Structural Control: Introduction and Fruitful Research Areas

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Active (Responsive) Structures

Under Normal Load

Load → Structure → Response

$$m\ddot{x} + c\dot{x} + kx = f(t)$$

Under Extreme Load

Load → Structure → Response

$$m\ddot{x} + c\dot{x} + kx + \Gamma(x) = F(t)$$

Structural Protective Systems

Passive Systems

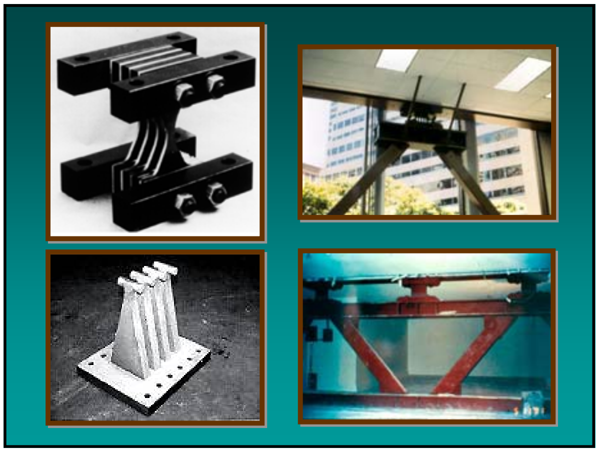
Seismic Isolation
- Elastomeric Bearings
- Lead Rubber Bearings
- Sliding Friction Pendulum

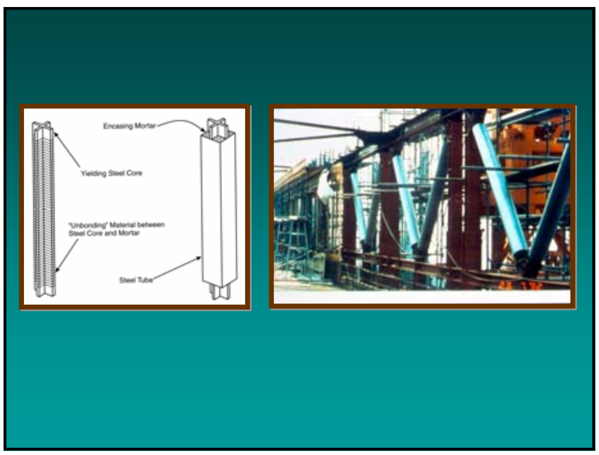
Dampers
- Metallic
- Friction
- Viscoelastic
- Viscous Fluid
- TMD
- TLD

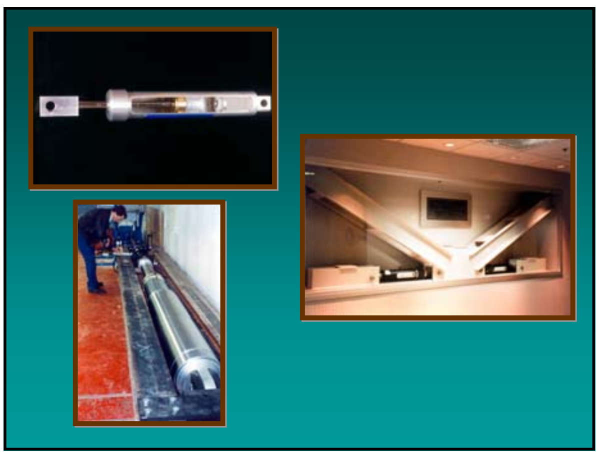
Active and Semi-active Systems

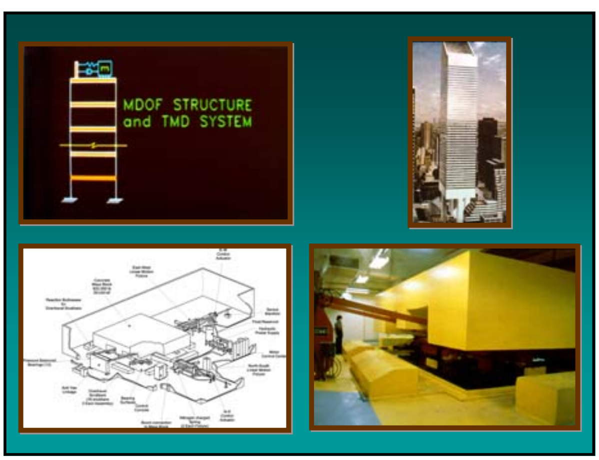
Electro-hydraulic Systems
- Active Bracing
- Active Mass Damper
- Variable Stiffness and Damping

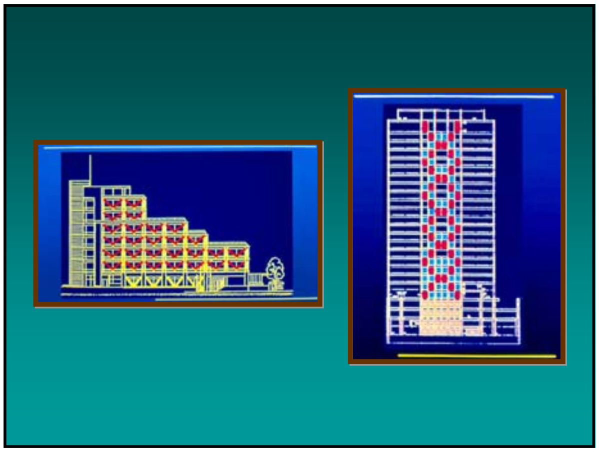
Smart Materials
- Shape Memory Alloy
- Piezoelectric Layer
- ER Fluid
- MR Fluid

