
Effects on tower axial response




(a) Mass proportional damping scheme (b) Rayleigh's damping scheme

## Effects of Vertical Ground Motion and Damping

Effects on Tower Acceleration Response

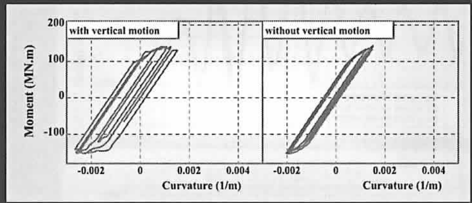



(a) Mass proportional damping scheme (b) Rayleigh's damping scheme

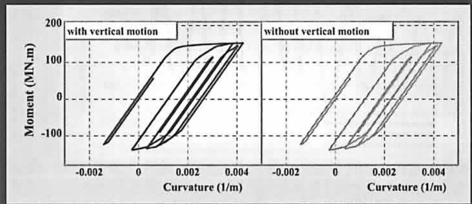
## Effects of Vertical Ground Motion and Damping

Effects on tower flexural response

(a) Mass proportional damping scheme




(b) Rayleigh's damping scheme




## Seismic Performance of Cable-stayed Bridge Towers

(1)Finite Element Model

(2)Vertical Ground Motion and Damping

(3)Construction Initial Imperfections

(4)Tower Model Shapes

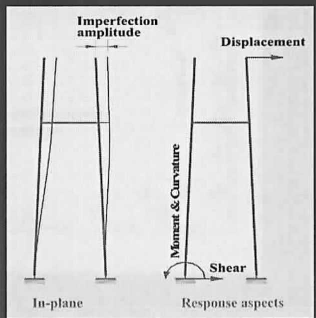
(5)Low Yield Material

(6)Passive Control Devices

## Effects of Construction Initial Imperfections

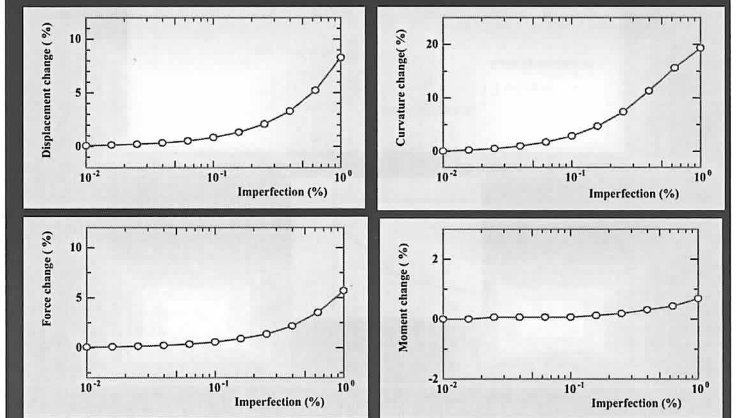
- Geometric Imperfections Treatment

Geometric imperfection amplitude (0.01 up 1% of tower height).

