Vibration Control and Benchmark Problems on Bridges

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Atigre, Kolhapur
Bridges on Konkan Railways
Catastrophic Failures of ‘Lifeline’ structure !!!
Catastrophic Failures

Collapse of 18-Span Fuji Hanshin Expressway
1995 Kobe Earthquake

Premature Shear Failure of RC Columns Resulted from Insufficient Development Length

Shear Failure

Insufficient Confinement
Seismic Design Approach

Traditional

- Fixed to ground
- Amplification of Acceleration
- Structural and Non-structural Damage
- Capacity is increased to meet the demand

With controllers

- Seismic demand reduced
- Reduced deck accelerations and drifts
- Deck is decoupled from substructure
- No non-structural damage
- Seismic and wind control
- Suitable for retrofitting
Conventional Design Approach..

- Structures: To resist earthquake through strength, ductility & energy absorption
- Earthquake / Wind Excitations: Inelastic deformation of a structure by formation of plastic hinges
- Emphasis on increasing strength of structure to resist earthquake induced forces.
- **Allow damages.. prevent collapse.**
- Design forces considered are very small compared to the actual Earthquake forces.
- \( \Delta_{\text{design}} \ll \Delta_{\text{actual}} \). Permanent deformations through yielding
0.2 \leq T \leq 1.2 \text{ sec.} - \text{Close to the pre-dominant periods of earthquake induced ground accelerations: results in amplification of response.}

Bridges: Extremely vulnerable to damage – Relatively large deck mass supported by slender columns. Large displacements - large shear forces in the piers

Effort of protection of bridges against earthquakes: Focused on minimizing shear forces transmitted to piers.
Vibration Control of Structures

- Dynamic loading on Bridges due to Earthquakes, high-wind, barge impact, blast, flood
- Masonry, concrete (RCC & PSC) and steel provide a large amount of structural stiffness.
- Provide very little damping
- An alternate seismic design philosophy ensuring life-safety during strong earthquakes, minimum damage to the structural system: Vibration control
Transfer the vibration energy of the main structural system to an auxiliary oscillator system (Isolator/ Damper / STU).
Reduce the flow of input excitation energy in to the main structural system.
Subject the structure to additional damping.
Prevent the Bridge from exhibiting resonance due to an external excitation.
Provide a structural system with controllable forces.
Classification of controlled structures

- Conventional Structures
  - Beam, Column
  - Frame & Shear walls
  - Shear Wall, Bracing

- Passive Vibration Control
  - Base Isolation
    - Viscous Damper
    - Mass Damper Absorber

- Semi-Active and Active Vibration Control
  - Active Mass Driver
  - Active Tendon
  - Active Stiffness Adjustable System
Limitations of existing international codes and standards for Vibration control on structure.

If Mass (Ms) & Stiffness (Ks) are both doubled, response is halved approximately.

On the other hand An auxiliary damper with a mass 

\[ M_d = \left[ \frac{M_s}{300} \right] \] can reduce the response by 50%.
Passive Control Devices: Isolators

**Merits:**
- Simple, stable, with fixed properties.
- Forces developed at the location of the device.
- No energy added to the structure
- Independent functioning without external power supply
- Isolation systems: Elastomeric and friction type

**Demerits:**
- Control force depends only on the local information.
- Unable to adapt to structural changes and varying loading conditions
- Limited effectiveness when the structure is founded on soft ground.
Base Isolation: Aseismic design philosophy

- Seismic isolation: separation of upper structure from base (Buildings) or from down structure (substructure of bridges / staging of ESR)
- Flexibility is increased by inserting additional elements in structure, known as *isolators*.
- Time Period of the total System is Elongated
- The structure remains operational after a major earthquake
- The isolator behaves as **Rigid** system under Wind or Minor Earthquake and as **Flexible** system under severe earthquake
Merits of Seismic Isolation

- Seismic isolation system absorbs larger part of seismic energy.
- Therefore, vibration effects of soil to upper structure are drastically reduced.
- Forces, accelerations and drifts are substantially reduced.
- During a Richter 8 Earthquake, a seismically isolated bridge will behave as if it was experiencing a 5.5 earthquake.
- Safest or most cost effective ways of designing a structure in a highly seismic zone.
The American River Bridge installed with FPS
I-40 Mississippi River Bridge: Memphis, Tennessee
Infinity bridge-Tuned Mass Dampers
Lead rubber bearing (1975) New Zealand Bearing

