特　別　講　演　会

平成 23 年　3 月　10 日

名古屋工業大学 鶴舞キャンパス

講演題目：「Seismic Design of Highway Bridges in California」

平成22年度SGST特別講演会　議事録

日時　：平成23年3月10日(木)　14：00〜15：30
場所　：名古屋工業大学
出席者：後藤，海老澤，永田，奥村（名工大)、北根（名大)、宇佐美（名城大)、中野（愛知県)、山田（中日本HW.E)、前野（名公社)、室井，佐々木（日鉄トピー)、山田（日車)、安藤，織田，中川（瀧上)、および学生

15名(敬称略)

講　演　者：Lian Duan,Ph.D.
講演項目：Seismic Design of Highway Bridges in California
※土木学会CPDプログラム認定番号　JSCE10-0957

講演内容：

講演者のLian Duan博士は、カリフォルニア道路局（CALTRANS）の上級橋梁技術者であり、「BRIDGE ENGINEERING HANDBOOK」の著者でもある。本講演の主題は、主にカリフォルニアにおける高速道路の耐震設計に関するものであった。

講演内容としては、アメリカ合衆国における耐震設計の発展、CALTRANSの耐震性能基準、標準耐震設計などがメインであり、コンクリート橋、鋼橋のそれぞれにおける耐震設計手法について詳細にご説明を頂いた。

すべて英語によるご説明（通訳なし）であったが、大変興味深い内容であり講演後には活発な質疑応答が取り交わされた。

以上//

講演題目：「Seismic Design of Highway Bridges in California**」**
※土木学会 CPD プログラム認定番号　JSCE10-0957

講演者：カリファルニア道路局（CALTRANS）の上級橋梁技術者　Dr. Lian Duan 氏
会場：名古屋工業大学　鶴舞キャンパス（愛知県名古屋市）
講演日時：平成 23 年 3 月 10 日（木）　14:00～15:30

講演要旨：
　アメリカ合衆国における耐震設計の発展, CALTRANS の耐震性能基準, 標準耐震設計および, コンクリート橋, 鋼橋のそれぞれにおける耐震設計手法の説明.

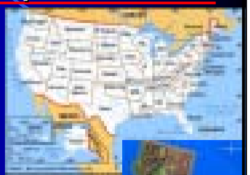
PRESENTATION OUTLINE

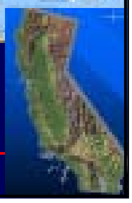
- Evolution of Seismic Design
- Seismic Performance Criteria
- Current Seismic Design
- Concrete Bridges
- Steel Bridges
- Summary

Evolution of Seismic Design

Recent Significant Earthquakes in USA

- 1971 San Fernando (Mw6.7)
  - 53 Death, $1 Billion Lose
- 1989 Loma Prieta (Mw =7.0)
  - 62 Death, $6-7 Billion Lose
- 1994 Northridge (Mw = 6.7)
  - 56 Death, $15 ~30 Billion Lose

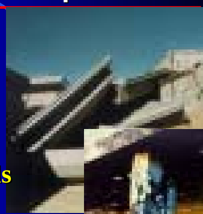




Evolution of Seismic Design

1971 San Fernando Earthquake

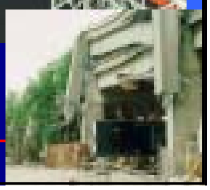
- Milestone –Modern Seismic Design and Retrofit Practice
- Strength
- Ductility – Ductile Details
- Continuity - Restrainers



Evolution of Seismic Design

1989 Loma Prieta Earthquake

- Most Damage in 20th Century
- Major Improvement for Ductility Design
  - MTD 12-4
  - Caltrans BDS 1990



Evolution of Seismic Design

1994 Northridge Earthquake

- Short Seat Width
- High Vertical Acceleration
- Retrofitted Bridges
  - Minor Damage
- Seismic Performance Criteria
- Displacement-Based Approach

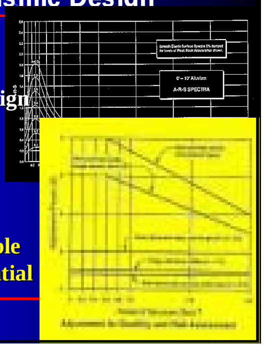
1

Evolution of Seismic Design

- Provide Public Safety
  - 37,060,000 Residents
  - 25,000 Highway Bridges
- Prior to 1971
  - Lateral Load = 2~6% DL
- 1972-1989 Criteria
  - Site, Soil Response And Bridge Behavior
- 1990-1994
  - Force-Based Seismic Design
- 1994-present
  - Performance And Displacement-Based Seismic Design

