Self-Introduction

Educations

- **B.Eng. Department of Civil Engineering, Huazhong University of Science and Technology, Wuhan, P. R. China, July 1986.**
- **M.Eng. Department of Civil Engineering, Graduate School of Engineering, Nagoya University, Nagoya, Japan, March 1991**
- **D.Eng. Department of Civil Engineering, Graduate School of Engineering, Nagoya University, Nagoya, Japan, March 1994**

Self-Introduction

Appointments

1994 Research Associate, Nagoya University, Japan

1996 Assistant Professor, Nagoya University, Japan

1998 Associate Professor, Nagoya University, Japan

2008 Professor, Meijo University, Japan

Research Fields

Behavior of structural members and systems, with particular emphasis on:

1. **Seismic and Damage Control Design,**
2. **Seismic Performance Evaluation and Retrofit, and**
3. **Ultimate Behavior of Steel and Steel-Concrete Composite Structures.**

Ph. D. Students Supervised or Jointly Supervised

1. **Gao, S.B.: Numerical Study on Seismic Performance Evaluation of Steel Structures, October 1995 - September 1998 (jointly supervised).**
2. **Zheng, Y.: A Seismic Design Methodology for Thin-Walled Steel Structures through the Pushover Analysis, October 1997 - September 2000 (jointly supervised).**
3. **Susantha, K.A.S.: Development of Capacity and Demand Prediction Methodology for Concrete-Filled Steel Structures, October 1998 - September 2001.**
4. **Praween Chusilp: Experimental and Numerical Study on Cyclic Shear Behavior of Steel Structures, October 1999 - September 2002 (jointly supervised).**
5. **Lu, Z.H.: Seismic Performance Evaluation and Retrofitting Methodology for Steel Arch Bridges, October 2001 - September 2004.**
6. **Chen, Z.Y.: Performance-Based Seismic Design Approach for Steel Bridges with Structural Control Devices, October 2003 - September 2006.**
7. **Chen, X.: Seismic Demand of Structural Control Dampers Used in Seismic Performance Upgrading of Steel Bridges, October 2007 - September 2010.**
8. **Suzuki, T.: Seismic Behavior of Steel Structures with Welding Defects, April 2009 - present.**

Doctoral Researchers Supervised or Jointly Supervised

1. **Luo, X.Q.: Development of SMA Dampers and Applications to Steel Structures, April 2008 - March 2010.**
2. **Wang, C.L.: Development of High Performance BRB Dampers and Applications to Steel Structures, April 2010 - present (jointly supervised).**
3. **Kang, L.: Development of Seismic Performance Evaluation Methods for Steel Structures with Welding Defects, April 2011 - present.**

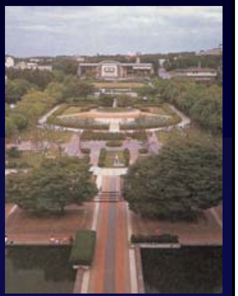
Major Universities in Japan

Top Seven National Universities (Former Imperial Univ.)

- Kyushu University
- Osaka University
- Kyoto University
- Nagoya University
- The University of Tokyo
- Tohoku University
- Hokkaido University

Top Two Private Universities

- Waseda University
- Keio University



Major Universities in Central Japan

Two National Universities

- Nagoya University
- Nagoya Institute of Technology

More Than 30 Private Universities

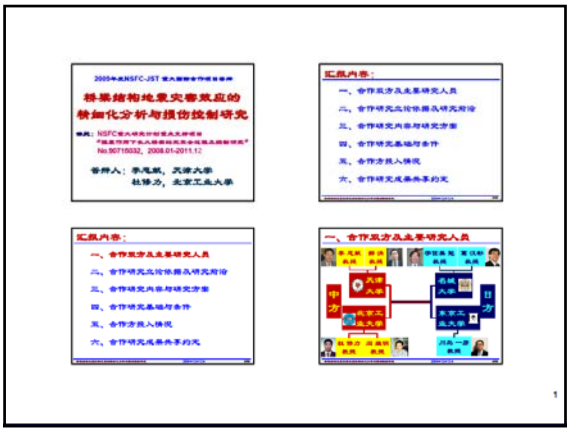
- Meijo University
- Chubu University
- Aichi Institute of Technology
- Chukyo University
- Nanzan University

Advanced Research Center for Seismic Experiments and Computations (ARCSEC)

Advanced Research Center for Seismic Experiments and Computations (ARCSEC)

JST-NSFC International Collaborative Research Project (2010-2012)

Seismic Damage Control and Performance-based Seismic Design of Bridge Structures



TOPICS OF STRUCTURAL ENGINEERING

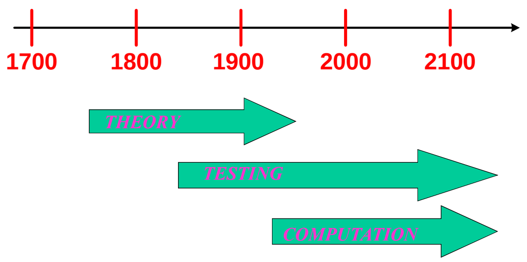
- Introduction of steel bridges in the world
- Seismic design of steel structures
- Maintenance of steel structures
- Seismic design of concrete structures
- Material development for sustainable concrete structures

STRUCTURAL ENGINEERING

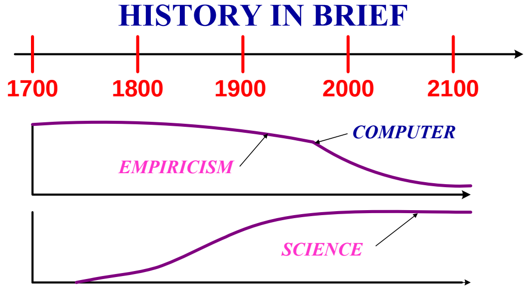
Three elements of designing structures

Economical
Safe, and
Beautiful

STRUCTURAL ENGINEERING HISTORY IN BRIEF



STRUCTURAL ENGINEERING HISTORY IN BRIEF



NEW STRUCTURES SINCE 1950

- Welding as a reliable joining method
- Rivets replaced by HS bolts
- Welded plate girder bridges
- Composite beams, columns, frame systems
- Cable-stayed bridges
- Aluminum, CF steel, Stainless steel structures
- Prestressed concrete structures
- Prefabricated structures

INTELLECTUAL DEVELOPMENTS SECOND HALF of 20th CENTURY

- Probability-based design methods
- Matrix analysis of structures
- Structural dynamics
- Earthquake design methods
- Post-buckling strength of plates and shells
- FEM
- Fatigue
- Brittle fracture theory
- Computerized design

TOOLBOX AVAILABLE IN 2011

- Organizational and building skills and resources
- Material choices
- Analysis and design methods

The Computer: the universal facilitator

Organizational and building skills and resources

- Fabrication
- Transportation
- Erection
- Maintenance
- Demolition
- Project management
- Quality control

Material choices

- Very extensive menu: concrete, wood, steel, masonry, aluminum, stainless steel, FRP(fiber reinforced polymers)
- Creative challenge: combinations of materials!

Analysis and design methods

- Numerical methods of increasing sophistication, as needed for a given condition
- Programs for automatic analysis and design.

MOST IMPORTANT FACT

- Without the computer we cannot exist
- How to tame the "computer beast"?
- Learn fundamentals of structural theory
- Check by more than one method
- Quality control at all levels!!!!!!!

WE CAN DESIGN ANYTHING!

- Complicated structures can be analyzed and designed
- Creativity can make structures act like a bird (Milwaukee art museum, Wisconsin, USA)

WE CAN DESIGN ANYTHING!

- *Complicated structures can be analyzed and designed*
- *Creativity can make structures act like a bird (Milwaukee art museum , Wisconsin, USA)*

CHALLENGES FOR STRUCTURAL ENGINEERS

- **Rehabilitation for new use**
- **Evaluate and repair damaged structures**
- **Deconstruction of large structures**
- **Design for ca*t*astrophes: earthquake, windstorm, ice storm, water surge, fire, blast, etc.**
- **Life-cycle design: build, *r*enovate, de*m*olish**

CHALLENGES FOR STRUCTURAL ENGINEERS

- **Design for rapid construction**
- **"Green" structures**
- **"Sustainability"**
- **Structures with control mechanisms: active, passive**
- **Monitoring behavior of structures**
- **Creative use of new materials**
- **Coastal structural engineering**

CHALLENGES FOR STRUCTURAL ENGINEERS

- **Performance-based design methods**
- **Special research-based advanced design projects**
- **Planning→Testing→Verigfication→ Parametric studies→Design criteria**
- **Application to major project**
- **Probability-based design for special structures**

AISC DEFINITION OF PERFORMANCE-BASED DESIGN

- *"An engineering approach to structural design that is based on agreed-upon performance goals and objectives, engineering analysis and quantitative assessment of alternatives against those design goals and objectives using accepted engineering tools, methodologies and performance criteria."*

PERFORMANCE-BASED DESIGN IN EARTHQUAKE ENGINEERING

EXAMPLE in USA:

"Recommended Seismic Design Criteria For New Steel Moment-Frame Buildings."

(FEMA 350)

Note: FEMA = Federal Emergency Management Agency)

CHALLENGES FOR DESIGN STANDARDS

- How to deal with Performance-Based Design?
- How can building authorities validate designs without formulas (FEM)?
- How to develop codes for repair, rehabilitation, re-use, new types of structures, new materials?
- The answer: Continue to keep a healthy research infrastructure.

RESEARCH OPPORTUNITIES

- Laboratories are better than ever
- Field testing to monitor and to assess strength
- Testing from another site via communications network
- Provide each structural engineer to engage sometimes in research as part of professional experience

PERFORMANCE-BASED DESIGN IN EARTHQUAKE ENGINEERING

EXAMPLE in Japan:

see ……

Guideline for Seismic and Damage Control Design of Steel Bridges, edited by T. Usami (2006.9)
Chinese edition (2008)

Standard Specifications for Steel and Composite Structures:
IV Seismic Design

(published in 2008)

Features of the Guidelines

- Performance-based seismic and damage control limit state design
- Steel bridge piers and complex bridge structures are covered.
- Inelastic dynamic analysis based design
- Dual-level methodologies; displacement-based and strain-based performance evaluation methods

Contents

1. Why steel thin-walled structures are popular in Japan?
2. Types of damage observed in Kobe Earthquake.
3. Repair and retrofit methods after Kobe Earthquake.
4. Seismic performance evaluation by experiment and numerical analysis.
5. Seismic retrofit techniques.
6. Recent progresses in seismic design of steel structures.

Statistical Data of Bridge Piers in Nagoya Expressway Public Corporation

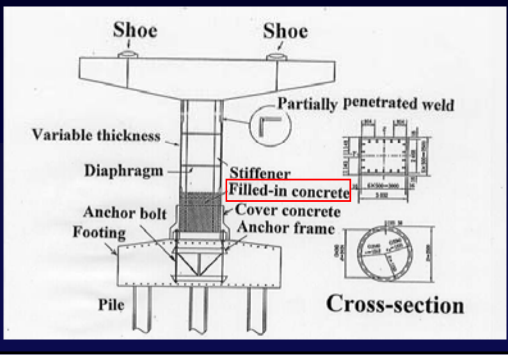
	Steel		RC		Total
	Box	Pipe	Rect.	Circ.	
No. of piers	267	113	615	80	1075
Construction years	1971～1994				

Features of Steel Bridge Structures

- **Thin-walled** box (or pipe) sections
- Stiffened by longitudinal ribs and diaphragms
- Susceptible to **local buckling**

STEEL BRIDGE PIERS CONSTRUCTED IN THE NAGOYA URBAN HIGHWAY

General View of Steel Bridge Piers



Key Parameters (Box bridge piers)

1. Width-thickness ratio of flange plate

$$R_f = \frac{b}{n \cdot t}\sqrt{\frac{12(1-\nu^2)}{4.0 \cdot \pi^2}\frac{\sigma_y}{E}}$$

2. Slenderness ratio of column

$$\bar{\lambda} = \frac{KL}{r}\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}}$$

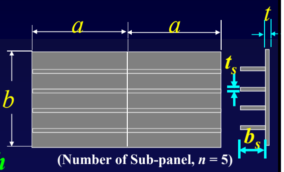
3. Stiffness of longitudinal stiffeners

$$\gamma / \gamma^*$$

Key Parameters (Box bridge piers)

4. Slenderness ratio of longitudinal stiffeners between diaphragms

$$\bar{\lambda}_s = \frac{1}{\sqrt{Q}} \frac{a}{r_s} \frac{1}{\pi} \sqrt{\frac{\sigma_y}{E}}$$



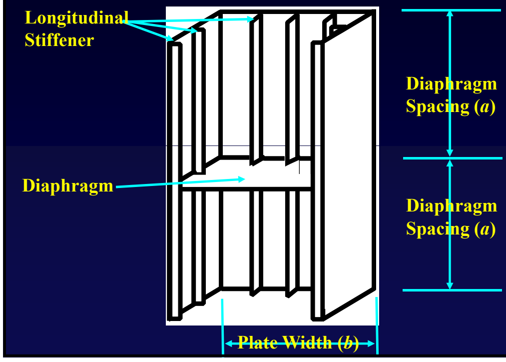
5. Aspect Ratio: α

$\alpha = a / b$

6. Concrete height : *lc/h*

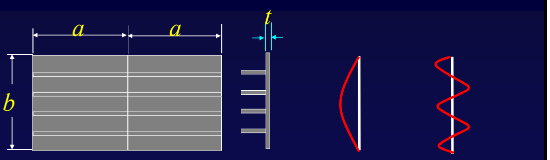
7. Axial force : P/P_y

Example of Column Sections



Limitations of R and γ/γ^* before and after the Kobe Earthquake

$R_f \leq 0.7$, $\gamma/\gamma^* = 1.0$ → $R_f \leq 0.5$, $\gamma/\gamma^* \geq 1.0$

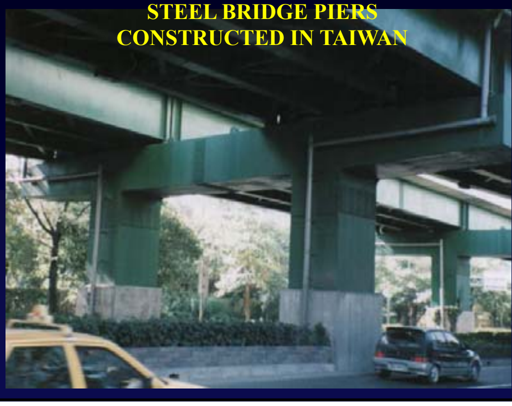


(a) $\gamma/\gamma^* < 1$ (b) $\gamma/\gamma^* \geq 1.0$

STEEL BRIDGE PIERS NEWLY CONSTRUCTED IN THE NAGOYA URBAN HIGHWAY

STEEL BRIDGE PIERS CONSTRUCTED IN OSAKA

STEEL BRIDGE PIERS CONSTRUCTED IN TAIWAN



Summary

Steel bridge piers are popular in Japan, because construction space is limited in urban area.