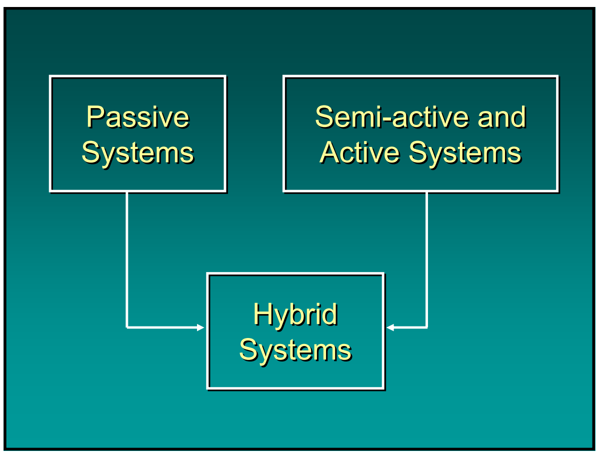


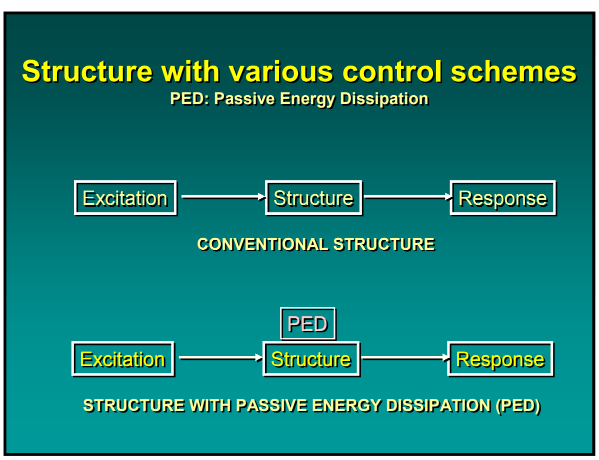

Encasing Mortar
Yielding Steel Core
"Unbonding" Material between
Steel Core and Mortar
Steel Tube

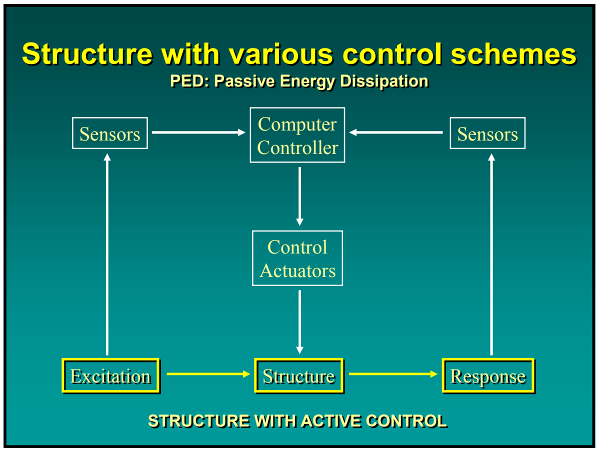


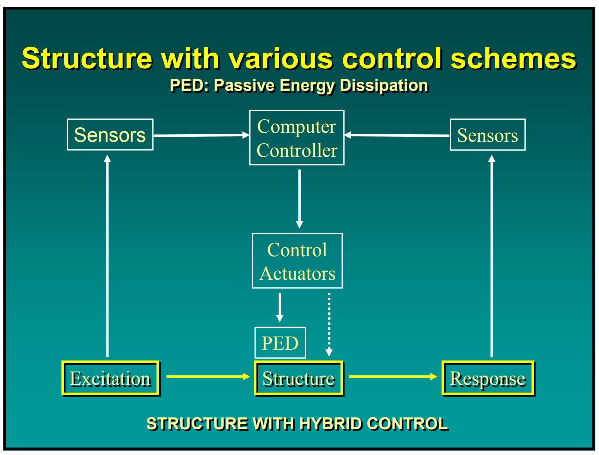

MDOF STRUCTURE
and TMD SYSTEM

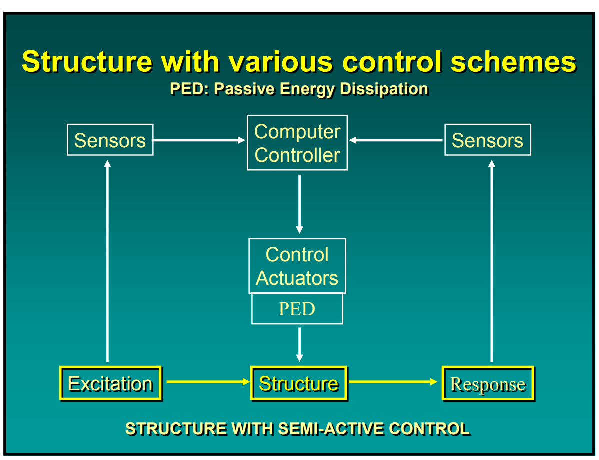



Passive Systems
Semi-active and Active Systems
Hybrid Systems

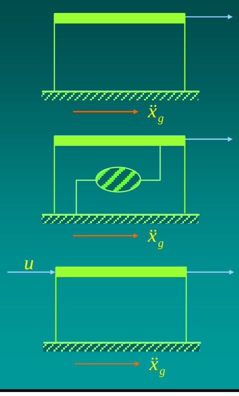

Structure with various control schemes
PED: Passive Energy Dissipation
Excitation
Structure
Response
CONVENTIONAL STRUCTURE
PED
Excitation
Structure
Response
STRUCTURE WITH PASSIVE ENERGY DISSIPATION (PED)


Structure with various control schemes
PED: Passive Energy Dissipation
Sensors
Computer Controller
Sensors
Control Actuators
Excitation
Structure
Response
STRUCTURE WITH ACTIVE CONTROL


Structure with various control schemes
PED: Passive Energy Dissipation
Sensors
Computer Controller
Sensors
Control Actuators
PED
Excitation
Structure
Response
STRUCTURE WITH HYBRID CONTROL