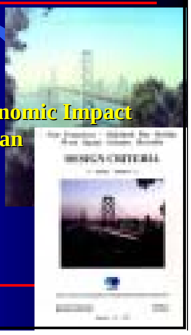
Evolution of Seismic Design
Caltrans 1990 Seismic Design

- No-Collapse Design – ARS
- Linear Analysis
- Z- factors, Force-Based Design
- Properly Designed Details
- Simple/Easy
- Does Not Directly Address Inelastic Nature
- Does Not Provide - A Reliable Indication of Damage Potential



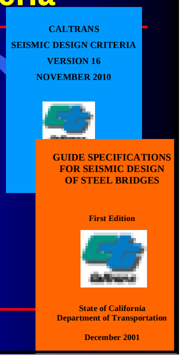
Caltrans Seismic Performance Criteria

Important Bridge
- Required For Post Earthquake Immediate to Open
- Closure Would Create Major Economic Impact
- Critical To A Local Emergency Plan
- Project Specific Criteria
- Two-Level Design
  - Functionality - Minimum Damage
  - Safety - Repairable Damage



Caltrans Seismic Performance Criteria

Standard Bridges
- Any Structure Not Designated as Important
- One -Level Design - No Collapse
- Standard Bridges
  Seismic Design Criteria 2010
  Seismic Design Guideline 2001
- Nonstandard Bridges
  Project-Specific Criteria

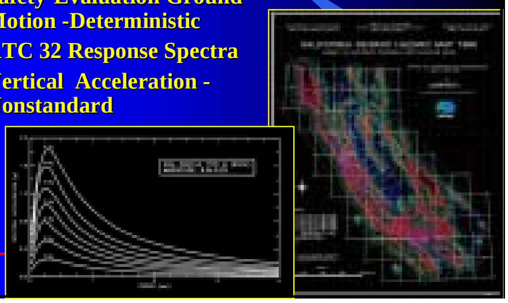


Current Seismic Design
General

- Performance-Based Concept
- Displacement-based Design Approach
- Strong -Beam Weak -Column Preference
- Capacity Design
  - For Essentially Elastic Components
- Ductile Details
  - For Ductile Components
  - Predetermined Locations

Current Seismic Design
Earthquake Ground Motion

- Safety-Evaluation Ground Motion -Deterministic
- ATC 32 Response Spectra
- Vertical Acceleration - Nonstandard



2

Current Seismic Design

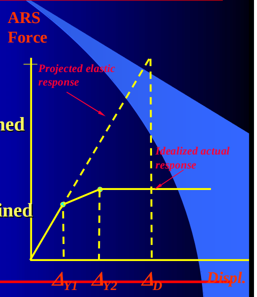
Primary Design Criteria - Displacements

Global Displacement and Local Ductile Members

$\Delta_D < \Delta_C$

Δ_D - Displacement Demand Obtained by Elastic Response Spectra Analysis

Δ_C - Displacement Capacity Obtained by Push-Over Analysis



Current Seismic Design

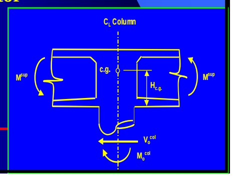
Capacity Design Concept - Forces

Capacity-Protected Components Adjacent to Ductile Components

$F_D < F_C$

F_D - Force Demand Obtained from Joint Equilibrium by Considering Over-strength Factor for Ductile Components

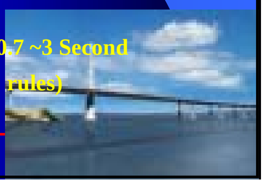
F_C - Force Capacity Determined by Caltrans SDC or AASHTO Specifications



Current Seismic Design

Seismic Demands - Displacement

- Equivalent Static Analysis
- Elastic Dynamic Analysis
  - Effective component stiffness
    - Concrete cracking
    - Axial loads
    - Steel residual stress
- Target fundamental period 0.7 ~3 Second
- Multi-direction effects (30% rules)



Current Seismic Design

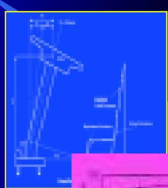
Seismic Capacity - Displacement

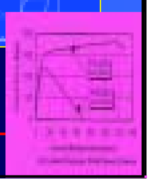
- Inelastic static analysis (IAS)
  - push-over analysis
    - Elastic-plastic hinge
    - Refined plastic hinge
    - Distributed plasticity