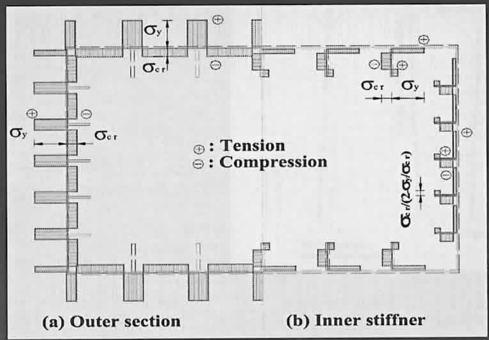



## Effects of Construction Initial Imperfections

Geometric Imperfection Effects

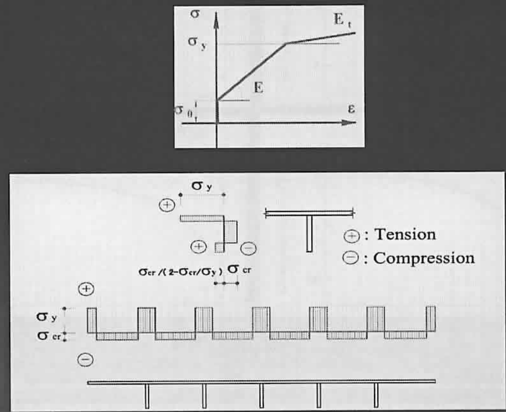


## Longitudinal Residual Stresses Computational Model



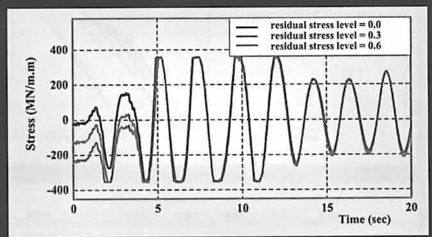

## Effects of Construction Initial Imperfections

### Longitudinal Residual Stresses Computational Model

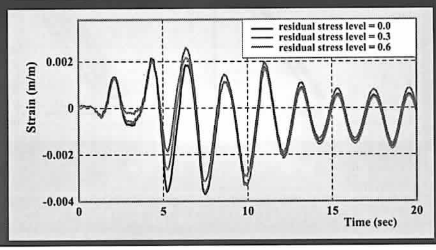



## Longitudinal Residual Stresses Effects

(a) Stress of compression residual stress at tower base

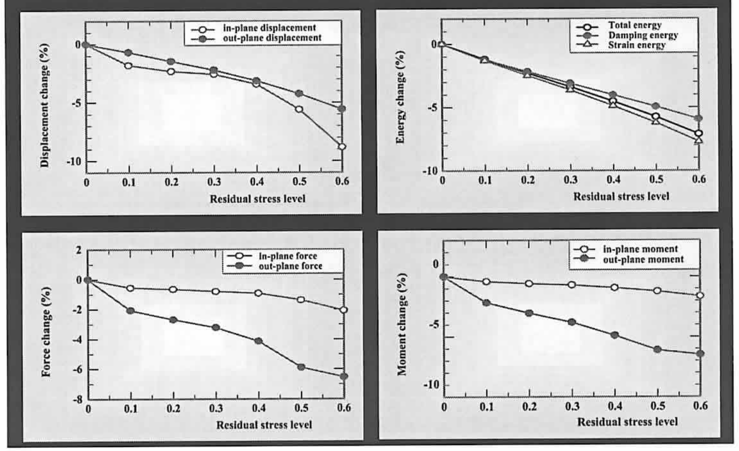



(b) Strain of compression residual stress at tower base



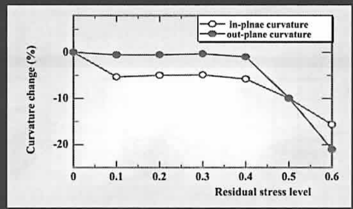

## Effects of Construction Initial Imperfections

### Longitudinal Residual Stresses Effects

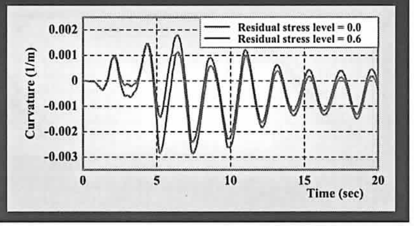


## Longitudinal Residual Stresses Effects

(a) Curvature and residual stress at tower base




(b) Time history of curvature at tower base




## Seismic Performance of Cable-stayed Bridge Towers

(1)Finite Element Model