Compared with RC columns,
- Cross-section of steel piers can be relatively small.
- Steel piers can be fabricated in shop.

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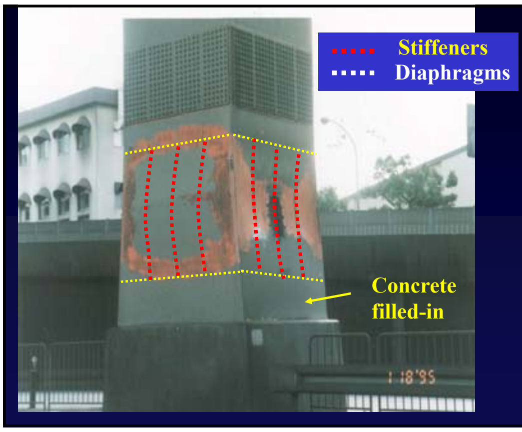
Failure Modes of Steel Bridge Structures

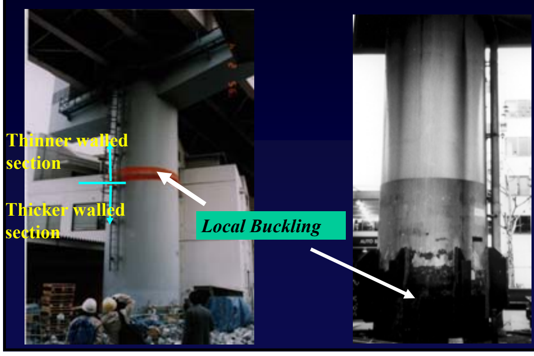
Damaged Steel Bridge Piers in Kobe Earthquake

Local Buckling

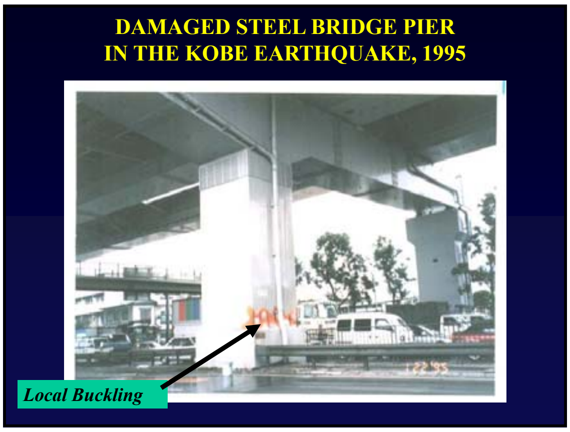
Local & Global Interactive Buckling

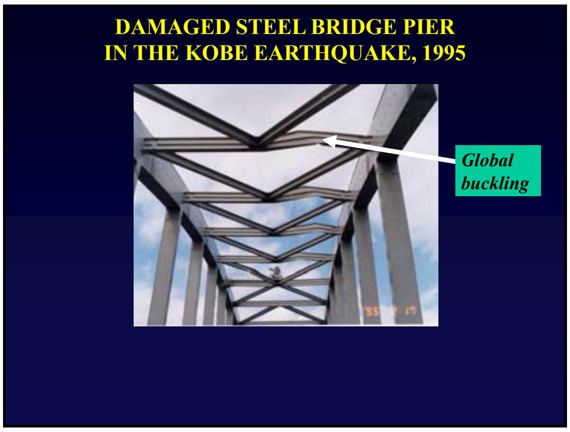


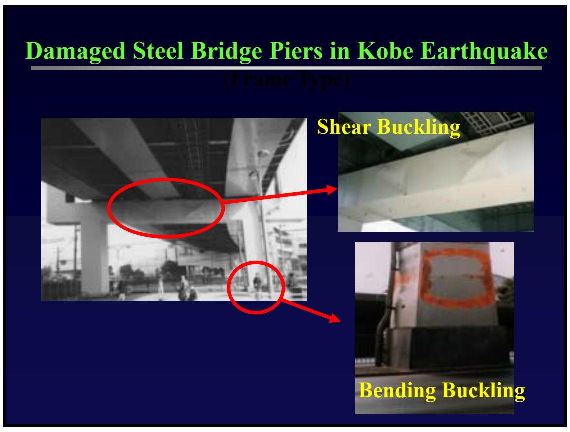
DAMAGED STEEL BRIDGE PIER IN THE HYOGO-KEN NANBU EARTHQUAKE, 1995

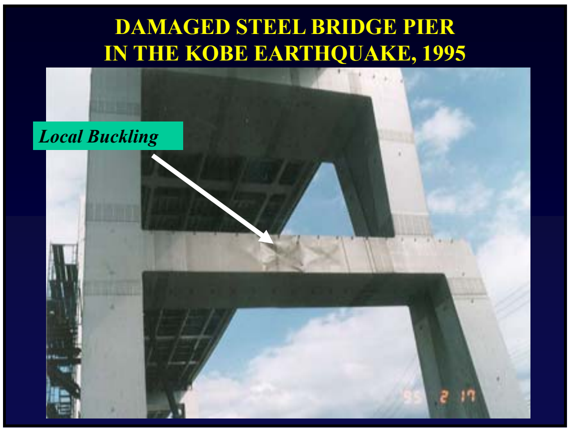


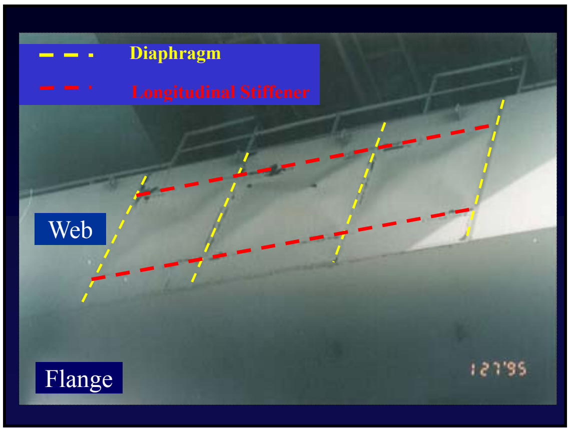

DAMAGED STEEL BRIDGE PIER
IN THE KOBE EARTHQUAKE, 1995
Thinner plates
Thicker plates
Local Buckling


DAMAGED STEEL BRIDGE PIER
IN THE KOBE EARTHQUAKE, 1995
Local Buckling


DAMAGED STEEL BRIDGE PIER
IN THE KOBE EARTHQUAKE, 1995
Global
buckling


Damaged Steel Bridge Piers in Kobe Earthquake
Shear Buckling
Bending Buckling


DAMAGED STEEL BRIDGE PIER
IN THE KOBE EARTHQUAKE, 1995
Local Buckling


Diaphragm
Longitudinal Stiffener
Web
Flange

Damaged Steel Bridge Piers in Kobe Earthquake

Damaged Steel Bridge Piers in Kobe Earthquake

Local Buckling & Crack

DAMAGED STEEL BRIDGE PIER IN THE KOBE EARTHQUAKE, 1995

Crack

Summary of Failure Modes of Steel Bridges

Failure modes of steel bridge structures under strong earthquakes can be

1. Failure due to local buckling (bending or shear) in thin-walled structures
2. Failure due to crack (extremely low cycle fatigue) in relatively thick-walled structures
3. Failure due to combined buckling and crack

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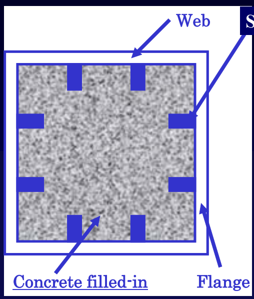
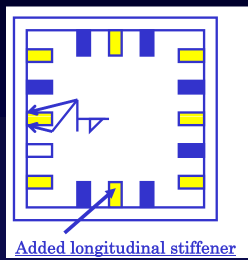
Repair Methods for Steel Bridge Piers

Retrofit Methods for Steel Bridge Piers



- ✓Strength and ductility capacity can be improved, because local buckling of steel plates can be delayed or prevented.
- ✓Construction time can be reduced
- ✓Damage due to vehicle collision can be minimized

Retrofit Methods for Steel Bridge Piers



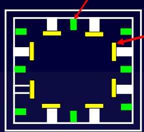
As a result,
R will be reduced and
γ/γ* will be increased.

↓

The buckling mode will be moved from a global mode to high modes or
No local buckling occurs.

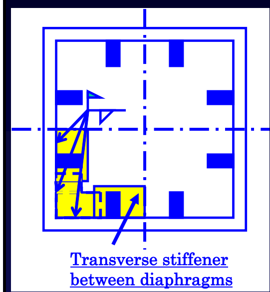
Retrofit Methods for Steel Bridge Piers

Adding longitudinal stiffeners



Strengthening longitudinal stiffeners

Retrofit Methods for Steel Bridge Piers

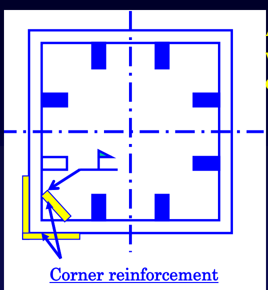


As a result,
α will be reduced.

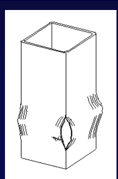
↓

γ/γ* will be increased.

Retrofit Methods for Steel Bridge Piers



As a result,
welding crack at the corner will be prevented



Summary of Seismic Retrofit Proposals for Steel Bridge Piers

(1) Concrete filled-in
- Low strength concrete
- *lc* ≒ *0.2* ～ *0.3 h*
- Both strength and ductility are enhanced.

(2) Reinforcing longitudinal stiffeners
- Target value : γ → 3γ*

(3) Adding transverse stiffeners
- Target value : α → 0.5
- γ/γ* ratio of longitudinal stiffeners is also enhanced.