Current Seismic Design

Seismic Capacity - Displacement

- Mainly Dependent on Plastic Hinge Behavior and Structure Configuration
- Structural Stability (P-Δ)





Current Seismic Design

Displacement Limit

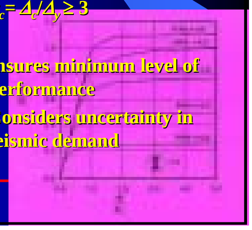
Displacement Demand Limit $\mu_D = \Delta_D/\Delta_Y$

- Single Column Bents $\mu_D < 4$
- Multi-Column Bents $\mu_D < 5$
- Pier Walls (weak axis) $\mu_D < 5$
- Pile Shafts (prismatic) μ_D = *
- Pile Shafts (enlarged) $\mu_D < 1$
- Piles (driven & drilled) $\mu_D < 1$

* Same as supported column

Minimum Displacement Capacity

- $\mu_c = \Delta_c/\Delta_y \geq 3$
- Insures minimum level of performance
- Considers uncertainty in seismic demand

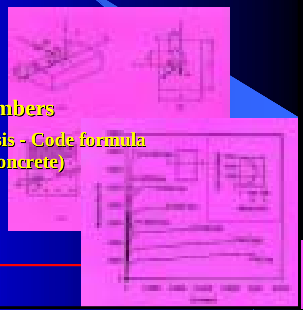


Concrete Bridges

- Flexural Capacity
- Shear Capacity
- Design Practice
  - Proportioning
  - Column Reinforcement
  - Superstructures
  - Hinge Seats

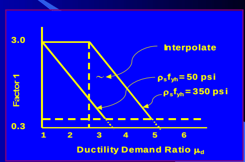
Concrete Bridges
Flexural Capacity

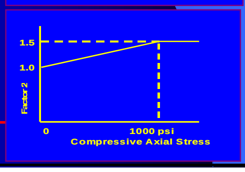
- Ductile Members
  - *M-P-ϕ* analysis
- Capacity-Protected Members
  - *M-P-ϕ* or strength analysis - Code formula (ε_{cu} limited to 0.003 for concrete)



Concrete Bridges
Shear Capacity – Inside Plastic Hinge

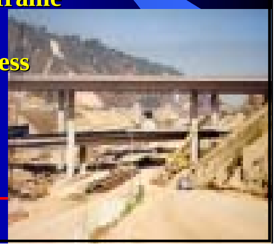
- Shear Capacity
  $V_n = V_c + V_s$
- Concrete v_c
  $F_1 \times F_2 \times \sqrt{f'_c} \le 4\sqrt{f'_c}$
  - Ductility
  - Axial compressive stress
- Steel Reinforcement V_s
  - Nominal material properties





Concrete Bridges
Design Practice - Proportioning

- Periods of adjacent frames
  $T_1/T_2 \ge 0.7$
- Bent stiffness within a frame
  $k_1^e/k_2^e \ge 0.5$
- Adjacent column stiffness
  $k_1^e/k_2^e \ge 0.75$
- *P-Δ* Effects
  $P_{dl}\Delta_D < 0.20M_p^{col}$

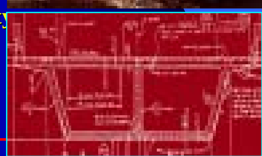


Concrete Bridges
Design Practice - Column Reinforcement

- Lateral Confinement Based on
  - Displacement Demand
  - Minimum Ductility
- Joint Shear Consideration
  - Limit Principal Stresses
  - Additional Reinforcement in Column - Superstructure Connections

Concrete Bridges
Design Practice - Superstructure

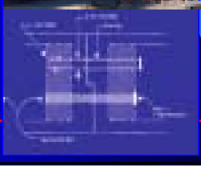
- Vertical Acceleration
  - Equivalent Static Load
- Mild Steel Requirement
  - Nominal Flexural Superstructure Capacity
  - Shear Capacity at Bent Cap Girder Interface



4

Concrete Bridges
Design Practice - Hinge Seats

- Redundancy
  - Restrainers
  - Extenders
- Balanced Frames
  - 60 cm Min. Seat
  - SRSS Displacements
- Unbalanced Frames
  - Rigorous Analysis