Structure with various control schemes
PED: Passive Energy Dissipation
Sensors
Computer Controller
Sensors
Control Actuators
PED
Excitation
Structure
Response
STRUCTURE WITH SEMI-ACTIVE CONTROL

Basic Principles



Structure

$$m\,\ddot{x} + c\,\dot{x} + k\,x = -\,m\,\ddot{x}_g$$

Structure with Passive Systems

$$m\,\ddot{x} + c\,\dot{x} + k\,x + \Gamma\,x = -\,m\,\ddot{x}_g$$

Structure with Active, Semi-active and Hybrid Control

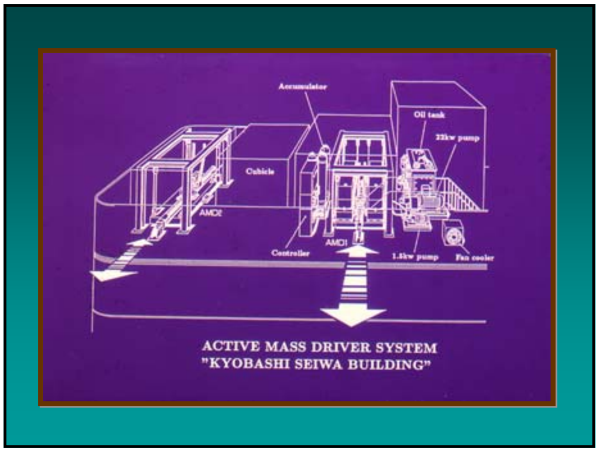
$$m\,\ddot{x} + c\,\dot{x} + k\,x = -\,m\,u - m\,\ddot{x}_g$$

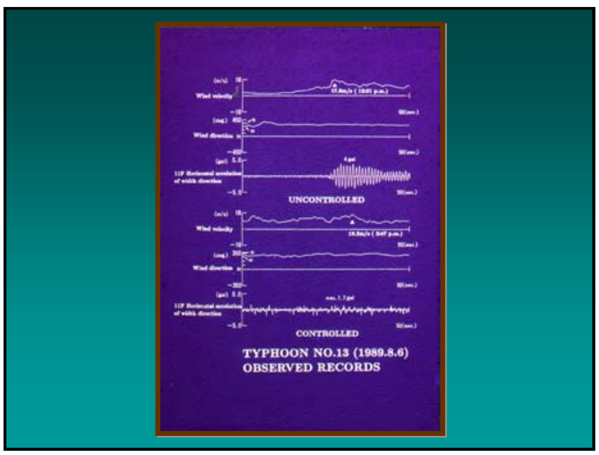
with: $u = \frac{\Gamma\,x}{m}$ we have

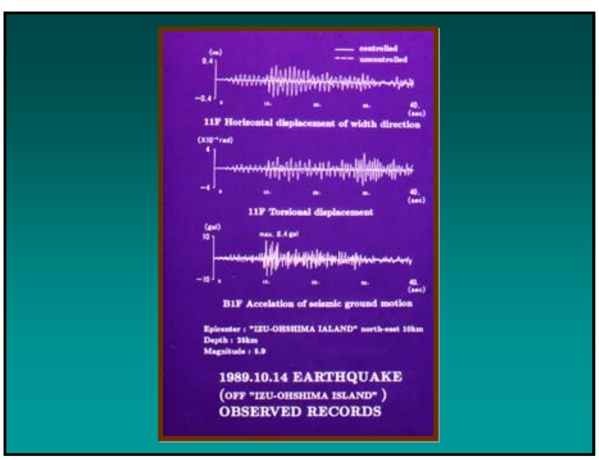
$$m\,\ddot{x} + c\,\dot{x} + k\,x + \Gamma\,x = -\,m\,\ddot{x}_g$$

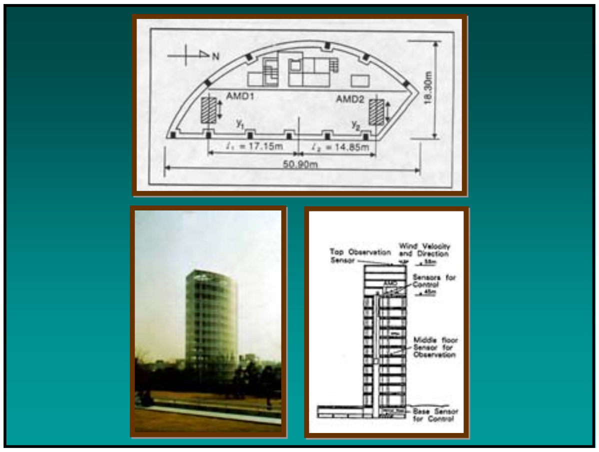
Advantages over Passive Systems

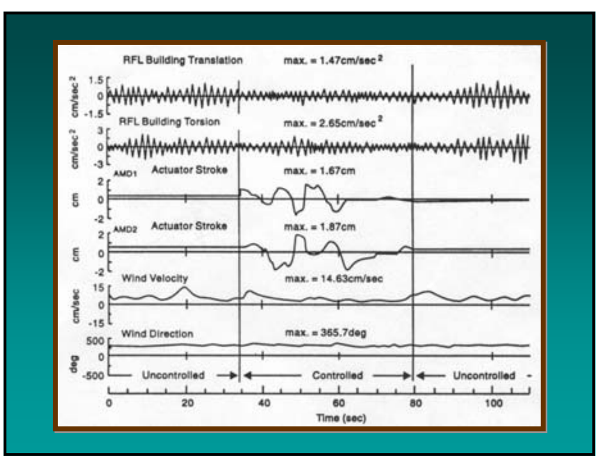
- Adaptability to Load Variability
- Enhanced Effectiveness in Response Modification
- Applicability to Multi-hazard Situations
- Selectivity of Control Objectives