- Steel Shims: Provide high vertical stiffness to support structure weight while limiting lateral bulging of rubber
- Rubber Layers: Provide lateral flexibility - Low horizontal stiffness
- Lead plug: Provides source of energy dissipation
- Provide 10 to 30% damping
- Large shear deformation capacity
- Self - centering
- Life ~ 50 years
Full-Scale Bearing Prior to Dynamic Testing

1.3 m (4.3 ft)

25.4 cm (10 in.)
Shear Deformation of Elastomeric Bearing

Deformed Shape

Load Cell
Linear Mathematical Model for Rubber Bearings

\[ P(t) = k_{\text{eff}} u(t) + c_{\text{eff}} \dot{u}(t) \]

- \( k_{\text{eff}} \) = Effective stiffness at design displacement
- \( c_{\text{eff}} \) = Effective damping coefficient associated with design displacement
Elastomeric Bearing Hysteresis Loops

Diagram showing the relationship between shear force, axial force, displacement, and different types of elastomeric bearings (Lead-Rubber Bearing, High Damping Rubber Bearing, Low Damping Rubber Bearing).

- Shear Force
- Axial Force
- Displacement

Different colors and lines represent various bearing types and their hysteresis loops.
Spherical Sliding Bearing: Friction Pendulum System (FPS)

Concave Plate and Slider for FPS Bridge Bearing
- Seismic retrofit of Benicia-Martinez Bridge, San Francisco, CA
- 7.5 to 13 ft diameters
- Displ. Capacity of 13 ft bearings = +/- 4.3 ft
Idealized FPS : Hysteresis Loop

**Diagram Explanation:**
- **Shear Force** and **Axial Force** are shown with a displacement indicating the hysteresis loop.
- The diagram illustrates the relationship between force, displacement, and effective stiffness ($K_{eff}$).
- The equation for force ($F$) is given as:
  \[ F = \frac{W}{R} u + \mu W \, \text{sgn}(u) \]
Computer Software for Analysis of Base-Isolated Structures

- ETABS: Linear and nonlinear analysis of buildings
- SAP2000: General purpose linear and nonlinear analysis
- DRAIN-2D: Two-dimensional nonlinear analysis
- 3D-BASIS: Analysis of base-isolated buildings
Consists of describing the structure in terms of ‘system parameters’ such as mass and stiffness.

The mathematical formulation to calculate the response of the system is done using **STATE SPACE method**.

This method analyzes the response of the system using both displacement and velocity as independent variables: called as states.
Consists of a piston in the damper housing filled with compound of silicone.

The damper dissipates the energy through the movement of a piston in highly viscous fluid, using the concept of fluid orificing.
Semi – Active Control

- Semi-active control uses the building’s response and a feedback feature to develop control forces
- Requires a small power source
- Variable stiffness
- Variable damper
  - Friction
  - Fluid
Semi – Active Control Devices

- Variable Stiffness Devices
- Controllable Friction Devices
- Variable Orifice Dampers
- Controllable Fluid Dampers and
- Controllable Tuned Mass/Tuned Liquid Dampers
Hydraulic dampers - Arasu Bridge - Fukuoka

Photo 1: Hydraulic damper at the Arasu Bridge, Fukuoka

Photo 2: Viscous-shear type damper at the Meiko-Central Bridge, Nagoya. The elastic seal material is also inserted under the anchorage cover to reduce bent of cable.
Magnetorheological Damper

- Major part of SA Control system.
- Use MR fluids for producing control force.
- MR fluids consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium (silicon oil).
- When exposed to magnetic field, align along the magnetic flux.
- Very low power requirement (less than 50W)
- Low voltage (5-12V).
Objective : To identify most promising control strategy for alleviating dynamic response of structure

Direct comparison of effectiveness of competing control strategies applied to the test-bed structure (Building / Bridge)

Response : Measured to standardized set of loads : In terms of defined performance indices.