25

Steel Bridges

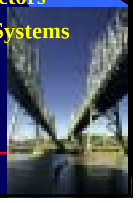
- Earthquake Damage
- Design Requirements
- Ductile Seismic Resisting Systems
- Ductile Components
- Capacity-Protected Components

Steel Bridges
Earthquake Damage

- Steel Bridges Performed Better than Concrete Bridges
- Unseating of Superstructures
- Brittle Failure in Concrete Columns
- Anchorage Failure and Buckling of End Cross Frames

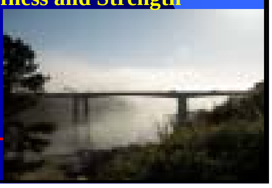
Steel Bridges
Design Requirements

- Proportions
- Materials
- Effective Net Sections
- Effective Length
- Limiting b/t Ratios
- Limiting Slenderness Parameters
- Built-up Members
- Shear Connectors
- Restraining Systems
- Welding



Steel Bridges
Design Requirements - Proportions

- Provide Effective Load Paths and Continuity
- Reduce Seismic Demands and Effects
- Achieve Desired Performance
- Ductile Members - at Transition and Splice Locations - Changes in Stiffness and Strength Shall Not Exceed 50%



Steel Bridges
Design Requirements - Materials

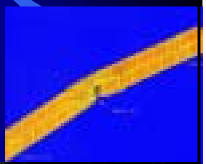
- Ductile Components
  - Grade 345 (F_y = 345 Mpa) and Compatible Steels
  - Grade 250 (F_y = 250 Mpa) Shall Not Be Used due to Its Wide Range Between F_{ye} and F_u
- Expected Yield Strength $F_{ye} = R_y F_y$

Application	R_y
Plate and all other products	1.1
Hot-rolled structural shapes and bars	
ASTM A36	1.5
A572 Grade 42	1.3
All other grades	1.1
Hollow Structural Section	
ASTM A500, A501, A618 and A84	1.3
Steel Pipe - ASTM A53	1.4

30

5

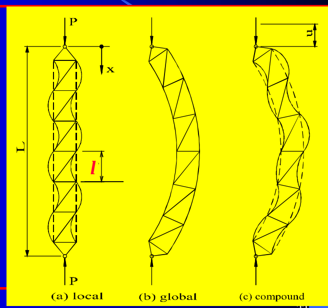
Steel Bridges
Design Requirements
- Limiting Slenderness Ratios -
- Avoid Early Reduction of Strength and Ductility due to Local/Global Buckling
- Ductile Components - Inelastic
- Capacity-Protected Components-Elastic
- Limiting Slenderness Parameters
  - Compression Member λ_{cr}
  - Flexural Member λ_{br}
- Limiting Width-Thickness Ratios
  - Ductile Component - λ_p
  - Capacity-Protected Component - λ_r



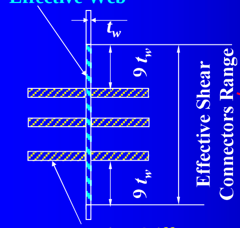

Steel Bridges
Design Requirements - Built-up Members

To Avoid Significant Effects of Compound Buckling

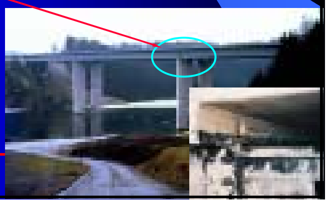
l/r < 3/4 (KL/r)



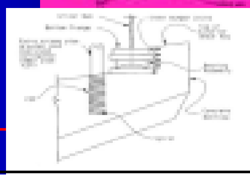
Steel Bridges
Design Requirements - Shear Connectors



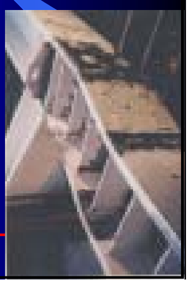
Effective Shear Connectors for Transverse Seismic Loads - Effective Bearing Supporting Length



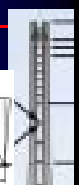
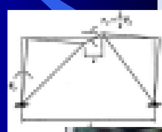
Steel Bridges
Design Requirements - Restraining Systems
- No Rocker Bearings
- Prefer Continuous Girders
  - Elastomeric Bearings
  - PTFE Spherical Bearings
  - Isolation Bearings
- Restraining Systems
  - Shear Keys - Pipe, Concrete Blocks