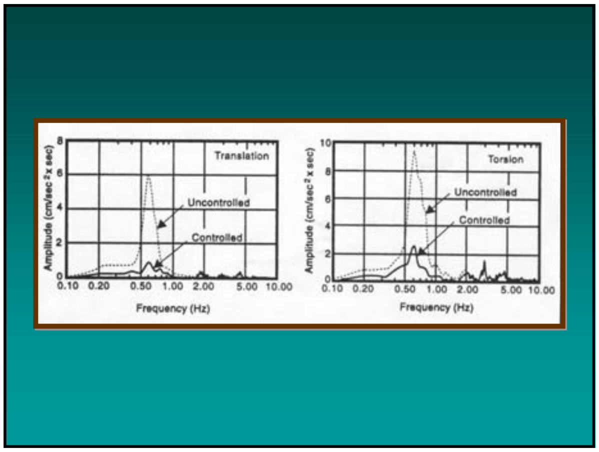

Accumulator
Oil tank
22kw pump
Cubicle
AMD2
AMD1
Controller
1.5kw pump
Fan cooler
ACTIVE MASS DRIVER SYSTEM
"KYOBASHI SEIWA BUILDING"

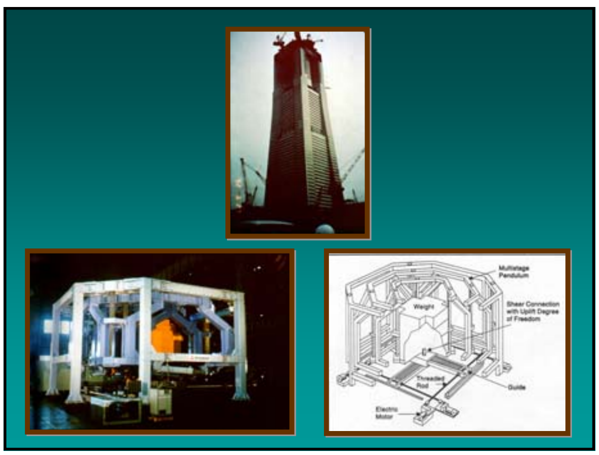

Wind velocity
Wind direction
UNCONTROLLED
Wind velocity
Wind direction
CONTROLLED
TYPHOON NO.13 (1989.8.6)
OBSERVED RECORDS

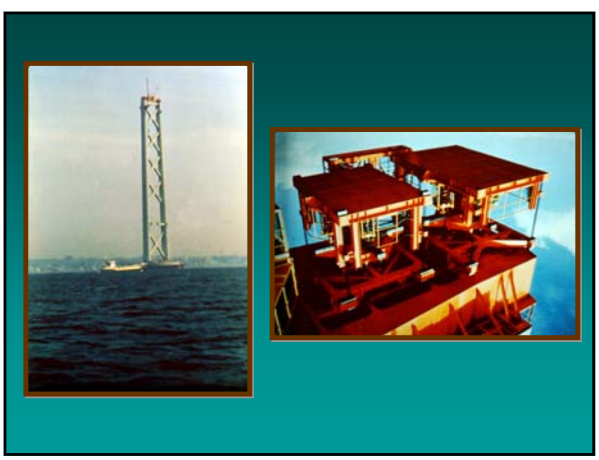

controlled
uncontrolled
0.4
−0.4
40.
(sec)
11F Horizontal displacement of width direction
4
−4
40.
(sec)
11F Torsional displacement
(gal)
−10
40.
(sec)
B1F Accelation of seismic ground motion
1989.10.14 EARTHQUAKE
(OFF "IZU-OHSHIMA ISLAND")
OBSERVED RECORDS

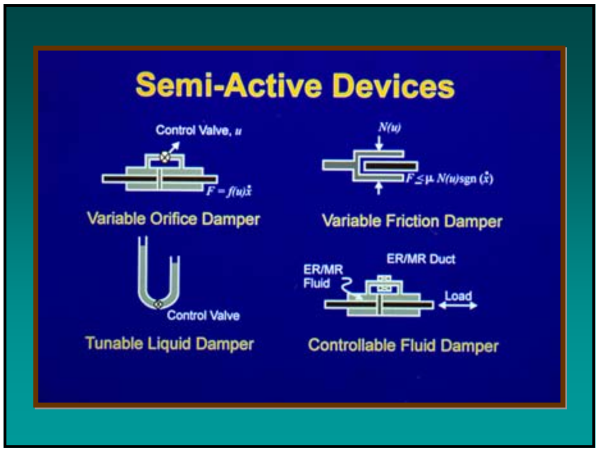

N
AMD1
AMD2
18.30m
17.15m
14.85m
50.90m
Top Observation Sensor
Wind Velocity and Direction
Sensors for Control
Middle floor Sensor for Observation
Base Sensor for Control

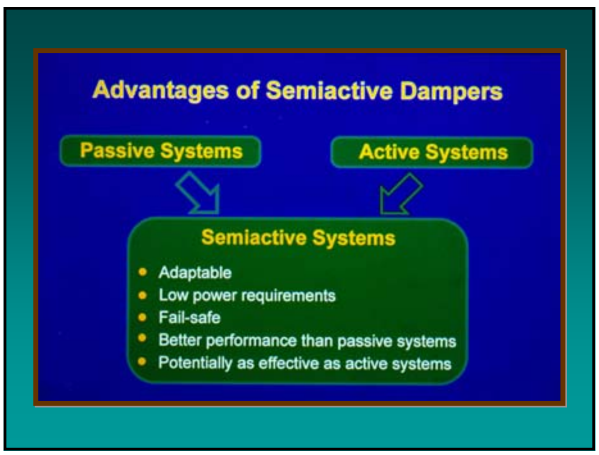

RFL Building Translation
max. = 1.47cm/sec²
RFL Building Torsion
max. = 2.65cm/sec²
AMD1 Actuator Stroke
max. = 1.67cm
AMD2 Actuator Stroke
max. = 1.87cm
Wind Velocity
max. = 14.63cm/sec
Wind Direction
max. = 365.7deg
Uncontrolled
Controlled
Uncontrolled
Time (sec)