(4) Corner reinforcement

Inside View of Retrofitted Pier

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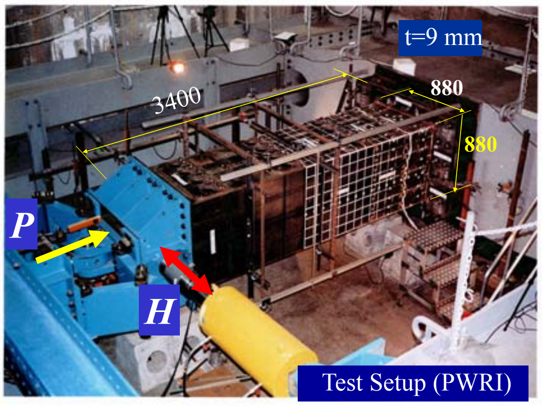
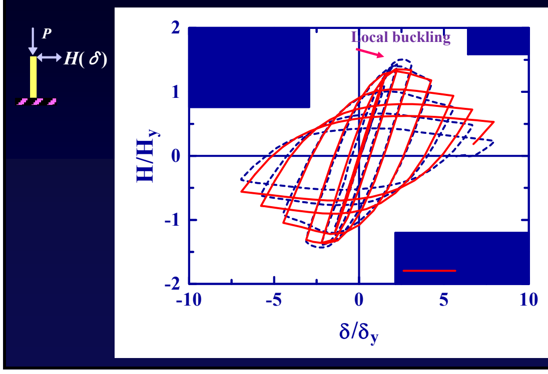
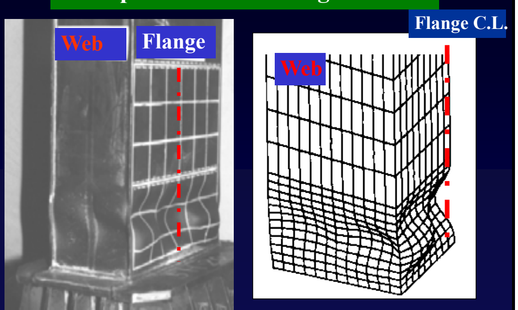


Comparison between Test and Analysis



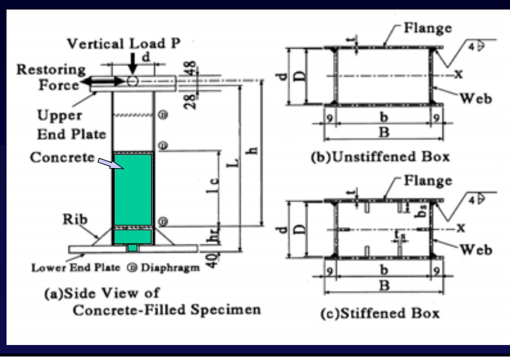
Comparison of Buckling Modes

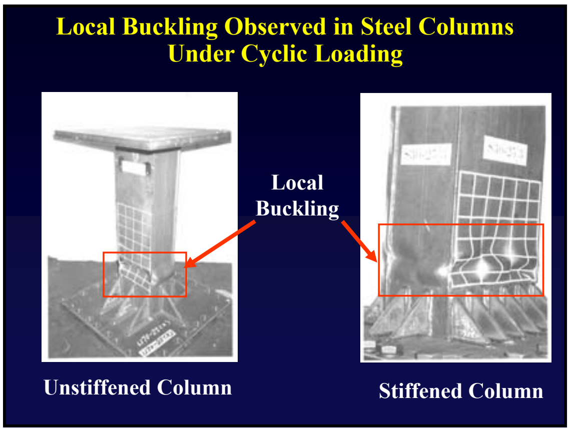


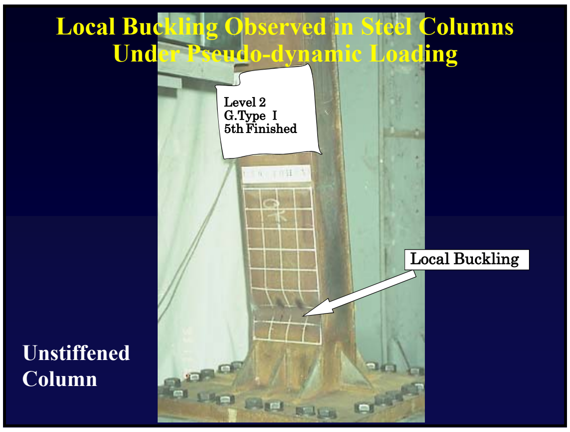
Test

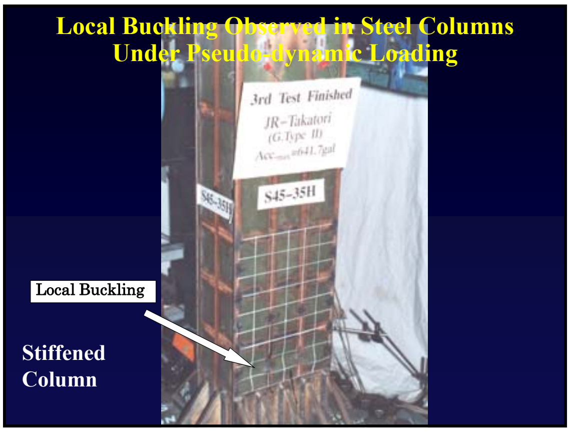
Analysis

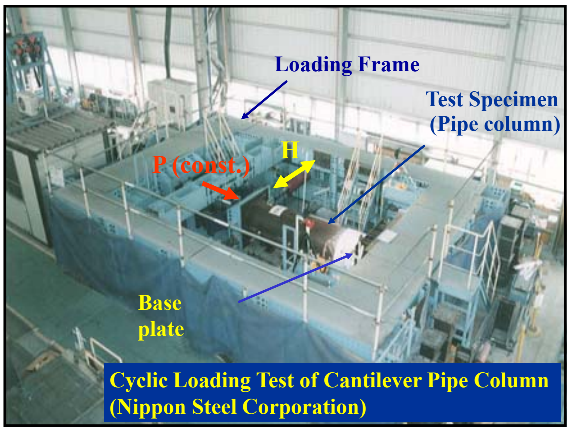
TEST SPECIMENS

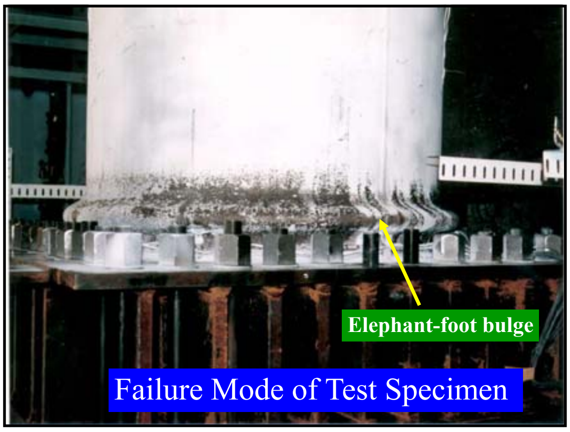


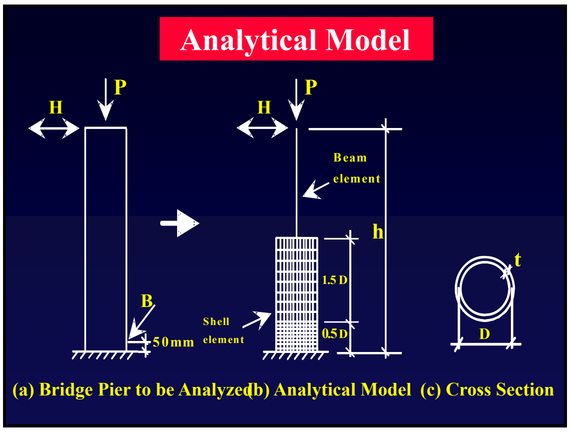

Local Buckling Observed in Steel Columns
Under Cyclic Loading
Local
Buckling
Unstiffened Column
Stiffened Column

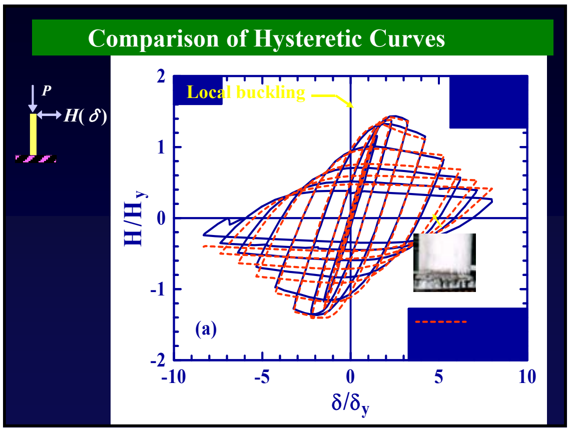

Local Buckling Observed in Steel Columns
Under Pseudo-dynamic Loading
Level 2
G.Type I
5th Finished
Local Buckling
Unstiffened
Column

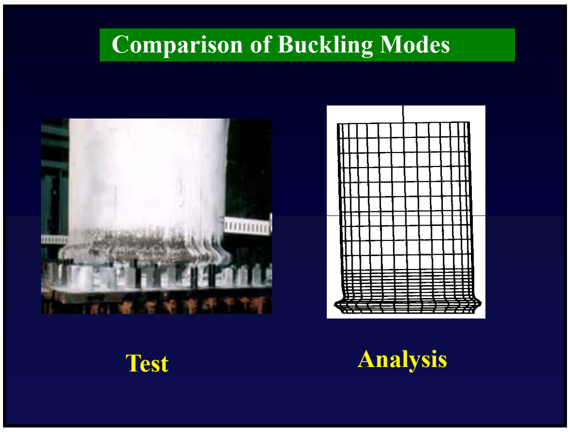

Local Buckling Observed in Steel Columns
Under Pseudo-dynamic Loading
3rd Test Finished
JR-Takatori
S45-35H
Local Buckling
Stiffened
Column

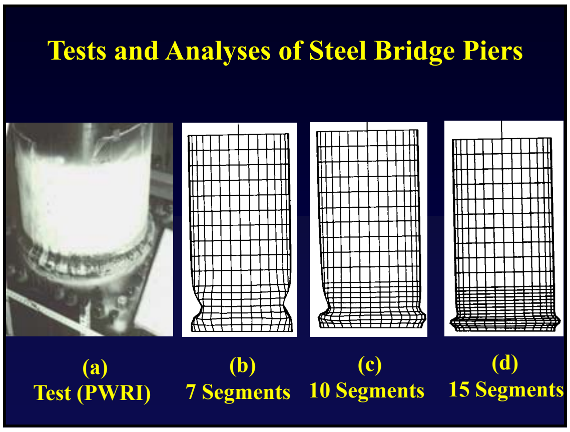

Loading Frame
Test Specimen
(Pipe column)
P (const.)
H
Base
plate
Cyclic Loading Test of Cantilever Pipe Column
(Nippon Steel Corporation)

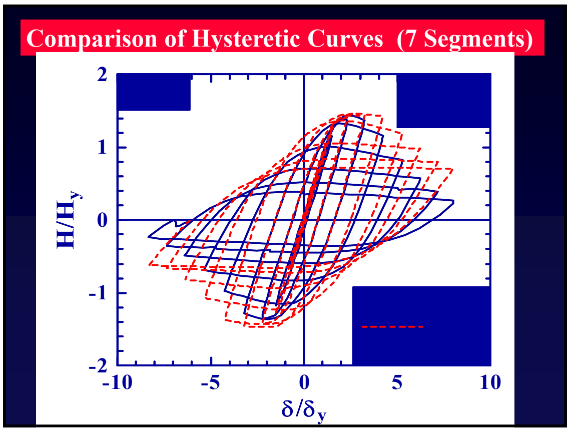

Elephant-foot bulge
Failure Mode of Test Specimen

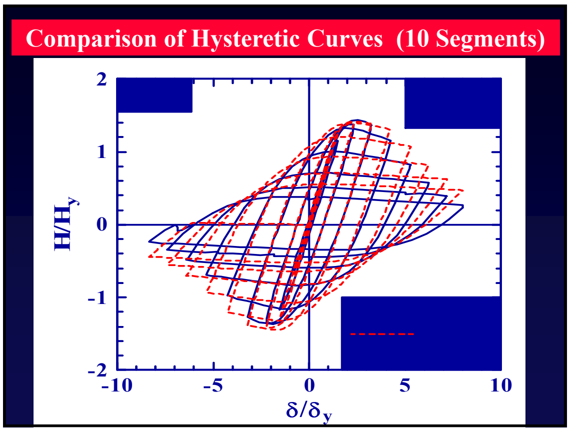

Analytical Model
H
P
B
50mm
Beam
element
h
1.5 D
0.5 D
Shell
element
t
D
(a) Bridge Pier to be Analyzed
(b) Analytical Model
(c) Cross Section

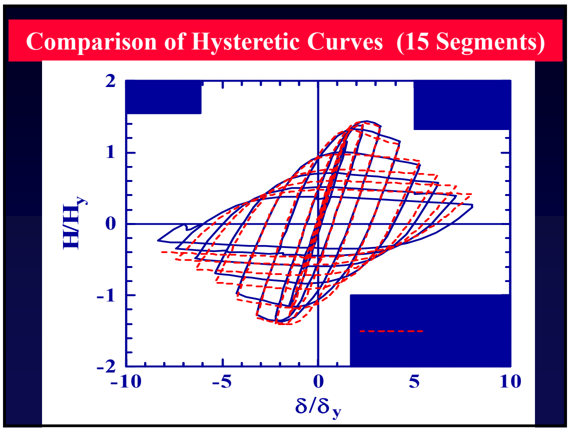

Comparison of Hysteretic Curves
P
H(δ)
Local buckling
H/Hy
δ/δy
(a)
2
1
0
-1
-2
-10
-5
0
5
10


Comparison of Buckling Modes
Test
Analysis


Tests and Analyses of Steel Bridge Piers
(a)
Test (PWRI)
(b)
7 Segments
(c)
10 Segments
(d)
15 Segments


Comparison of Hysteretic Curves (7 Segments)
H/Hy
δ/δy
2
1
0
-1
-2
-10
-5
0
5
10

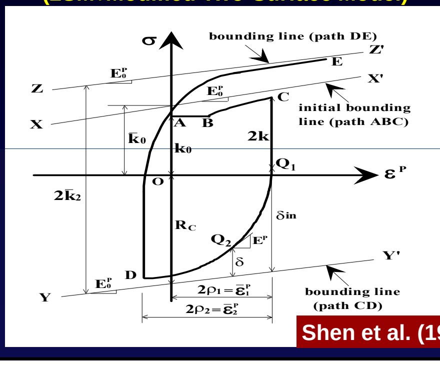

Comparison of Hysteretic Curves (10 Segments)
H/Hy
δ/δy
2
1
0
-1
-2
-10
-5
0
5
10