(2)Vertical Ground Motion and Damping

(3)Construction Initial Imperfections

(4)Tower Model Shapes

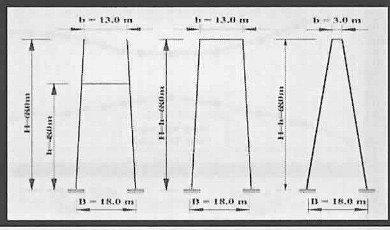
(5)Low Yield Material

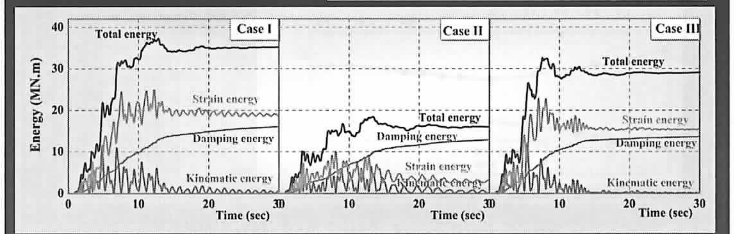
(6)Passive Control Devices

## Effects of Tower Modal Shapes

| Mode type | Tower modal shapes | | |
|---|---|---|---|
| | Case I | Case II | Case III |
| $H_1$ | 2.072 | 2.928 | 1.727 |
| $L_1$ | 0.934 | 0.935 | 0.935 |
| $T_1$ | 0.773 | 0.761 | 0.543 |

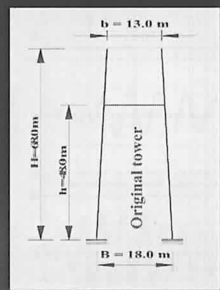
Case Ⅰ Case Ⅱ Case Ⅲ

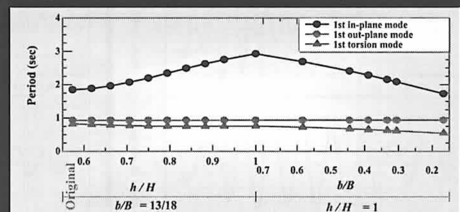


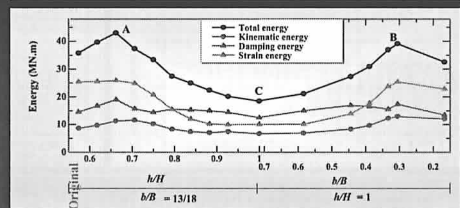




## Effects of Tower Modal Shapes

The steel tower dynamic response depends to large extent on tower modal shapes including the horizontal beam position and its elements relative strength.



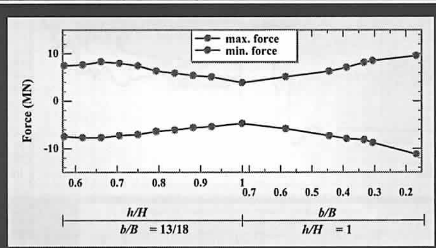



## Effects of Tower Modal Shapes

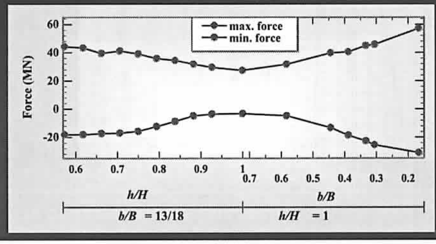
(a)

In-plane shear at tower base & horizontal beam height/length relationship

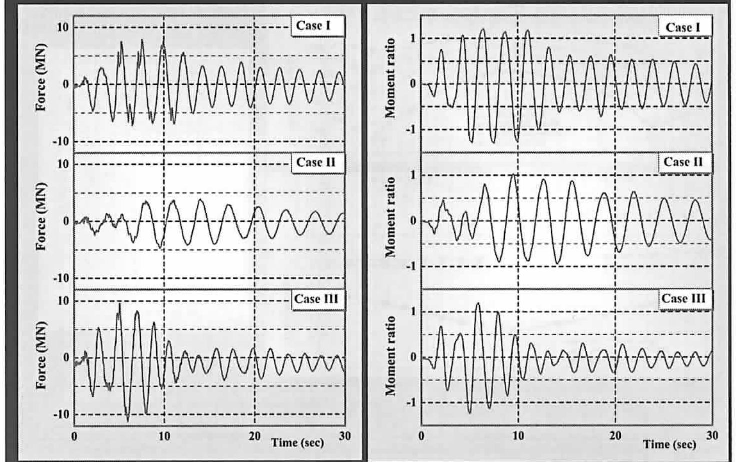



(b)