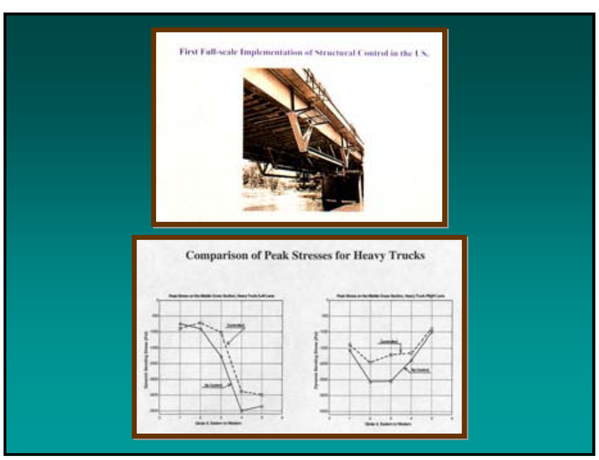

Translation
Uncontrolled
Controlled
Amplitude (cm/sec² x sec)
Frequency (Hz)
Torsion
Uncontrolled
Controlled
Amplitude (cm/sec² x sec)
Frequency (Hz)

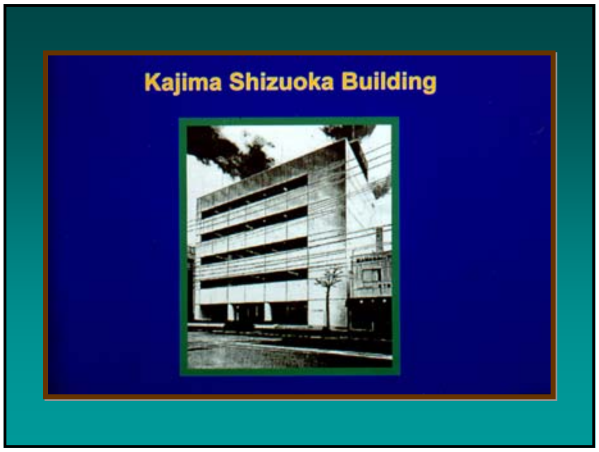

Multistage Pendulum
Weight
Shear Connection with Uplift Degree of Freedom
Threaded Rod
Guide
Electric Motor

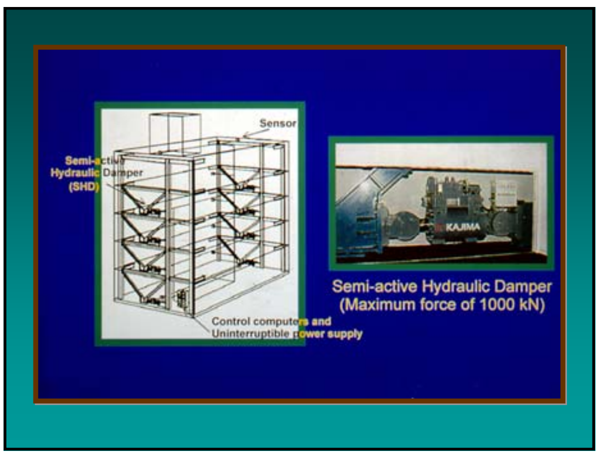


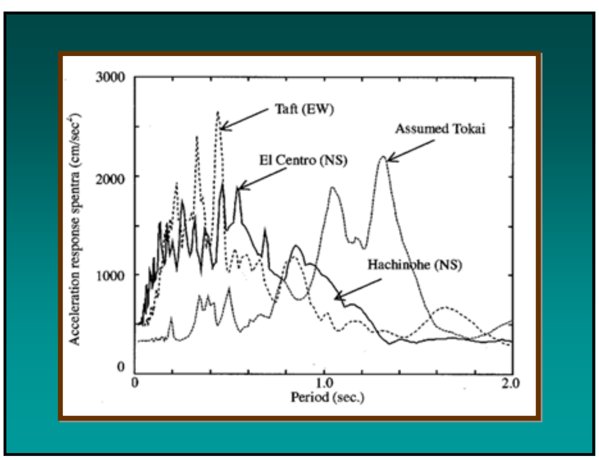

Semi-Active Devices
Control Valve, u
F = f(u)ẋ
Variable Orifice Damper
N(u)
F ≤ μ N(u)sgn (ẋ)
Variable Friction Damper
Control Valve
Tunable Liquid Damper
ER/MR Duct
ER/MR Fluid
Load
Controllable Fluid Damper

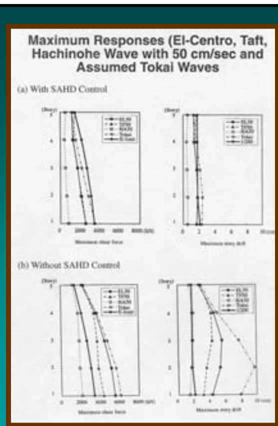

Advantages of Semiactive Dampers
Passive Systems
Active Systems
Semiactive Systems
Adaptable
Low power requirements
Fail-safe
Better performance than passive systems
Potentially as effective as active systems

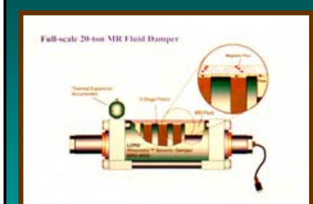

First Full-scale Implementation of Structural Control in the U.S.
Comparison of Peak Stresses for Heavy Trucks