Comparison of Hysteretic Curves (15 Segments)
H/Hy
δ/δy
2
1
0
-1
-2
-10
-5
0
5
10

Effect of Material Models

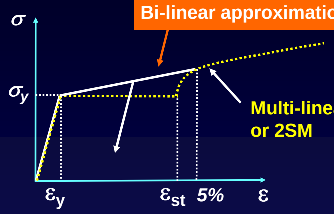
2SM
B-IH
B-KH

Uniaxial Cyclic Stress-Plastic Strain Curve (2SM : Modified Two-Surface Model)

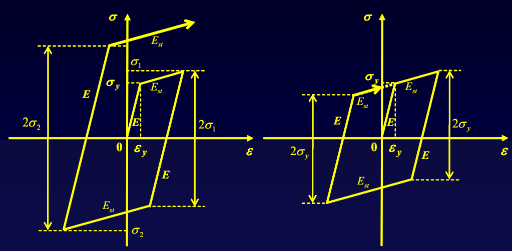


Shen et al. (1995)

Other Cyclic Models for Steel

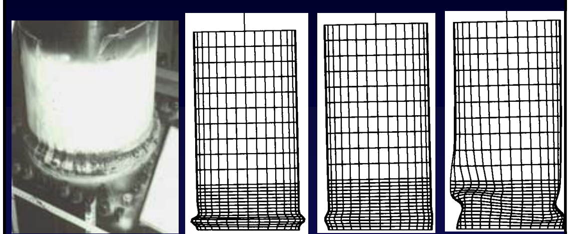


B-KH - Bilinear Kinematic hardening model
B-IH - Bilinear Isotropic hardening model



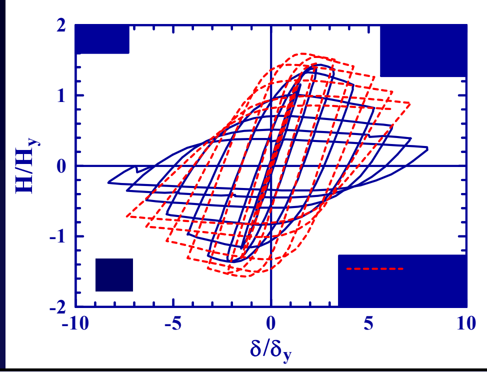
(a) B-IH (b) B-KH

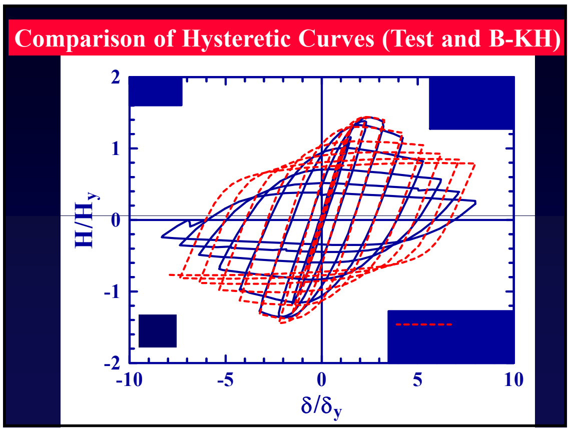
Comparison of Buckling Modes (Different Constitutive Law)

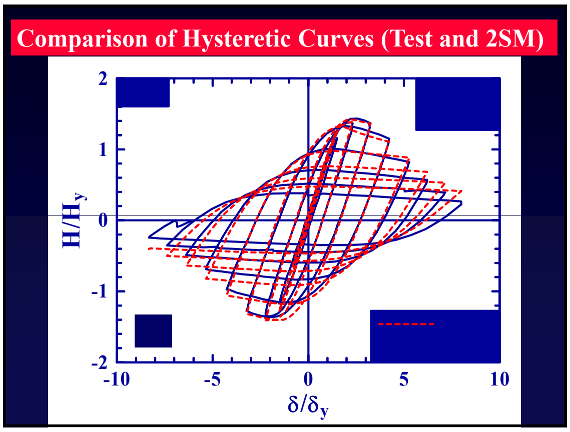


(a) Test (PWRI) (b) 2SM (c) B-KH (d) B-IH

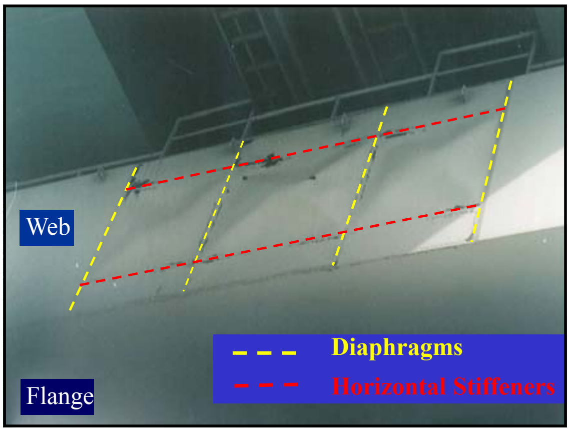
Comparison of Hysteretic Curves (Test and B-IH)

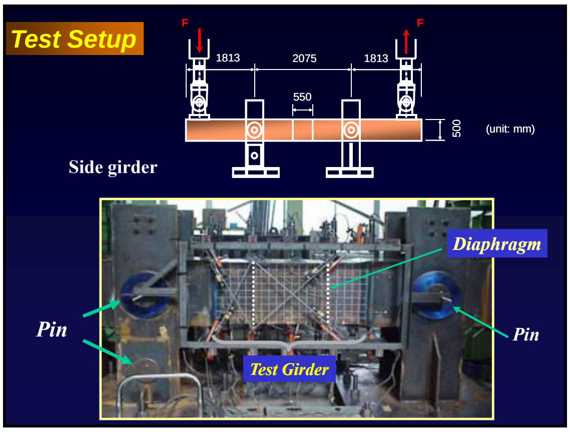


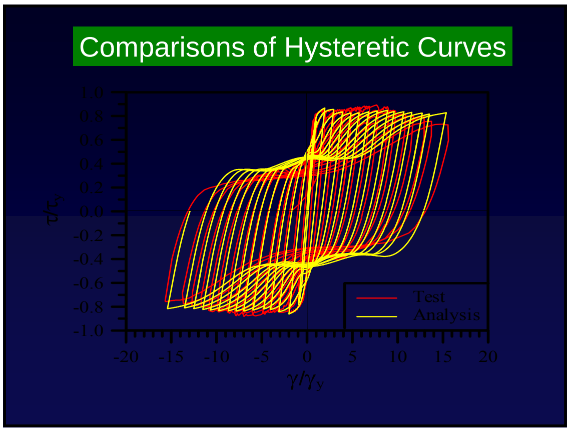

Comparison of Hysteretic Curves (Test and B-KH)
H/Hy
δ/δy
2
1
0
-1
-2
-10
-5
0
5
10


Comparison of Hysteretic Curves (Test and 2SM)
H/Hy
δ/δy
2
1
0
-1
-2
-10
-5
0
5
10

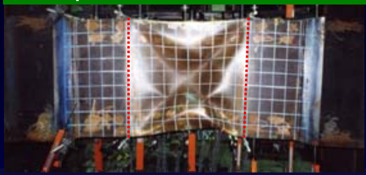

Shear Buckling in Frame-type Pier Beam


Web
Flange
Diaphragms
Horizontal Stiffeners

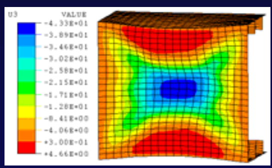

Test Setup
F
F
1813
2075
1813
550
500
(unit: mm)
Side girder
Diaphragm
Pin
Pin
Test Girder


Comparisons of Hysteretic Curves
Test
Analysis
γ/γy
-20
-15
-10
-5
0
5
10
15
20

Comparisons of Deformation Modes



Test



Analysis

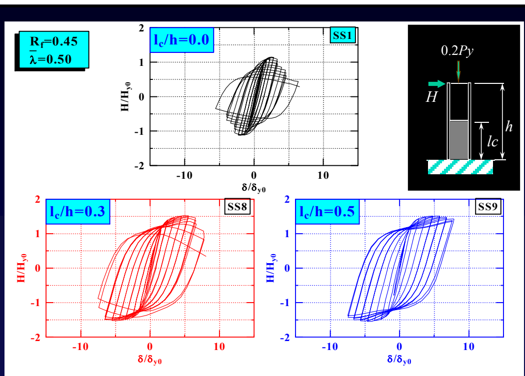
Summary

In the case of damage caused by either local buckling or ductile crack , they can be reproduced by cyclic and pseudo-dynamic tests and accurately simulated by advanced numerical analyses.

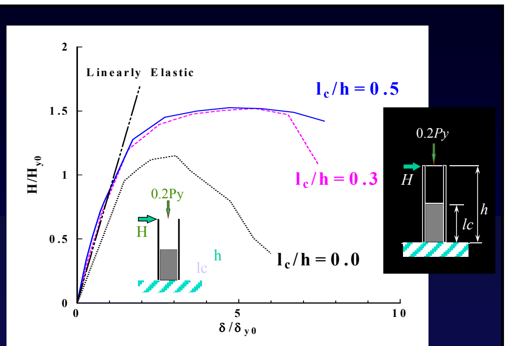
Contents

1. Why steel thin-walled structures are popular in Japan?
2. Types of damage observed in Kobe Earthquake.
3. Repair and retrofit methods after Kobe Earthquake.
4. Seismic performance evaluation by experiment and numerical analysis.
5. Seismic retrofit techniques.
6. Recent progresses in seismic design of steel structures.

Filling Concrete In Steel Sections



Effect of the Filled-in Concrete Length

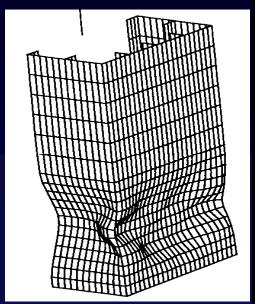


Effect of the Filled-in Concrete Length
(Envelope Curves)

SS8 (lc=0.3) SS9 (lc=0.5)

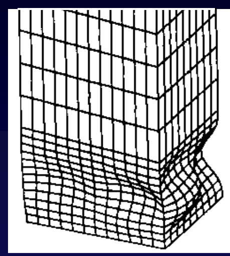
Reducing Width-thickness Ratio of Plates

Comparison of Buckling Modes



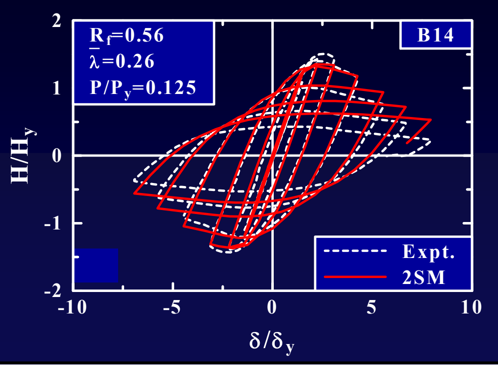
Test (PWRI) Analysis (2SM)

Comparison of Buckling Modes

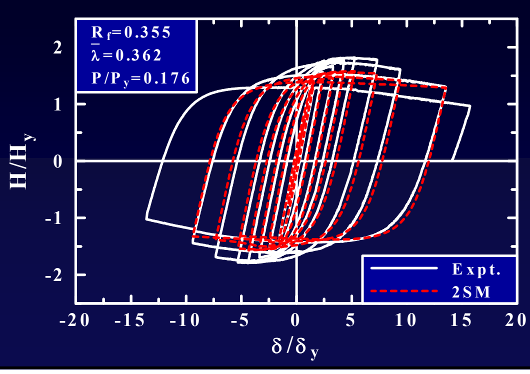


Test (Nagoya University) Analysis (2SM)

Comparison between Test and Analysis



Comparison between Test and Analysis



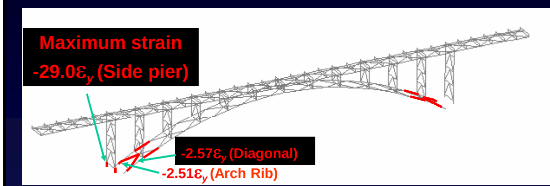
Adopting BRBs as Dampers

Application of BRBs in A Steel Arch Bridge (under Construction)

General View

Damaged Members

Original model without BRBs

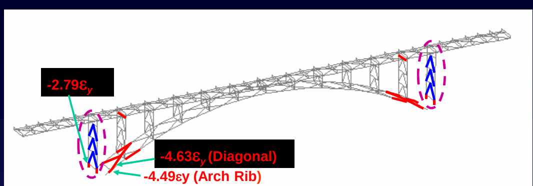


Due to the large axial force appeared at side pier base, severe plasticization occurs, and strain as large as 29ε_y appears

Damaged Members

Upgrading model Case 1

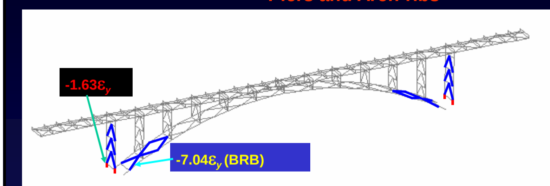
With BRBs for Side-Piers



Severe plasticization at side pier base is greatly mitigated, while arch rib end is still subjected to plasticity