Provide systematic way to evaluate newly developed control strategies
Benchmark Problems

- Seismically excited nonlinear buildings (Ohtori et al., 2004)
- Wind-excited tall buildings (Yang et al., 2004)
- Earthquake-excited Cable-Stayed bridge (Dyke et al., 2003)
- Benchmark Highway Bridge (Agrawal et al., 2005)
Choice of Control System

- Important Features of the structure
- Height, plan dimensions, symmetry / asymmetry of the building
- Total span of the bridge, continuous / simply supported spans
- Number of continuous spans
- Seismic Zone
- Frequency of vibration: Past records
**Benchmark Highway Bridge**

- Case I: Bridge deck fixed to outrigger and isolated at the abutments (16 control devices); Case II: Bridge deck also isolated at the outrigger (20 control devices)

- Located near two major faults (~ 20 km): strong seismic considerations

- Two span-four lane continuous PC Highway bridge with skewed abutments

- Six real bi-directional earthquake ground motions

- Evaluation criteria: Deck displacement and acceleration, Pier base shear etc.
Phase I: Bridge deck fixed to outrigger and isolated at the abutments. (control devices =16)

Phase II: Bridge deck also isolated at the outrigger (control devices=20)

Located near two major faults (~ 20 km)

Two span - four lane continuous Highway bridge with abutments skewed at 33°

Bridge deck : 3 cells PC box girder , Central bent : PC outrigger

Total mass of the bridge = 4,237,544 kg , Mass of deck = 3,278,404 kg

Actual bridge : At each abutment : 4 traditional non-seismic elastomeric pads and 4 viscous fluid dampers

Effect of Soil structure interaction is considered

Nonlinear Evaluation model : 430 DOFs (Phase I); 442 DOFs (Phase II)

Uncontrolled response : Bridge with LRBs at each deck end-abutment junction

T= 0.813 sec

Six real bi-directional earthquake ground motions
Various controllers

- **Sample Passive Control**: Nonlinear fluid viscous dampers
- **Sample Semi-active Control**: MR dampers
- **Sample Active Control**: Ideal hydraulic actuators
- **Maximum device capacity**: 1000 kN
- **16 Dampers**: ~50% control force of the deck mass
- **20 Dampers**: ~62% control force of the deck mass
- **Other isolators used**: FPS, VFPS, VFPI,
- **Other dampers used**: Viscous dampers, Variable dampers, Piezo-electric friction dampers, Pseudo-negative stiffness dampers.
Nonlinear fluid viscous dampers (1000 kN)

- 8 Dampers provide ~ 50% control force of the deck mass
- 10 Dampers provide ~ 62% control force of the deck mass

Due to additional control devices at the center:

- Substantial reduction in pier base shear, base moment and mid-span acceleration
- Large increase in mid-span deck displacement and isolator displacement
Evaluation Criteria and Earthquake Ground Motions

- Defined to evaluate functionality of the controller
- [Controlled response / Uncontrolled response] smaller values: superior performance of the device
- Evaluated in the Longitudinal (EW) and Transverse (NS) direction
- Peak responses and Normed responses

\[ \|\bullet\| = \sqrt{\frac{1}{t_f} \int_0^{t_f} (\bullet)^2 \, dt} \]

- Six earthquake ground motions: Represent global spectrum in terms of PGA, PGV, and soil properties.
  - North Palm Springs (1986)  
  - Chi-Chi (1999)
  - El Centro (1940)  
  - Northridge (1994)
  - Turkey (1999)  
  - Kobe (1995)
FPS : SIMULINK model

(Hysteretic model of frictional force of a sliding system)
Sliding isolators: Schematic diagram and Mathematical model
Force - displacement loops: Chi-Chi (1999)
Bearing displacement Time History: Chi-Chi (1999) Earthquake

- Uncontrolled (0.153 m)
- Friction (0.02 m)
- Nonlinear Friction (0.011 m)
- Two-Step Friction (0.014 m)
Comparison: Peak base shear

The chart compares the peak base shear for different control strategies and earthquake events. The control strategies include Samp, PA, Samp SA, Samp AC, Ali-FLC, FPS, VFPS, and PNS. The earthquake events are North Palm Springs (1986), Chi-Chi (1999), El Centro (1940), Northridge (1994), Turkey (1999), and Kobe (1995). The chart shows the peak base shear values for each strategy and event.
Comparison: Peak Isolator displacement