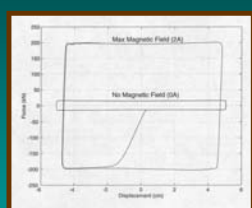

Kajima Shizuoka Building

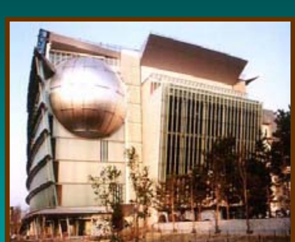

Sensor
Semi-active Hydraulic Damper (SHD)
Control computers and Uninterruptible power supply
KAJIMA
Semi-active Hydraulic Damper (Maximum force of 1000 kN)


Taft (EW)
Assumed Tokai
El Centro (NS)
Hachinohe (NS)
Acceleration response spectra (cm/sec²)
Period (sec.)
3000
2000
1000
0
0
1.0
2.0

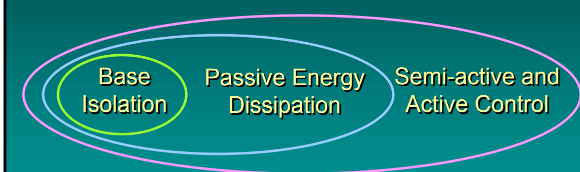

Maximum Responses (El-Centro, Taft, Hachinohe Wave with 50 cm/sec and Assumed Tokai Waves
(a) With SAHD Control
(b) Without SAHD Control


Full-scale 20-ton MR Fluid Damper


Max Magnetic Field (2A)
No Magnetic Field (0A)



Applicability of Newer Technologies



Impact

1. Structural Response Control
   - Structural Safety and Reliability
   - Natural Hazard Mitigation
   - Creative Engineering
2. Education
   - Interdisciplinary Approach
   - Innovation

Assessment

- Fundamentally Sound and Innovative
- Natural Evolution from Passivity to Adaptability
- Insensitivity to Load Variables
- Application to Other Extreme Loads
- Open to New Possibilities
  - Multi-purpose, Multi-functional
  - Longer, Taller, more open

Fruitful Research Areas

- ❑ Implementation of Structural Control Technology
- ❑ Critical Facilities and Contents
- ❑ Integrated Design

Theory:
- ❑ Algorithm Development
- ❑ Device Development
- ❑ Experiment
- ❑ Benchmark Studies

Theory:

- ❑ Algorithm Development
- ❑ Device Development
- ❑ Experiment
- ❑ Benchmark Studies

Practice:

- ❑ Algorithm Development
- ❑ Device Development
- ❑ Experiment
- ❑ Benchmark Studies

❑ Implementation-Related Issues

Frequently Asked Questions

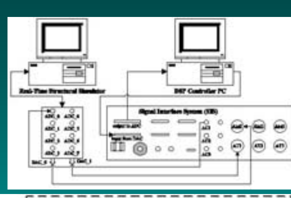
- ❑ Reliability
- ❑ Verification of Control Performance
- ❑ Cost

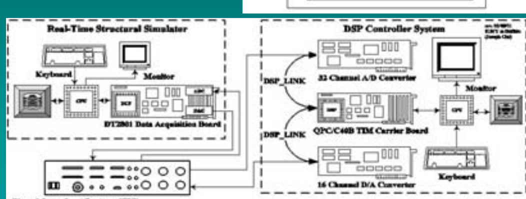
Contents

Computer-aided Control Performance Verification (CPV)

CPV

- Sampling Period of RTSS (T_s)
- Sampling Period of DSP Controller (T_u)
- Total Delay Time (t_d)
- Scaling Factors



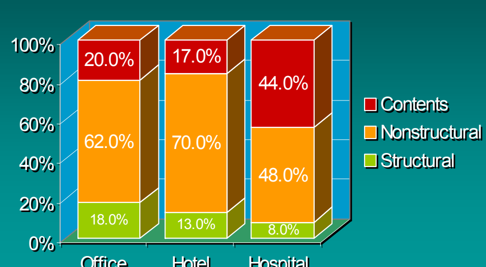


- Critical Facilities and Contents

Examples of Nonstructural Components

- Architectural Partitions
- Piping Systems
- Ceilings
- Mechanical and Electrical Equipment
- Exterior Cladding
- Contents

Investments in Building Construction (Miranda)



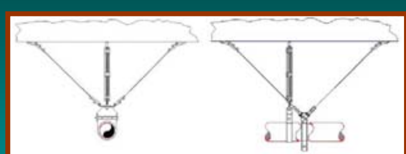
Direct Economic Loss due to Building Damage

- 1994 Northridge Earthquake (Kircher, 2003)
  Total: $18.5 Billion
  Nonstructural Related: ~ 50%

- 1994 Northridge Earthquake (Kircher, 2003)
  (Non-residential Buildings)
  Total: $6.29 Billion
  Nonstructural Related: $5.20 Billion (83%)

Improved Nonstructural Performance

- Better Engineered Conventional Anchors



Improved Nonstructural Performance

- Better Engineered Conventional Anchors (continued)

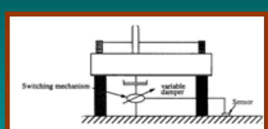
Improved Structural Performance

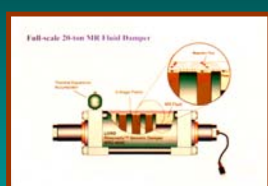
Nonstructural System	As Constructed	With Damping System	% Benefit	With Isolation System	% Benefit
	Economic Loss (in millions)				
Drift-related	$1,086	$ 407	63	$ 303	72
Acceleration-related	1,952	1,013	48	777	60
Contents/Inventory	2,162	1,124	48	862	60
Total	$5,200	$2,544	51	$1,942	63