Steel Bridges
Design Requirements - Welding
- Prefer CJP to Develop Strength of Member in Inelastic Region
- Not Recommend PJP
- Fillet Welds - Follow FCM QA/QC Procedure
- Recent Shear Link Tests Shown that Fillet Welds in Inelastic Region Performed Well



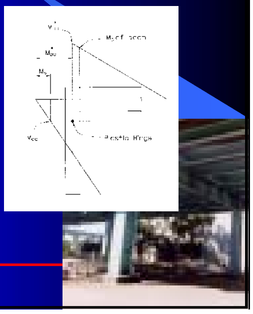
Steel Bridges
Ductile Substructure Systems
- Moment Resisting Frames
  - Steel Columns - Ductile -Inelastic
  - All Other Components Capacity-Protected - Essentially Elastic
- Concentrically Braced Frames
  - Bracing Members - Yielding in Tension and Inelastic Buckling in Compression
- Eccentrically Braced Frames
  - Shear Links - Ductile - Inelastic
  - All Other Components Capacity-Protected - Essentially Elastic


Steel Bridges
Moment Resisting Frames

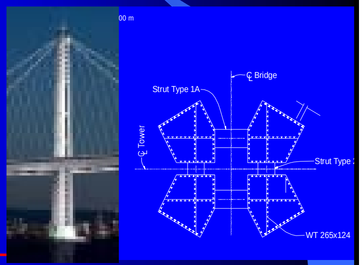
- Ensure a Weak-Column and Strong-Girder Design
- Beam-to-Column Strength

$$\sum M^*_{pb} \geq \sum M^*_{oc}$$



Steel Bridges
Eccentrically Braced Frames

- Shear Links - Inelastic
- Tower Legs - Essentially Elastic



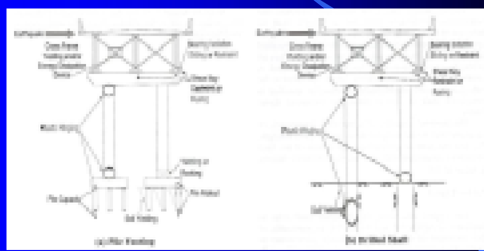
SFOBB East Main Tower

Steel Bridges
Eccentrically Braced Frames

SFOBB Full-scale Shear Links Test (UCSD)

39

Steel Girder Bridges



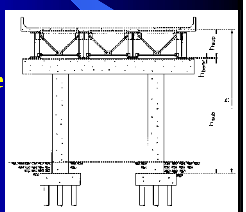
40

Steel Girder Bridges

Type 1 - Ductile Substructure with elastic Superstructure

Type 2 - Ductile End Cross Frame with elastic Substructure

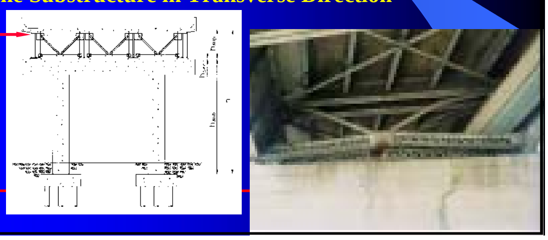
Type 3 - Elastic Sub/Superstructure with Base Isolation/Fusing Mechanism



41

Steel Girder Bridges
Ductile End Cross Frames

Better Inelastic Performance and Energy Dissipation Capacity to Limit the Seismic Forces Transferred to the Substructure in Transverse Direction



Steel Girder Bridges

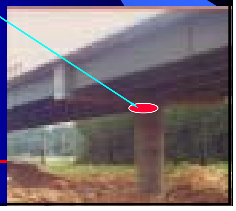
Ductile End Cross Frames

- Prefer in High Seismic to Reduce Seismic Effects in Transverse Directions for Stiff Substructures, Stiffness of Cross Frame to Substructure ≤ 2.0
- Expect Ductility Larger Than 4
- UNR 0.4 Scale Test
  - 18.3 m Long

Steel Girder Bridges

Integral Bent Connections

- Provide Continuity and Frame Action in the Longitudinal Direction - Steel Girder Moment Capacity > Overstrength Plastic Moment Capacity of Concrete Columns
- Reduce Overall Weight
  - Smaller Foundation
- Increase Overhead Clearance
- Eliminate Bearings