Vertical force at tower base & horizontal beam height/length relationship




## Effects of Tower Modal Shapes




(a) In-plane force time history at tower base (b) In-plane moment time history at tower base

## Effects of Tower Modal Shapes

(a)

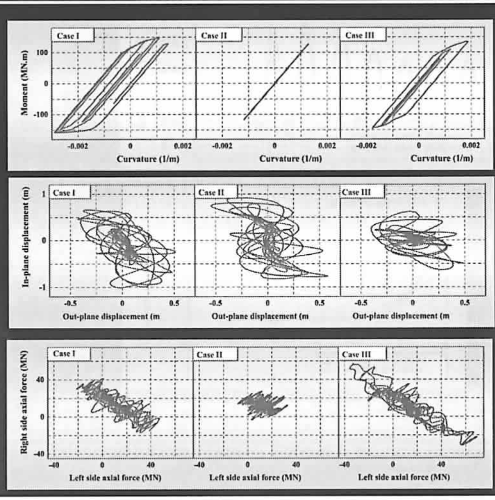
Moment & curvature relations at tower base

(b)

Trajectory of response sway displacement of tower top

(c)

Axial force relation at tower bases




## Seismic Performance of Cable-stayed Bridge Towers

(1)Finite Element Model

(2)Vertical Ground Motion and Damping

(3)Construction Initial Imperfections

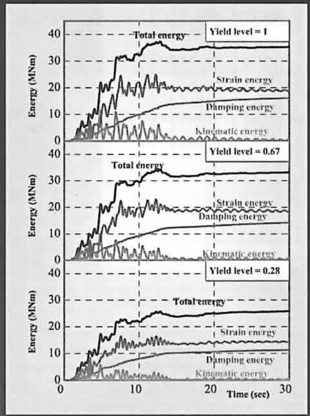
(4)Tower Model Shapes

(5)Low Yield Material

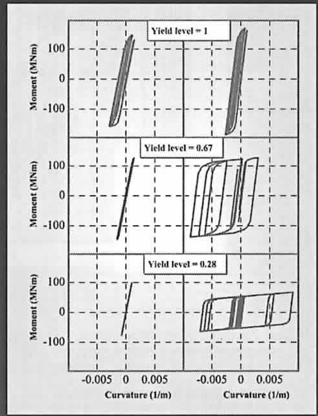
(6)Passive Control Devices

## Dynamic Response of Tower with Low yield material

### Low yield material energy dissipation system



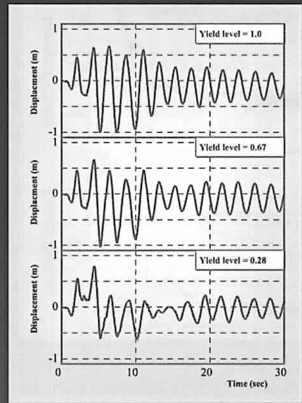

Energies time history of tower structure



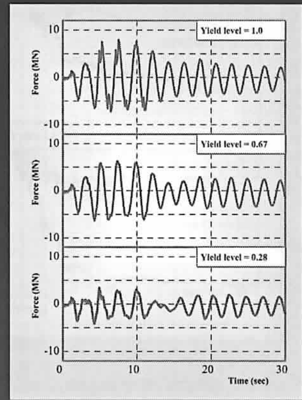

(a) At tower base (b) At horizontal beam end