The graph compares peak isolator displacement for different control strategies and earthquakes. The x-axis represents the control strategy, and the y-axis shows the peak isolator displacement. The strategies include Samp PA, Samp SA, Samp AC, Ali-FLC, FPS, VFPS, and PNS. The earthquakes are North Palm Springs (1986), Chi-Chi (1999), El Centro (1940), Northridge (1994), Turkey (1999), and Kobe (1995).
Benchmark Cable Stayed Bridge

- Control of cable stayed bridges: Unique and Challenging problem
- 2nd international workshop on Structural control (Hong Kong, 1996): Group formed to develop a benchmark control problem for bridges
Benchmark cable stayed bridge

Bill Emerson Memorial bridge
Benchmark Cable Stayed Bridge

- Three earthquake records and wind loads
- Base shear and base moment in the longitudinal and transverse direction
- Deck shear and deck moment in the longitudinal and transverse direction
- Evaluation criteria: Cable tension, Deck displacement, base shear in pylons
Missouri Cable Stayed Bridge
**Benchmark Bridge Model**

- Under construction in Cape Girardeau, Missouri, USA.
- To be completed in 2003.

- Missouri Side
  - 350 m main span
  - 142 m side span
  - 128 Cables

- Illinois Approach
  - 12 additional piers
  - 570 m
Benchmark Bridge Model

- Longitudinal excitation applied simultaneously.
- For proposed controllers, designers must define:
  - Sensor models and locations
  - Device models and locations
  - Control algorithm

\[ K(s) \]
Earthquakes Used

- El Centro
  PGA = 0.36g
- Gebze Turkey
  PGA = 0.26g
- Mexico City
  PGA = 0.14g
**Evaluation Criteria**

- **Peak Responses** ($J_1 - J_6$)
  - Base shear
  - Overturning moment
  - Cable tension
  - Deck displacement at abutment
  - Shear at deck level
  - Moment at deck level

- **Normed Responses** ($J_7 - J_{11}$)
  - Base shear
  - Overturning moment
  - Cable tension
  - Shear at deck level
  - Moment at deck level

- **Control Strategy** ($J_{12} - J_{18}$)
  - Peak control force and device stroke
  - Peak and total power required
  - Number of control devices and sensors
Seismic Control System
Using MR Dampers

- **Sensors**
  - Five accelerometers
  - Four displacement transducers
  - 24 force transducers for measuring control forces

- **Control Devices**
  - 24 MR dampers (capacity: 1000 kN/each)
Dynamic Models of MR Dampers

- Models for small-scale dampers
  - Bingham model (Stanway et al. 1985, 1987)
  - Simple Bouc-Wen model (Spencer et al. 1997)
- Model for large-scale damper
  - Modified Bouc-Wen model (Spencer et al. 1997)

24 MR Dampers: 1000 kN Capacity
### Optimized Parameters of Dynamic Model for MR Dampers

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Dynamic Degrees of Freedom

Reduced Order Model with 30 States
Control Strategy for Semiactive Control
Time-History Response: Base Shear Force

- El Centro earthquake: 71% reduction in peak
- Mexico City earthquake: 54% reduction in peak
- Gebze Turkey earthquake: 64% reduction in peak
Conclusions

- **First generation structures**: without any code / systematic procedures
- Design and analysis procedure for **Second Generation Structures** is available. Still, catastrophic failures are observed in severe earthquake attacks.
- Based on the performance of conventionally designed structures, there is a need for **Third Generation structures**.
  Practically: use of isolators (LRB and FPS) and limited applications (Viscous and MR) of dampers in the world.
Conclusions

- Vibrations: Seismic and wind
- Experimental validation of devices is necessary
- Inclusion of clauses in IS codes
- Newly developed control devices can be implemented in constructions.
- Devices can be used for retrofitting of existing structures.
- Commonly used isolators: LRB, FPS
- Commonly used dampers: Viscous dampers, Visco-elastic dampers, Friction dampers.
Thank you..