Reduction in direct economic loss through improved building performance of non-residential buildings (adapted from Kircher, 2003)

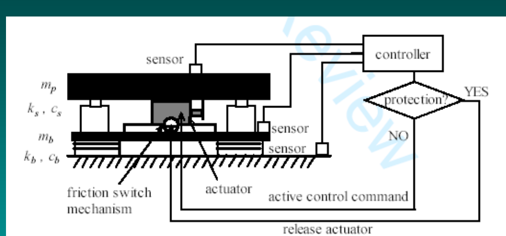
Improved Nonstructural Performance

- Newer Technologies (continued)



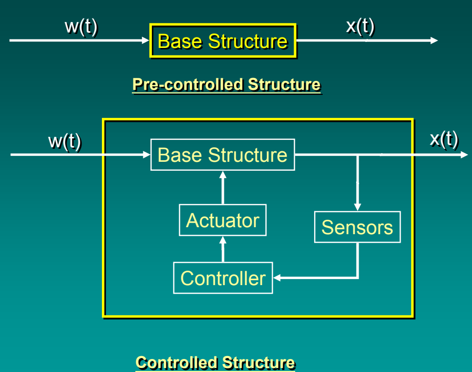


Semi-active device (Rana and Soong, 2004)



Configuration of a Hybrid platform (Xu and Li, 2005)

- Integrated Control/Structural System



A. Variational approach

Equation of motion:

$$\dot{\mathbf{z}}(t) = \mathbf{A}(\xi)\mathbf{z}(t) - \tilde{\mathbf{B}}(\xi)\tilde{\mathbf{f}}_S(\mathbf{z}) + \mathbf{B}(\xi)\mathbf{u}(t) + \mathbf{e}(t,\xi)$$

Problem:

Determine ξ and u(t) such that performance objective is achieved by, for example, minimizing

$$J(\mathbf{z},\xi,\mathbf{u}) = \int_0^{t_f} \left[\mathbf{z}^T\mathbf{Q}\mathbf{z} + \mathbf{u}^T\mathbf{R}\mathbf{u} + \gamma W(\xi,\mathbf{u}) \right] dt$$

Subjected to constraints such as:

$$\xi \geq \xi_s$$

A. Variational approach

Variational Calculus leads to:

$$\mathbf{Az} + \mathbf{Bu} - \tilde{\mathbf{B}}\tilde{\mathbf{f}}_S + \mathbf{e} - \dot{\mathbf{z}} = \mathbf{0}, \quad \mathbf{z}(0) = \mathbf{0}$$

$$2\mathbf{Qz} + \mathbf{A}^T\boldsymbol{\lambda} + \dot{\boldsymbol{\lambda}} = \mathbf{0}, \quad \boldsymbol{\lambda}(\mathrm{t_f}) = \mathbf{0}$$

$$2\mathbf{Ru} + \mathbf{B}^T\boldsymbol{\lambda} = \mathbf{0}$$

$$\boldsymbol{\lambda}^T\left(\nabla_\xi \mathbf{Az}\nabla_\xi \mathbf{Bu} - \nabla_\xi \tilde{\mathbf{B}}\tilde{\mathbf{f}}_S + \nabla_\xi \mathbf{e}\right) + \nabla_\xi W = \mathbf{0}$$

Over $t = (0, t_f)$ with $\xi \geq \xi_0$

B. Redesign approach

Equation of motion:

$$\dot{\mathbf{z}}(t) = \mathbf{A}(\xi)\mathbf{z}(t) - \tilde{\mathbf{B}}(\xi)\tilde{\mathbf{f}}_S(\mathbf{z}) + \mathbf{B}(\xi)\mathbf{u}(t) + \mathbf{e}(t,\xi)$$

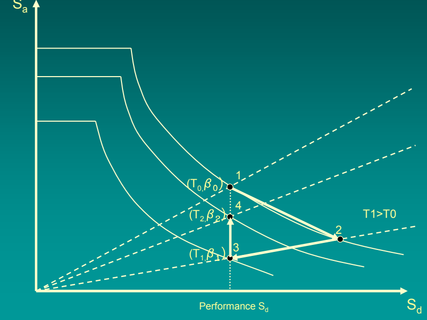
Step 1: Based on desired ξ, determine u(t) such that some structural performance is achieved;

Step 2: Determine optimal ξ and u(t) to achieve same structural performance by, for example, minimizing

$$\int_0^{t_f}\left[\mathbf{u}^T\mathbf{Ru}\right]dt$$

Subjected to constraints on ξ

B. Redesign approach



B. Redesign approach

Consider

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{e}(t)$$

Step 1: Control design based on desired ξ, giving

$$\mathbf{u}(t) = \mathbf{G}\mathbf{z}(t)$$

Step 2: Consider

$$(\mathbf{M}+\Delta\mathbf{M})\ddot{\mathbf{x}}(t) + (\mathbf{C}+\Delta\mathbf{C})\dot{\mathbf{x}}(t) + (\mathbf{K}+\Delta\mathbf{K})\mathbf{x}(t) = \mathbf{H}\mathbf{G}_a\mathbf{z}(t) + \boldsymbol{\eta} w(t)$$

where $\mathbf{u}_a(t) = \mathbf{G}_a\mathbf{z}(t)$

To achieve same performance objective, we have

$$\mathbf{H}\mathbf{G}\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix} = \mathbf{H}\mathbf{G}_a\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix} - [\Delta\mathbf{K} \quad \Delta\mathbf{C}]\begin{bmatrix}\mathbf{x}(t)\\ \dot{\mathbf{x}}(t)\end{bmatrix} - \Delta\mathbf{M}\ddot{\mathbf{x}}(t)$$
$$= \mathbf{H}\left(\mathbf{G}_{active} + \mathbf{G}_{passive}\right)\mathbf{z}(t)$$