Steel Girder Bridges

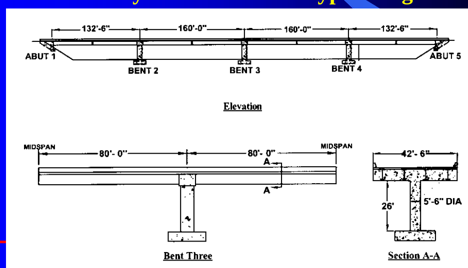
Integral Bent Connections

- Two research teams
  UCSD, Modjeski and Masters/Iowa State - Develop Seismic Details, Design Methodologies and Specifications
- UCSD component tests
  - Stiffeners on the Girder Web in the Cap Beam
  - Post-tensioning the Cap Beam

Steel Girder Bridges

Integral Bent Connections

UCSD System Test - Prototype Bridge



Steel Girder Bridges

Integral Bent Connections

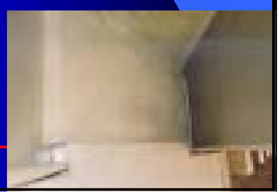
UCSD System Test - 0.4 Scale

- Column - Full Plastic Hinging
- Bent Cap and Superstructure - Essentially Elastic - Hairline Cracking during the Initial Stages of Loading, and Did Not Develop Any Further
- A New Design Alternative

Steel Girder Bridges

Concrete End Diaphragms

- Preferred Over Steel End Cross Frame at Seat Type Abutment
- Improve Mobilization of the Soil Behind the Abutments to Reduce Seismic Loads to Columns
  - Continuous with Deck and Extended as Close as Possible to Bottom Flange of the Girder
  - Connection with Steel Webs Shall Be Carefully Designed



8

Steel Bridges
Ductile Components

- Tension Members - Yielding in Gross Section and Prevented from Fracture and Block Shear Rupture
- Compression Members - Inelastic Flexural Buckling
- Flexural Members/Beam-Columns
  - Moment -Curvature Analysis
  - Expected Material Properties
  - Residual Stress
  - Out-of-Straightness

Steel Bridges
Capacity-Protected Components
Connections and Splices

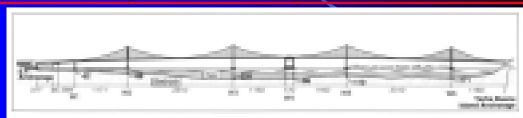
- Design to Resist Capacities of Members Spliced/Connected
  - Ductile Member - Overstrength
  - Capacity-Protected Members - Design Strength
- Yielding in Gross Section - Governing Failure Mode
- No Fracture and Block Shear Rupture

Steel Bridges
Capacity-Protected Components
Gusset Plate Connections

Shear-Moment-Axial Load Interaction

$$\frac{M}{M_n}+\left(\frac{P}{P_y}\right)^2+\frac{\left(\frac{V}{V_n}\right)^4}{\left[1-\left(\frac{P}{P_y}\right)^2\right]}=1$$

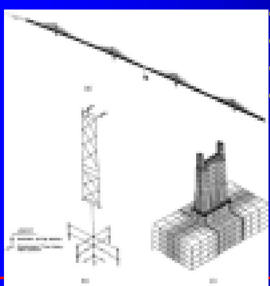
San Francisco-Oakland Bay Bridge West Span Retrofit



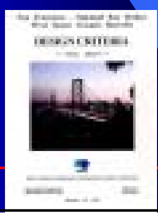
- Total Length = 3, 085 m – Double Deck - 5 Traffic Lanes, Completed in 1937
- Continuous Truss Spans = 262 m
- Two Suspension Spans = 2,823 m
- Main Span = 704 m, Side Span = 353.6 m

52

San Francisco-Oakland Bay Bridge West Span Retrofit



- Project Specific Criteria
- Two Level Design
- Safety and Functionality
- 3-D Time History Analysis



53

San Francisco-Oakland Bay Bridge West Span Retrofit

Seismic Retrofit Completed in 2004

54

9


San Francisco-Oakland Bay Bridge West Span Retrofit
Superstructure Retrofit
55


San Francisco-Oakland Bay Bridge West Span Retrofit
Superstructure Dampers
56


San Francisco-Oakland Bay Bridge West Span Retrofit
Tower Retrofit


San Francisco-Oakland Bay Bridge West Span Retrofit
Central Anchorage Pier 4 Retrofit
58


San Francisco-Oakland Bay Bridge West Span Retrofit
Pier Pedestals Retrofit
59


SUMMARY
● Evolution of Seismic Design
● Seismic Performance Criteria
● Current Seismic Design
● Concrete Bridges
● Steel Bridges
THANK YOU