## Dynamic Response of Tower with Low yield material

### Flexural and axial time history responses



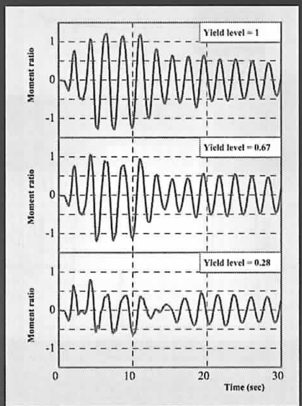

(a) In-plane displacement time history at tower top



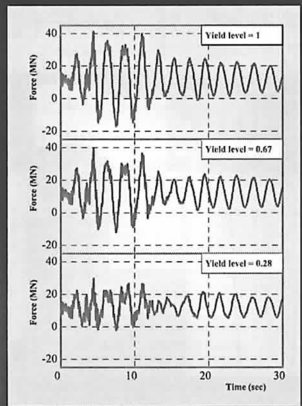

(b) In-plane shear force time history at tower base

## Dynamic Response of Tower with Low yield material

### Flexural and axial time history responses




(a) Moment ratio time history at tower base




(b) Vertical force time history at tower base

## Seismic Performance of Cable-stayed Bridge Towers

(1)Finite Element Model

(2)Vertical Ground Motion and Damping

(3)Construction Initial Imperfections

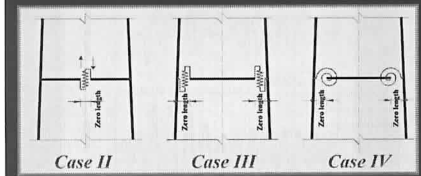
(4)Tower Model Shapes

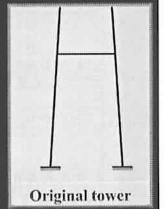
(5)Low Yield Material

(6)Passive Control Devices

## Passive Energy Dissipation system Model

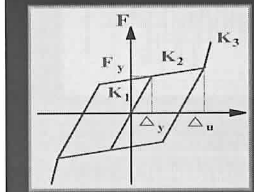
### Viscoelastic Type Connection Device Model

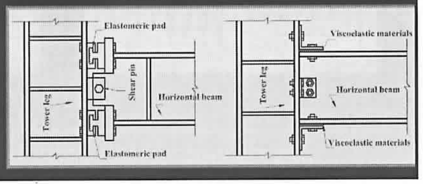



Rotation device
(Case IV)