Damaged Members

Upgrading model Case 2 With BRBs for both Side-Piers and Arch-ribs



Severe plasticization at side pier base is further mitigated, and arch rib end is in the elastic range

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Format of Performance Design

CAPACITY ≧ DEMAND

no → Redesign or Retrofit

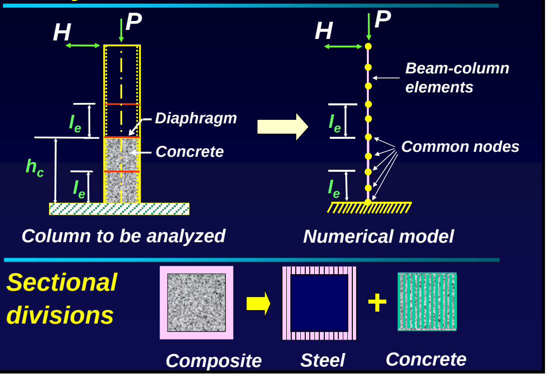
yes ↓ OK

Dual-Level Methodology

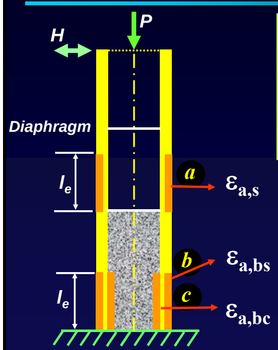
Method	Capacity	Demand	Performance check index
(1) Static/ Dynamic Method	Static Pushover Analysis	Dynamic Analysis of ESDOF	Displacement
(2) Dynamic Method	Failure Strain	E.-P. Time History Analysis	Strain

Capacity Prediction through Pushover Analysis

Analytical Model



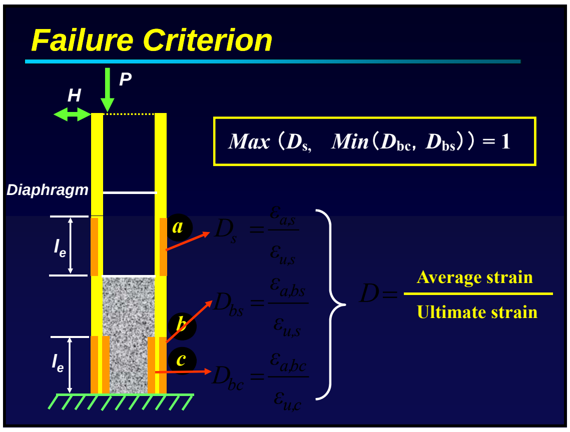
Failure Criterion

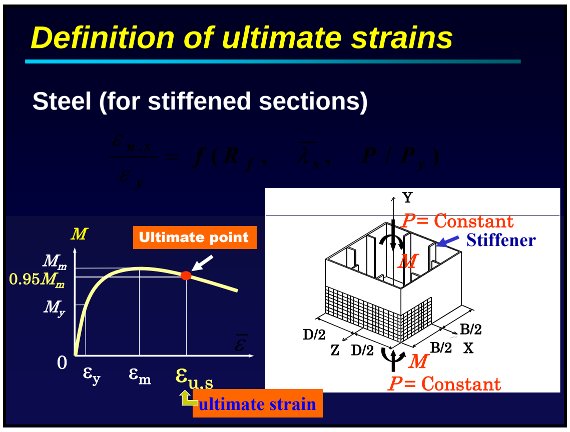


$l_e = Min\ (0.7b,\ l_d)$

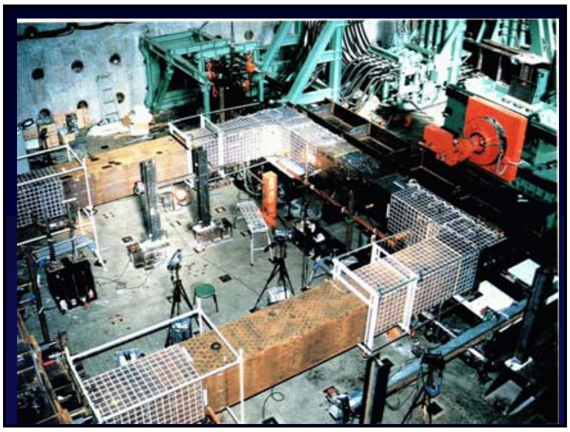
b: width of section
l_d: diaphragm spacing

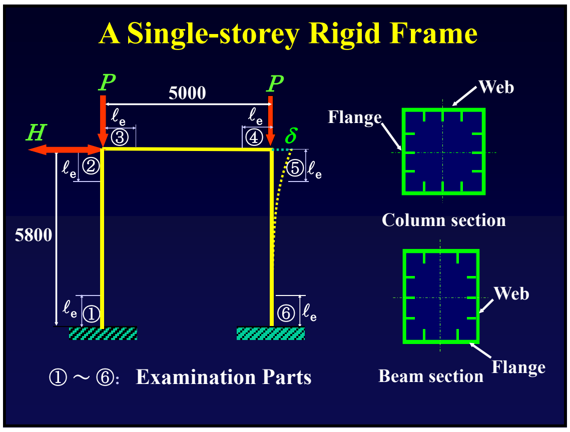
Monitor the average strain progression at outer fibers of steel and concrete elements along the effective failure lengths at regions a, b and c

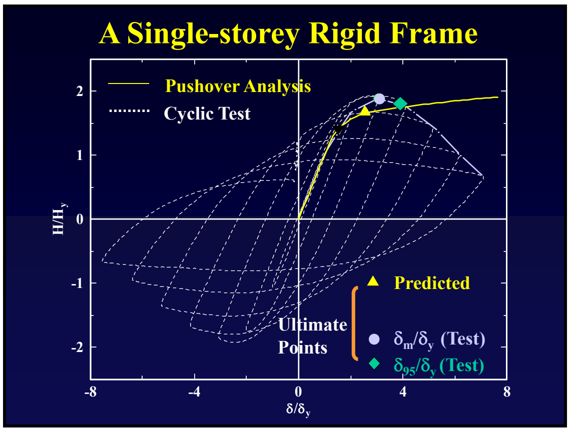




Example of Ductility Evaluation of Steel Frame

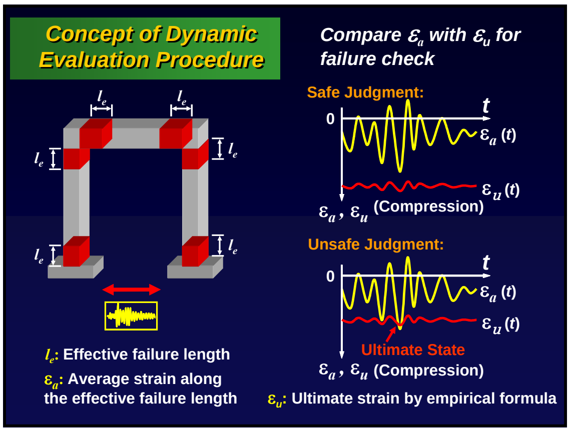


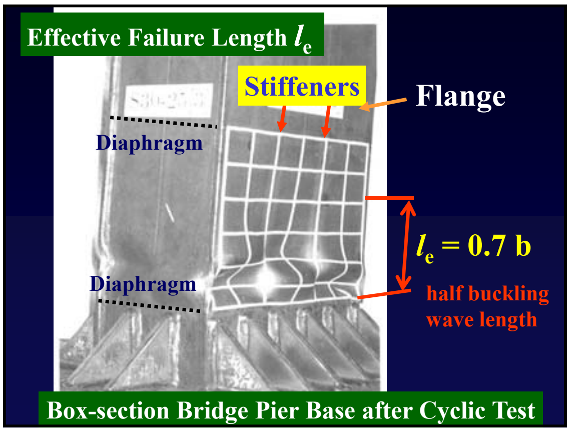




Example of Strain-based Verification Procedure
(Dynamic Evaluation Procedure)

Concept of Dynamic Evaluation Procedure





Verification Format (Strain-based Method)

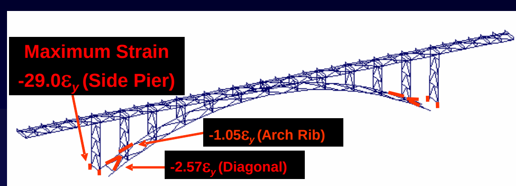
Structural Safety (Safe or Unsafe)	$\varepsilon_a)_{max} < \varepsilon_u$
Serviceability after Earthquake	$\varepsilon_a)_{max} < 2.0\varepsilon_y$

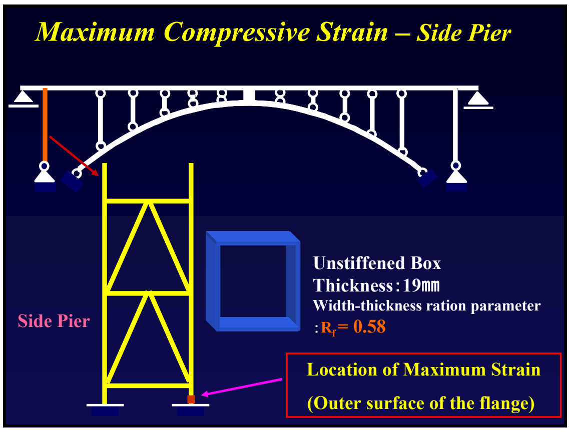
ε_u : Ultimate Strain (Capacity)

$\varepsilon_a)_{max}$: Average Response Strains within Failure Length

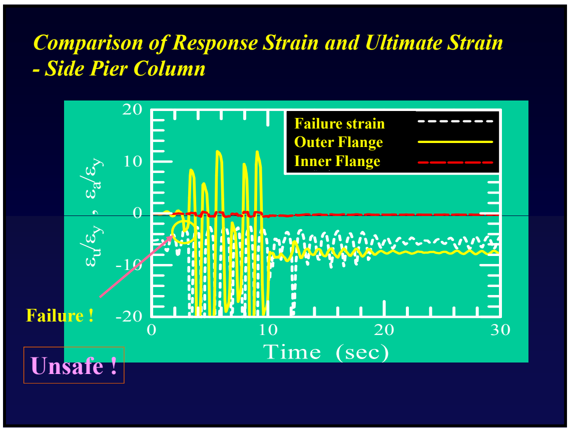
Example of Steel Arch Bridge

Damaged Components without Using BRBs
under Transverse Earthquake

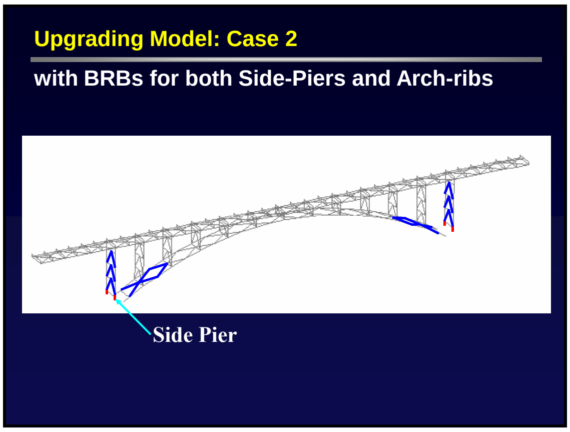




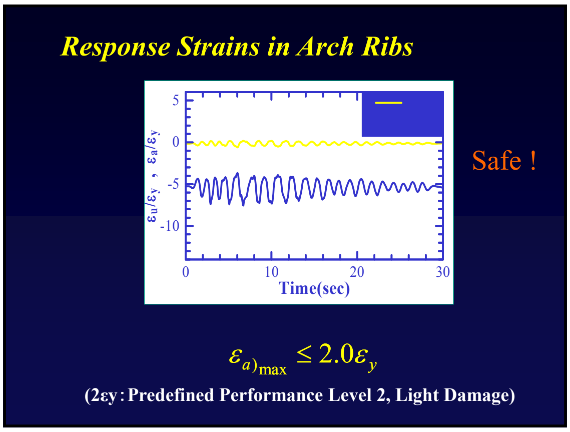
Maximum Compressive Strain – Side Pier
Side Pier
Unstiffened Box
Thickness：19㎜
Width-thickness ration parameter
：R_f= 0.58
Location of Maximum Strain
(Outer surface of the flange)



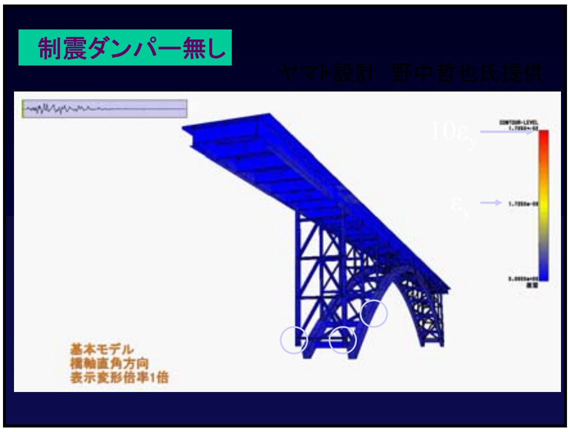
Comparison of Response Strain and Ultimate Strain
- Side Pier Column
Failure strain
Outer Flange
Inner Flange
$\varepsilon_u/\varepsilon_y$, $\varepsilon_a/\varepsilon_y$
Time (sec)
Failure !
Unsafe !