B. Redesign approach

where

$$\mathbf{G}_{active} = \mathbf{H}\mathbf{G}_a \qquad \mathbf{G}_{passive} = -\mathbf{I}_0\mathbf{B}_p\mathbf{G}_p\mathbf{B}_p^T\mathbf{L}$$

with

$$\mathbf{K}+\Delta\mathbf{K} = \mathbf{K}+\mathbf{B}_k\mathbf{G}_k\mathbf{B}_k^T \qquad \mathbf{G}_k = diag(\ldots,\Delta k_i,\ldots)$$
$$\mathbf{C}+\Delta\mathbf{C} = \mathbf{C}+\mathbf{B}_c\mathbf{G}_c\mathbf{B}_c^T \qquad \mathbf{G}_c = diag(\ldots,\Delta c_i,\ldots)$$
$$\mathbf{M}+\Delta\mathbf{M} = \mathbf{M}+\mathbf{B}_m\mathbf{G}_m\mathbf{B}_m^T \qquad \mathbf{G}_m = diag(\ldots,\Delta m_i,\ldots)$$

$$\mathbf{B}_p = \begin{bmatrix}B_k & 0 & 0\\ 0 & B_c & 0\\ 0 & 0 & B_m\end{bmatrix} \qquad \mathbf{G}_p = \begin{bmatrix}G_k & 0 & 0\\ 0 & G_c & 0\\ 0 & 0 & G_m\end{bmatrix} \qquad \mathbf{I}_0 = [I \quad I \quad I]$$

and

$$\mathbf{L} = \begin{bmatrix} I \\ \mathbf{M}^{-1}(\mathbf{H}\mathbf{G} - [\mathbf{K} \quad \mathbf{C}])\end{bmatrix}$$

B. Redesign approach

Under mild conditions

$$\mathbf{G}_a = \mathbf{G} + \mathbf{I}_0\mathbf{B}_p\mathbf{G}_p(\Delta\mathbf{M},\Delta\mathbf{C},\Delta\mathbf{K})\mathbf{B}_p^T\mathbf{L}$$

$\mathbf{G}_p$ and $\mathbf{G}_a$ are determined by minimizing, for example,

$$\int_0^{t_f}\left[\mathbf{u}^T\mathbf{R}\mathbf{u}\right]dt$$

Subjected to constraints on ΔM, ΔC, ΔK

Solution can be found by using, for example, Exterior Penalty Function Method

Numerical Example

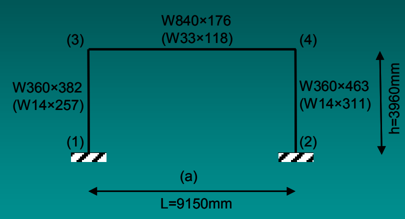


Figure 1. SDOF steel frame under white noise excitation

Numerical Example

Objective: a lighter structure maintaining drift equal to 0.5%

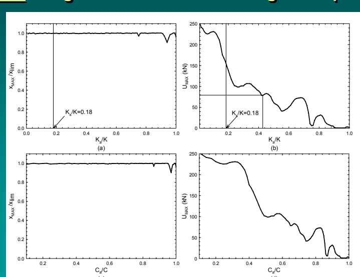


Figure 2. normalized maximum displacement (a) and maximum control force (b) versus normalized structural stiffness and damping (c-d)

Numerical Example

Step 1: Select a reduction of k of 60%

Table 1. Maximum response for white noise with pga of 0.25g

Uncontrolled			U_{max}=94.86kN		
(1)	(2)	(3)	(4)	(5)	(6)
Drift x_i [%]	$\ddot{x}_a$ [m/sec²]	M_{S0} (kg)	Drift x_i [%]	$\ddot{x}_a$ [m/sec²]	M_S (kg)
0.49	11.15	4959.5	0.50	5.81	2775.7

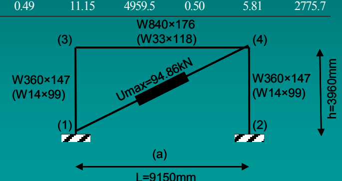


Figure 3. Steel frame under white noise excitation

Numerical Example

Step 2: Redesign subject to

$$\Delta \mathbf{M}/\mathbf{M} \geq -0.25, \qquad \mathbf{K} \geq \mathbf{K}_s = 0.18\mathbf{K}$$

Table 2. Optimal structural parameters after redesign for white noise with pga of 0.25g

M	K	C	M_{opt}	K_{opt}	C_{opt}	U_{opt}
kg	kN/m	kN sec/m	kg	kN/m	kN sec/m	kN
159450	76987.1	140.1	119587	29010.1	59.930	92.434

Table 3. Percentage increment or reduction of structural parameters

ΔM	ΔK	ΔC
(%)	(%)	(%)
-25	-62.3	-39.5

A substantially lighter structure can be designed to achieve a specific performance objective when an active brace is integrated into the structure in an optimal fashion

Advantages

- Easier quadratic mathematical format
- Rapid convergence
- Guarantees optimal control
- Applicable to nonlinear as well as multi-degree-of-freedom structures

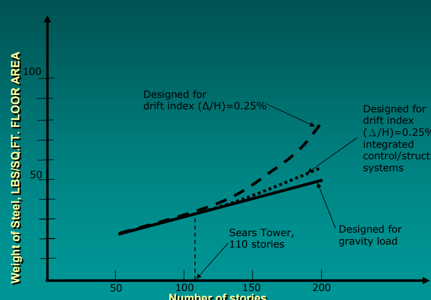
Conclusions

<u>Integrated control/structural systems can lead to:</u>

- New Structural Forms and Configurations;
- Lighter, longer, taller, more open structures;
- Multi-purpose and multi-functional

Sears Tower, Chicago

Integrated design



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