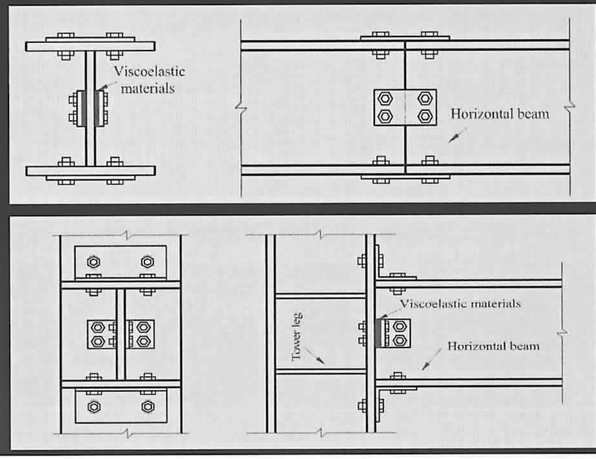
### Energy Device Mathematical Model



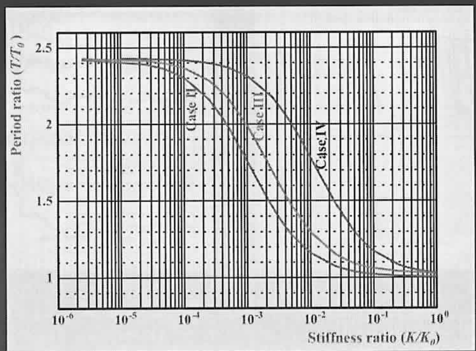

## Passive Energy Dissipation system Model

### Viscoelastic Type Connection Device Model

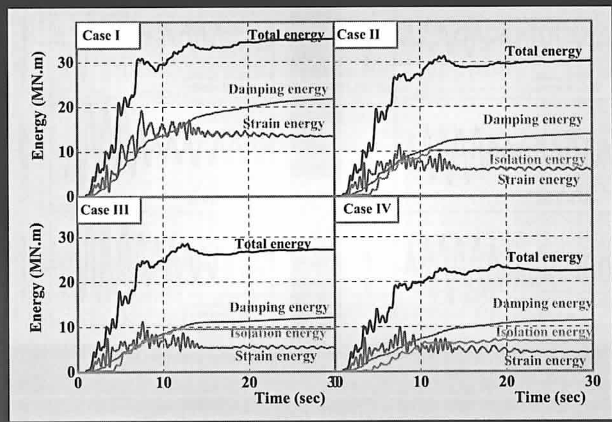



## Natural Vibration Analysis

- Natural period ratio ($T/T_0$) and stiffness ratio ($K/K_0$) relationship for the energy dissipation device system.
- $T_0$ = 2.072 sec. $K_0$ = 19.6 GN/m (sliding device), 196 GN·m/rad. rotation device.

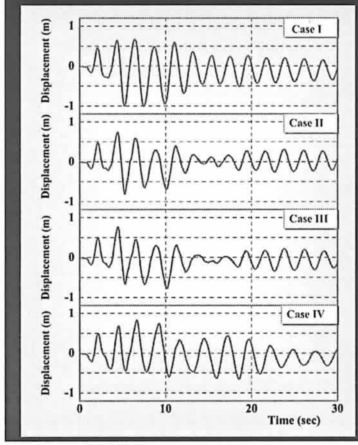


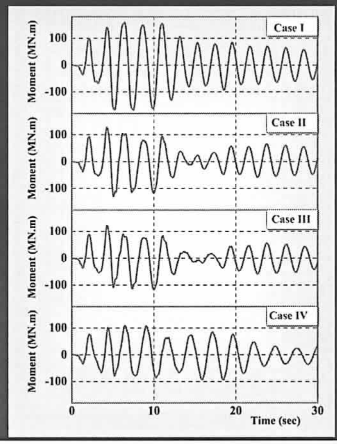

## Energy time history analysis



## Dynamic Response of Tower with Viscoelastic type connection

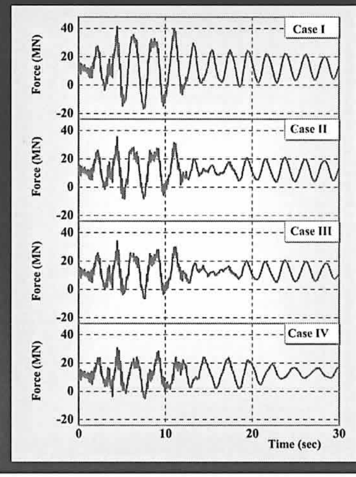
### Tower displacement and flexural moment responses




## Dynamic Response of Tower with Viscoelastic type connection

### Axial force response




## CONCLUSIONS

(1) The Rayleigh's damping could be recommend for conservative nonlinear seismic response of high-rise towers.

(2) The initial geometric imperfections of tower design of upper limit equal to 0.1%, slightly affect the tower seismic response.

(3) The residual stress effects on the tower seismic response are sensitive to its stiffness in the longitudinal and transverse directions.

(4) The inverted V-shaped tower has the largest axial force response, and the negative reaction makes the problem that the anchor bolts may fail in the lift up.

(5) The proposed energy dissipation system demonstrates its capability and effectiveness in reducing structural element forces and controlling tower maximum displacements.

(6) This technique could add damping primarily by material hysteresis and increase tower flexibility as the horizontal beam yield early attains.