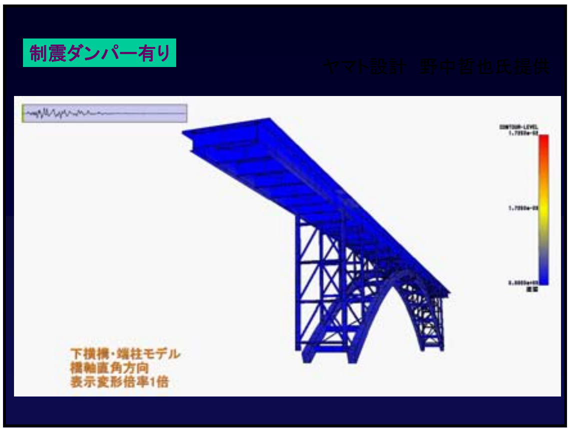
Upgrading Model: Case 2
with BRBs for both Side-Piers and Arch-ribs
Side Pier



Response Strains in Arch Ribs
$\varepsilon_u/\varepsilon_y$, $\varepsilon_a/\varepsilon_y$
Time(sec)
Safe !
$\varepsilon_{a)\max} \leq 2.0\varepsilon_y$
(2εy：Predefined Performance Level 2, Light Damage)



制震ダンパー無し
基本モデル
橋軸直角方向
表示変形倍率1倍



制震ダンパー有り
下横構・端柱モデル
橋軸直角方向
表示変形倍率1倍

Findings of Earthquake-Resistant Design

Guidelines for Stability Design of Steel Structures
Edited by T. Usami (published by JSCE)
Chapter 20 Steel Bridge Piers
By Ge, Ono and Maeno

Analysis and Design of Plated Structures
Volumn 1: Stability
Edited by N.E.Shanmugam and C.M.Wang (published by CRC)
Chapter 10 Analysing the strength and ductility of plated structures
By Usami and Ge

New Trend in Seismic Design

- **Earthquake-Resistant Design**
  Earthquake energy is absorbed by main members, through improving their ductility capacity
  Measures:
  use of thick-walled section, adding stiffeners (ribs), filling concrete inside hollow section
- **Damage-Control Design**
  Earthquake energy is absorbed by secondary members, through introducing (or replacing with) various damage control devices (energy dissipation members, dampers)
  Function:
  acting as fuse

Findings of Performance-based Damage Control Design

Guidelines for Seismic and Damage Control Design of Steel Bridges

Edited by T. Usami, JSSC
(published by Gihodo)

Limit States and Required Performance in Steel Bridge Structures

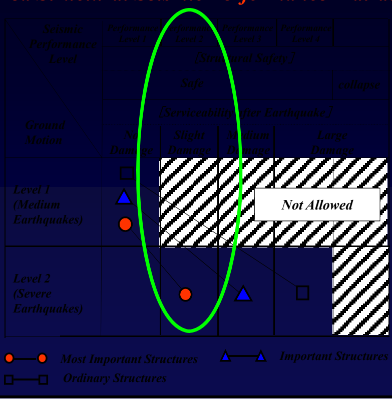
- Ultimate Limit state:
  Required performance: Structural safety

  -Local and overall buckling
  -Low cycle fatigue
- Damage Limit state:
  Required performance: Serviceability after earthquake

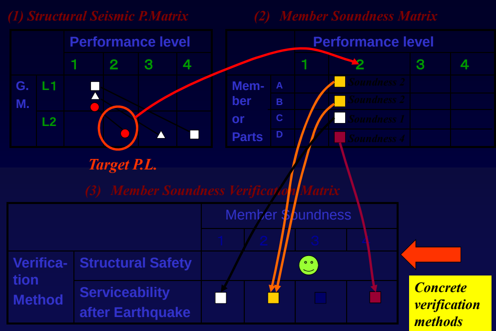
  -Structural damage due to inelastic deformation

Performance verification method must check all of these limit states!

Required Structural Seismic Performance Matrix



Verification Procedures



Dual-Level Verification Method

Method	Capacity R	Demand S	Remarks
(1) Displace-ment-based	Static Pushover Analysis	Dynamic Analysis of ESDOF	Applicable structures are limited
(2) Strain-based	Ultimate Strain	Dynamic Analysis	Any Structure

Performance Check: $\gamma \cdot S \leq R$

Comment on Displacement-based Method

The displacement-based method is acceptable, if the fundamental mode is dominant.

The condition is $\dfrac{M_{eff,1}}{M_{total}} \geq 0.75$

↑

Effective Mass Ratio of Fundamental Mode

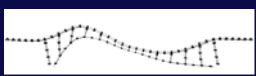
Inapplicability Example: Steel Arch Bridge in Longitudinal Direction

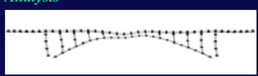
The displacement-based procedure is inapplicable in the Longitudinal Direction of the steel arch bridge.

Dominant mode

Deformation Mode changes during excitation, since there is not a governing mode in the longitudinal direction

ultimate mode during Pushover Analysis | *ultimate mode during Dynamic Analysis*



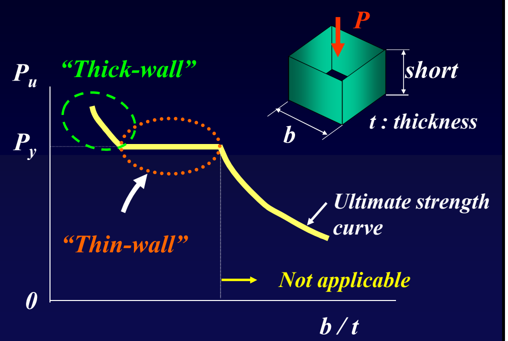


Strain-based Seismic Verification Method

Features of Steel Bridge Structures

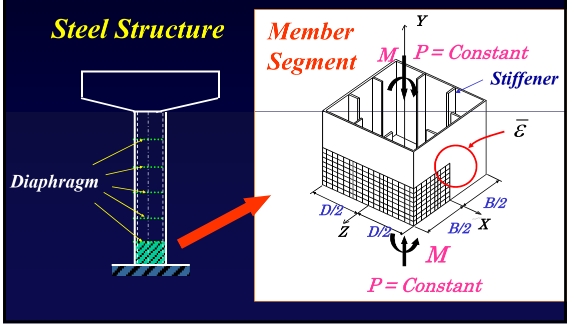
- Thin-walled box (or pipe) sections
- Stiffened by longitudinal ribs and diaphragms
- Susceptible to local buckling
- P-Δ effect should be considered

Definition of "Thin-wall" Structure

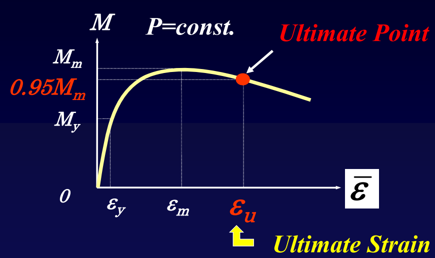


Preliminary Study
Ultimate Strain

Ultimate Compressive Strain (1)



Ultimate Compressive Strain (2)



$\bar{\varepsilon}$ = *Average Compressive Strain on the compression flange*

Ultimate Compressive Strain Formula of Member Segment

Stiffened box $\dfrac{\varepsilon_u}{\varepsilon_y} = f(R_f,\ \bar{\lambda}_s,\ N/N_y) \leq 20.0$

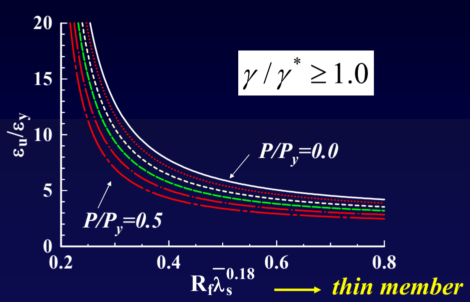
R_f = *Flange width-thickness ratio parameter*

$\bar{\lambda}_s$ = *Stiffener's slenderness ratio parameter*

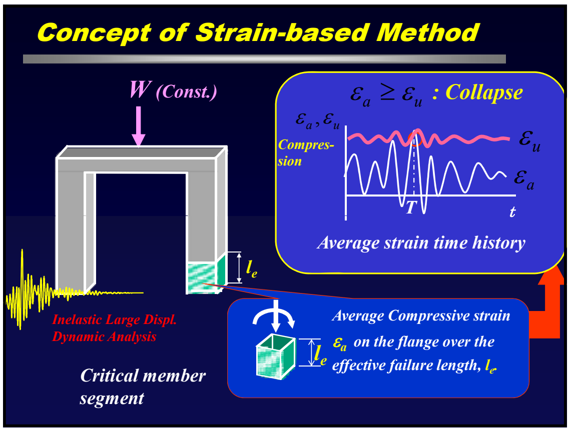
N/N_y = *Axial force ratio*

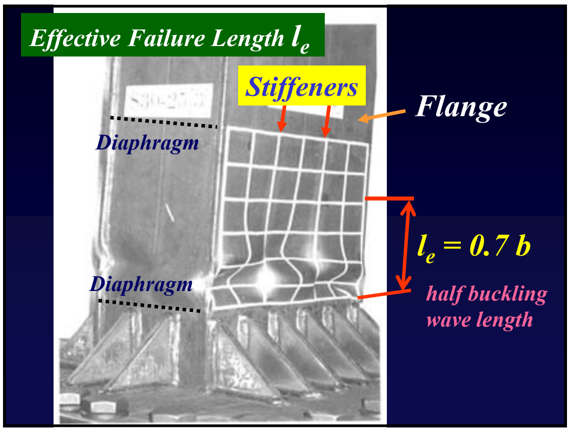
･･･*Unstiffened box, Pipe, H section.*

Ultimate Compressive Strain of Stiffened Box Member Segment

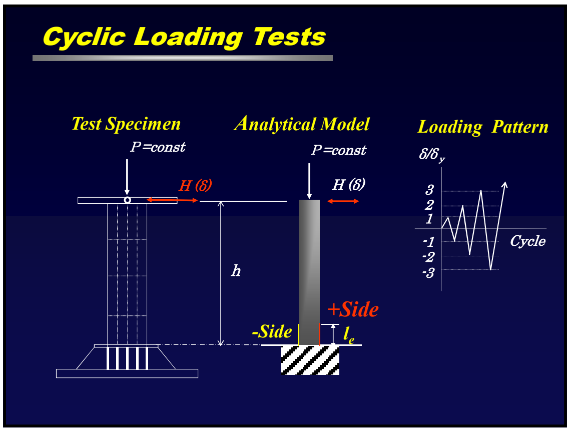


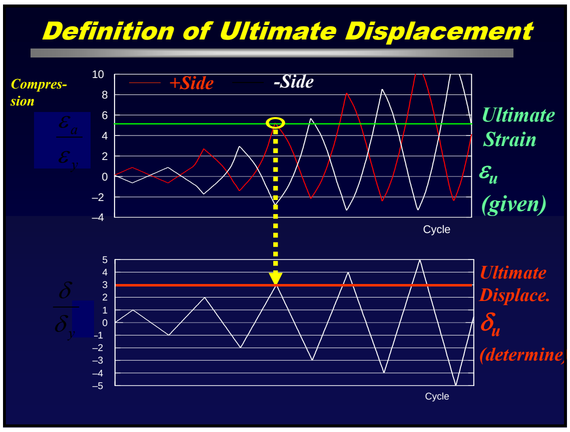
Strain-based Method

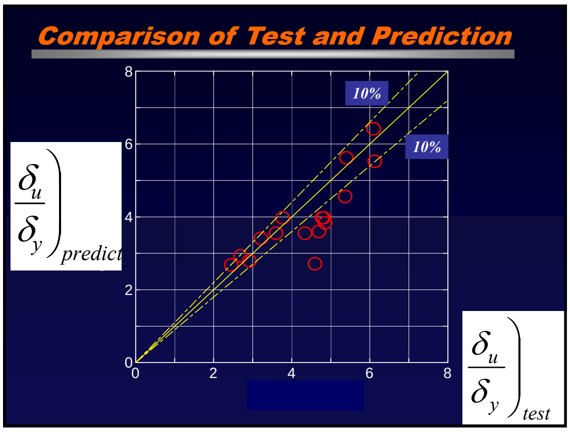


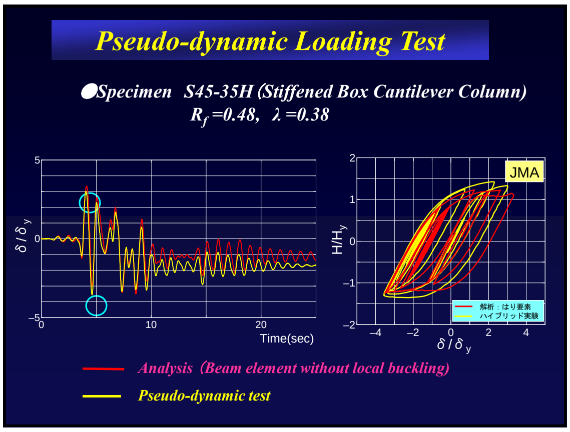


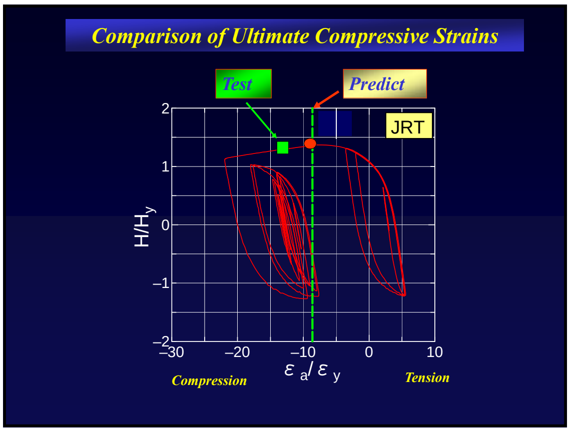
Validation of the Strain Method

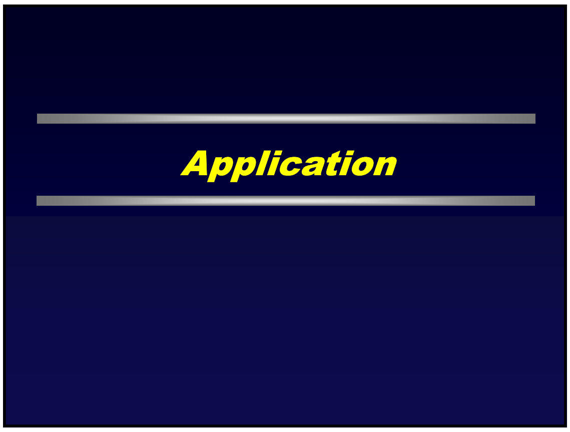


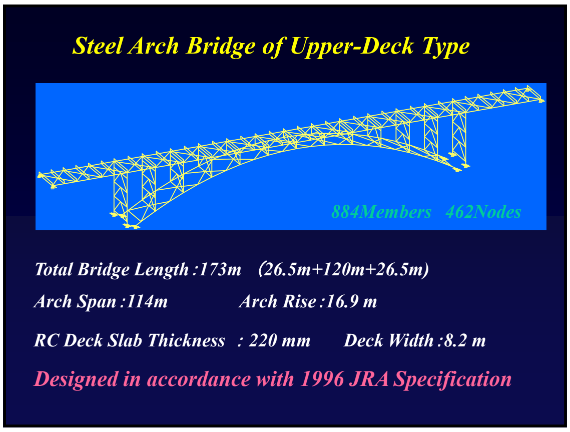


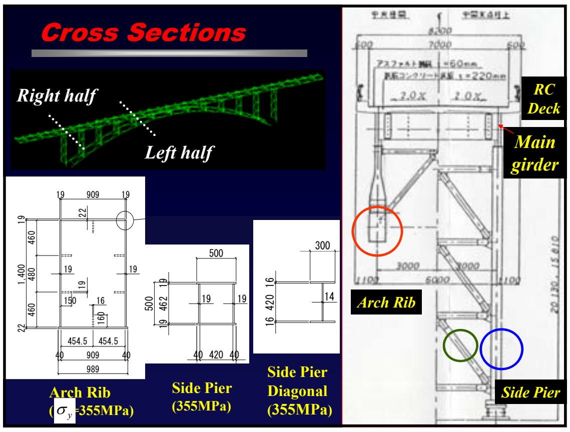


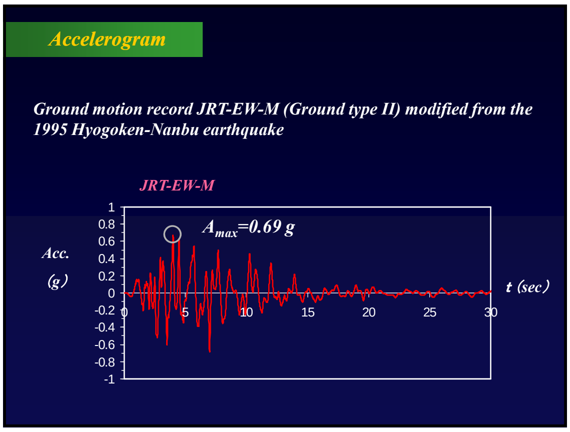

Pseudo-dynamic Loading Test
●Specimen S45-35H (Stiffened Box Cantilever Column)
R_f=0.48, λ=0.38
δ / δy
Time(sec)
H/Hy
JMA
δ / δy
Analysis (Beam element without local buckling)
Pseudo-dynamic test


Comparison of Ultimate Compressive Strains
Test
Predict
JRT
H/Hy
ε a/ ε y
Compression
Tension


Application

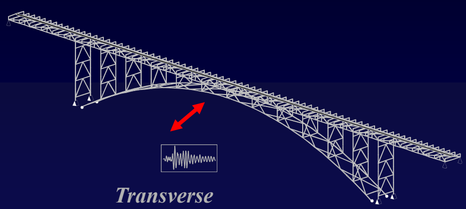

Steel Arch Bridge of Upper-Deck Type
884Members 462Nodes
Total Bridge Length :173m (26.5m+120m+26.5m)
Arch Span :114m Arch Rise :16.9 m
RC Deck Slab Thickness : 220 mm Deck Width :8.2 m
Designed in accordance with 1996 JRA Specification


Cross Sections
Right half
Left half
RC Deck
Main girder
Arch Rib
Side Pier
Arch Rib
(σy=355MPa)
Side Pier
(355MPa)
Side Pier Diagonal
(355MPa)


Accelerogram
Ground motion record JRT-EW-M (Ground type II) modified from the 1995 Hyogoken-Nanbu earthquake
JRT-EW-M
Amax=0.69 g
Acc.
(g)
t (sec)

Earthquake motion

Ground Condition: Class II

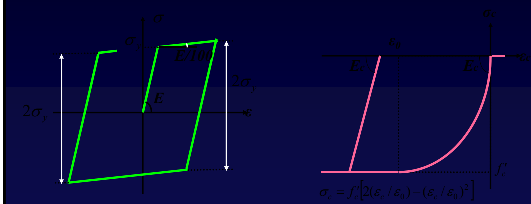


JRT-EW-M (PGA=0.70g)

JRA Spec.

Constitutive Laws

Steel | **Concrete**



Bi-linear Kinematic Hardening

f'_c =25.5MPa
ε_0=0.002
ε_u=0.0035

Seismic Response Analysis

Analysis: 3D Easto-plastic Large Displacement Dynamic Analysis

Damping : Mass Proportional with Damping Coeffi. =0.03

Element: Timoshenko Beam Element & Truss Element

Analysis Code: ABAQUS ver. 5.8

Target Seismic Performances

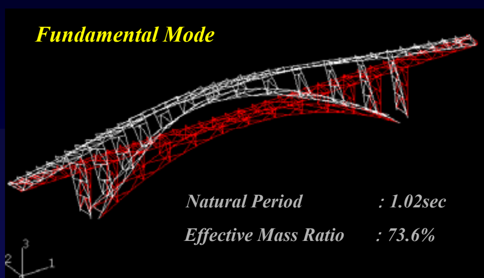
Most important Structure: Performance Level 2

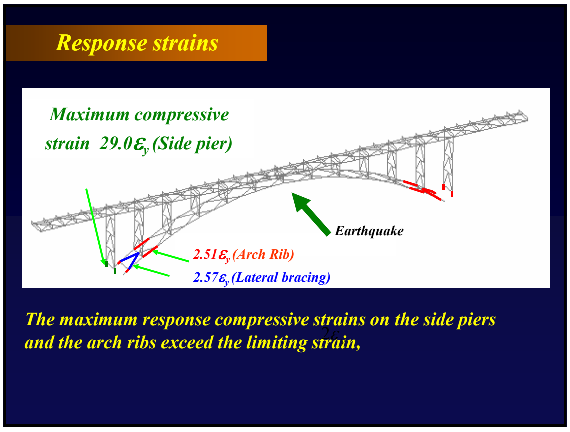
Structure	Performance
Super Structures (side piers, arch ribs, girders etc)	Member soundness 2 $\varepsilon_a)_{max} < 2.0\varepsilon_y$
Bearings	Member soundness 2 Elastic Limit
Seismic Damper (BRBs)	Member soundness 4 $\varepsilon_{max} < 20.0\varepsilon_y$

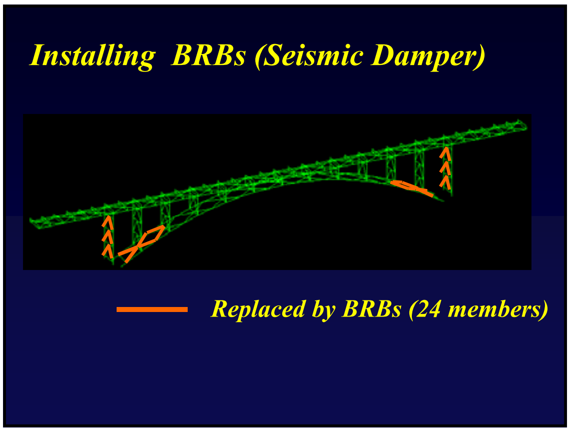
$\varepsilon_a)_{max}$: *Response average compressive strains within effective failure length*

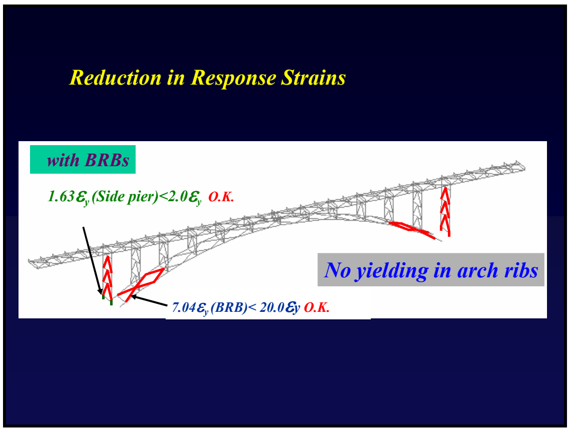
Transverse Direction Behavior

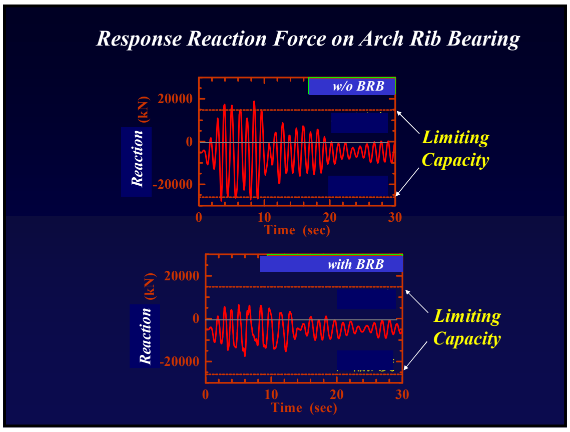
Eigen-value Analysis

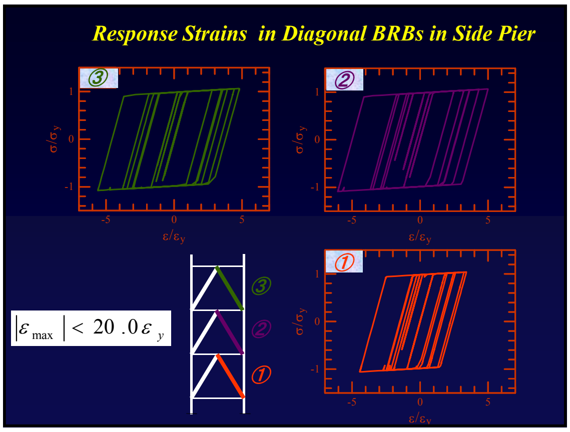


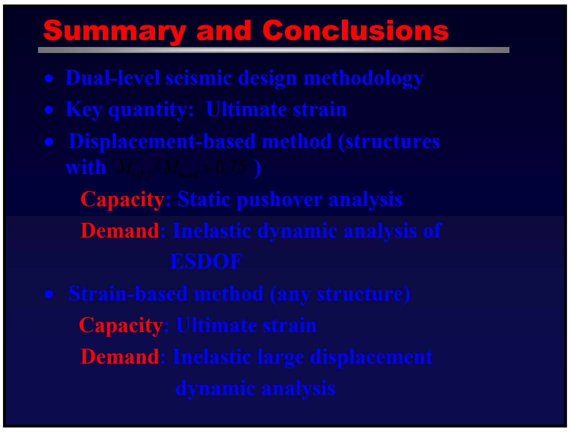

Response strains
Maximum compressive
strain 29.0ε_y (Side pier)
Earthquake
2.51ε_y (Arch Rib)
2.57ε_y (Lateral bracing)
The maximum response compressive strains on the side piers and the arch ribs exceed the limiting strain,


Installing BRBs (Seismic Damper)
Replaced by BRBs (24 members)


Reduction in Response Strains
with BRBs
1.63ε_y (Side pier)<2.0ε_y O.K.
No yielding in arch ribs
7.04ε_y (BRB)< 20.0ε_y O.K.


Response Reaction Force on Arch Rib Bearing
w/o BRB
Reaction (kN)
20000
0
-20000
0 10 20 30
Time (sec)
Limiting Capacity
with BRB
Reaction (kN)
20000
0
-20000
0 10 20 30
Time (sec)
Limiting Capacity


Response Strains in Diagonal BRBs in Side Pier
③
②
①
σ/σy
ε/εy
$|\varepsilon_{max}| < 20.0\varepsilon_y$


Summary and Conclusions
• Dual-level seismic design methodology
• Key quantity: Ultimate strain
• Displacement-based method (structures
with
Capacity: Static pushover analysis
Demand: Inelastic dynamic analysis of ESDOF
• Strain-based method (any structure)
Capacity: Ultimate strain
Demand: Inelastic large displacement dynamic analysis

Summary and Conclusions

- A strain-based seismic safety verification method by using full E.-P. time history analysis is proposed.
- Safety verification:

  Response strain $\leq$ Ultimate strain

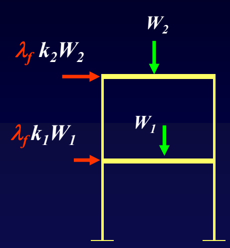
Displacement-based Method

Proposed Dual-Level Methodology

Method	Capacity R	Demand S	Performance check
(1) Displace-ment method	Static Pushover Analysis	Dynamic Analysis of ESDOF	Displace-ment
(2) Strain method	ultimate Strain	Dynamic Analysis	Strain

Performance Check: $\gamma \cdot S \leq R$

Capacity(1) - Static pushover analysis



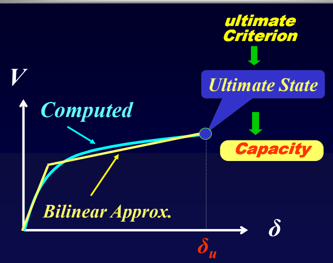
W_i : Weight of superstructure (=Constant)

k_i : Seismic coefficient(=S_a/g)

λ_f: Load factor (= monotonically increased)

- Elastoplastic large displacement analysis using bar elements

Capacity(2) : V- δ Relation

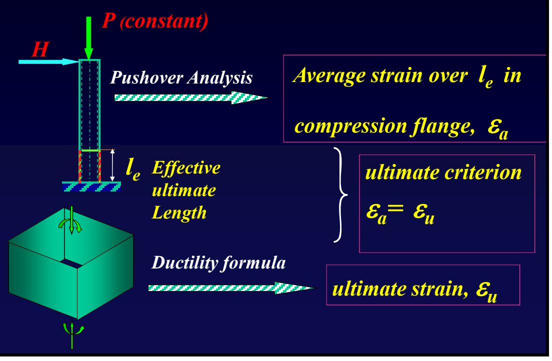


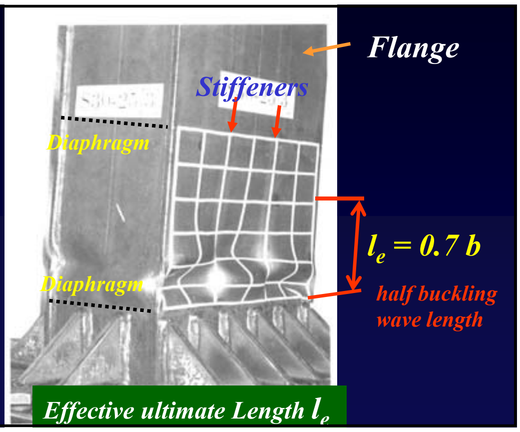
V = Base shear (=total lateral force)

δ = Displacement at a reference point

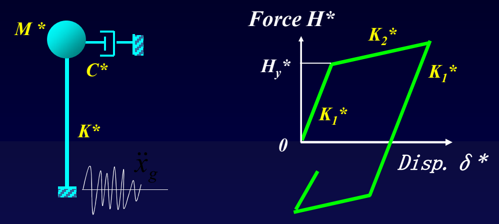
δ_u= Ultimate displacement

Capacity (3) - ultimate Criterion





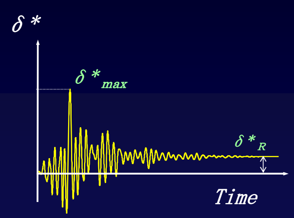
Demand (1): ESDOF Model



ESDOF Model

Restoring Force Characteristics
(from V-δ relation)
Kinematic Hardening Rule

Demand (2) : Nonlinear Time-history Analysis



ESDOF Demands
↓
MDOF Demands

Displacement Response of ESDOF

Performance Check

Demand		Capacity
δ_{max}	$\leqq$	δ_u
δ_R	$\leqq$	$\delta_R)_{lim}$

Transformation Equations

ESDOF ⟷ MDOF

$$H^* = \{\phi\}^T\{H\}$$

$$\delta^* = \frac{\{\phi\}^T[M]\{\phi\}}{\{\phi\}^T[M]\{1\}}\,\delta$$

$$M^* = \{\phi\}^T[M]\{1\}$$

$$C^* = \{\phi\}^T[C]\{\phi\}\frac{\{\phi\}^T[M]\{1\}}{\{\phi\}^T[M]\{\phi\}}$$

$$K^* = H_y^*/\delta_y^*$$

( )*: Quantities of ESDOF

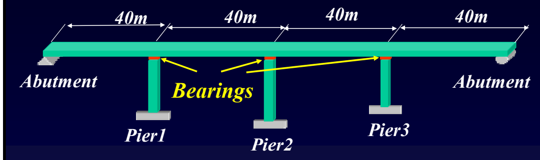
Examining the Proposed Method

Presupposition

The fundamental mode dominates in the original MDOF structure

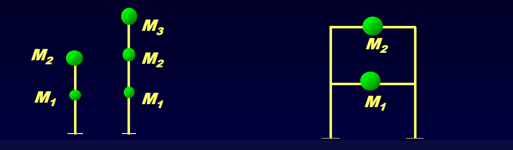
⟶ Conditions?

Structure (1)-Viaduct



- Bearings: (1) Pin, (2) Elastic Rubber, (3) Isolation
- Response directions: (a) Longitudinal
  (b) Transverse

Structure (2) – Columns and Frames

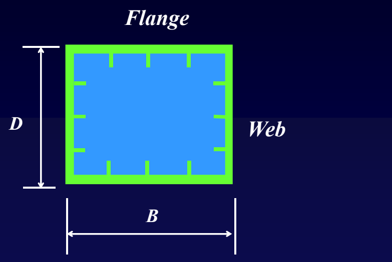


a) 2- or 3-DOF steel cantilever columns

b) 2-story steel frames

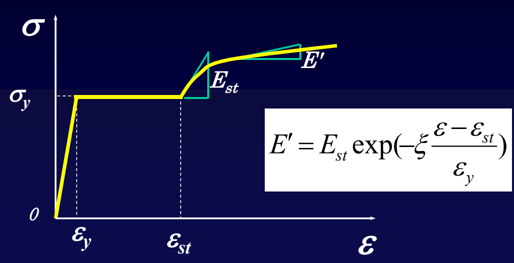
Varying Parameters:
Story mass ratio (M_2:M_1 or M_3:M_2:M_1)

Cross-section



Constant Thickness

S-S Diagram of Steel for Pushover Analysis

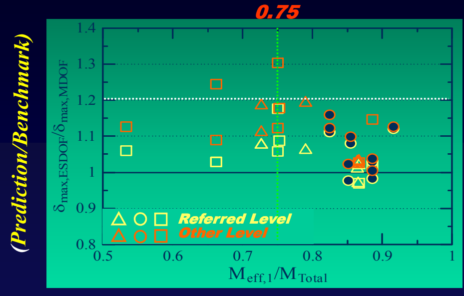


$$E' = E_{st}\exp\left(-\xi\frac{\varepsilon-\varepsilon_{st}}{\varepsilon_y}\right)$$

Benchmark Dynamic Analysis

- Dynamic analysis of original structures using Modified Two-Surface Model (Nagoya University, 1995) for cyclic elastoplastic constitutive law of structural steel
- P-Δ effect is considered
- Bar element and no local buckling

Result: Columns and Frames



(Effective Mass Ratio of 1st Mode)

Summary (continued)

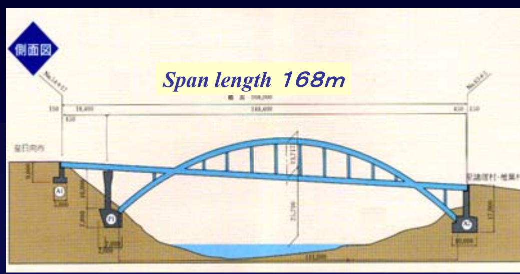
The condition is met for

- ***Cantilever columns *Frames***
  - -Uniform mass
  - -Top Heavy
- ***Viaducts in Longitudinal***
- ***Viaducts in Transverse***
  - -Symmetric pier stiffness
  - -Stiff Deck
  - -Elastic or Isolation Bearing

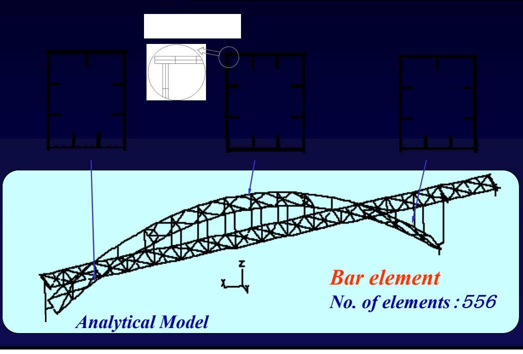
Application

Application to Steel Arch Bridge

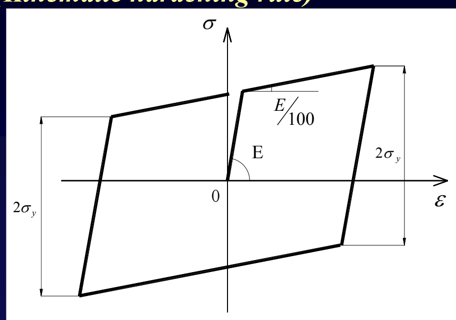
Dimensions

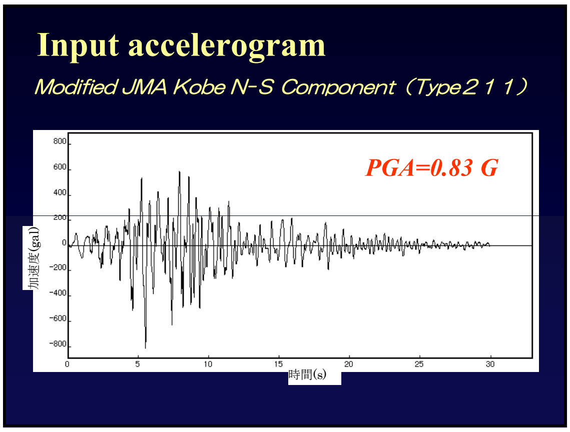


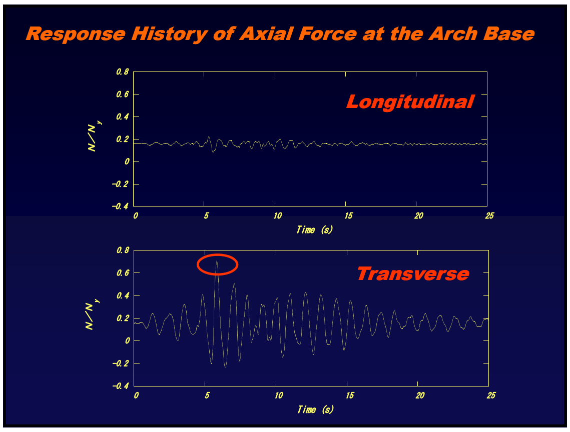
Cross-sections

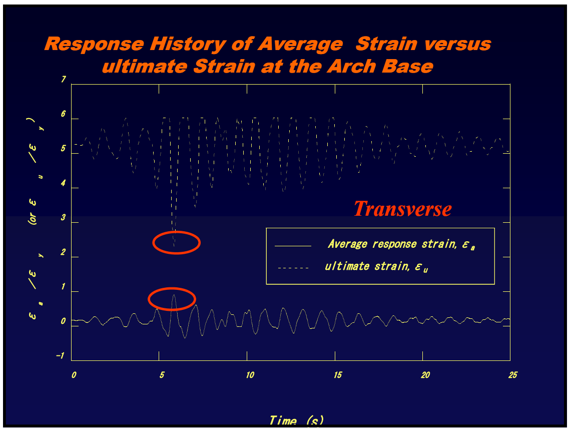


Stress-strain diagram for steel (Kinematic hardening rule)




Input accelerogram
Modified JMA Kobe N-S Component（Type2 1 1）
PGA=0.83 G
加速度(gal)
時間(s)


Response History of Axial Force at the Arch Base
Longitudinal
Transverse
Time (s)


Response History of Average Strain versus ultimate Strain at the Arch Base
Transverse
Average response strain, ε_a
ultimate strain, ε_u
Time (s)