Energy Dissipating devices in Seismic Regions

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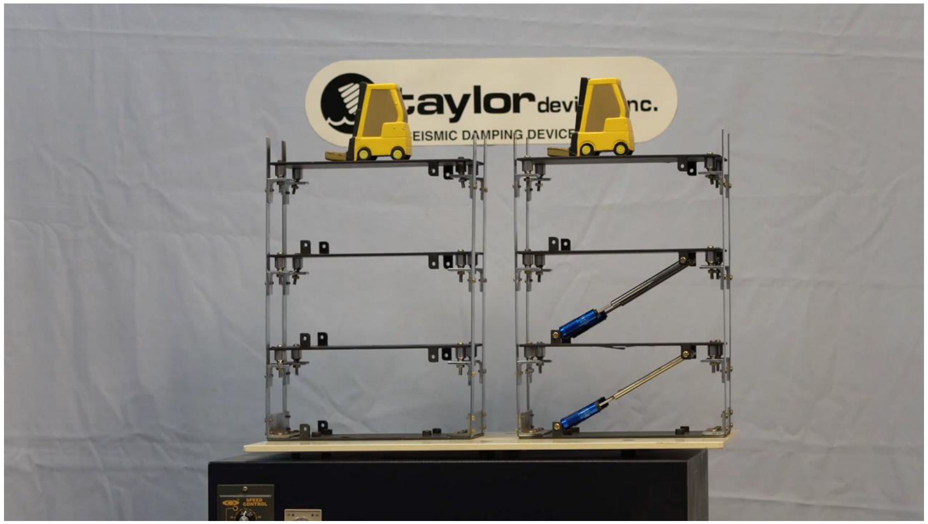
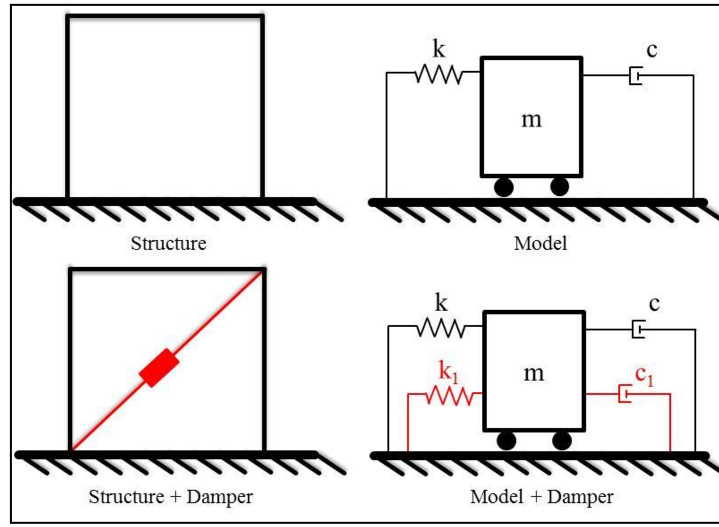
1. Introduction

- What are dissipating devices, also known as “Dampers”?





- Equation of motion

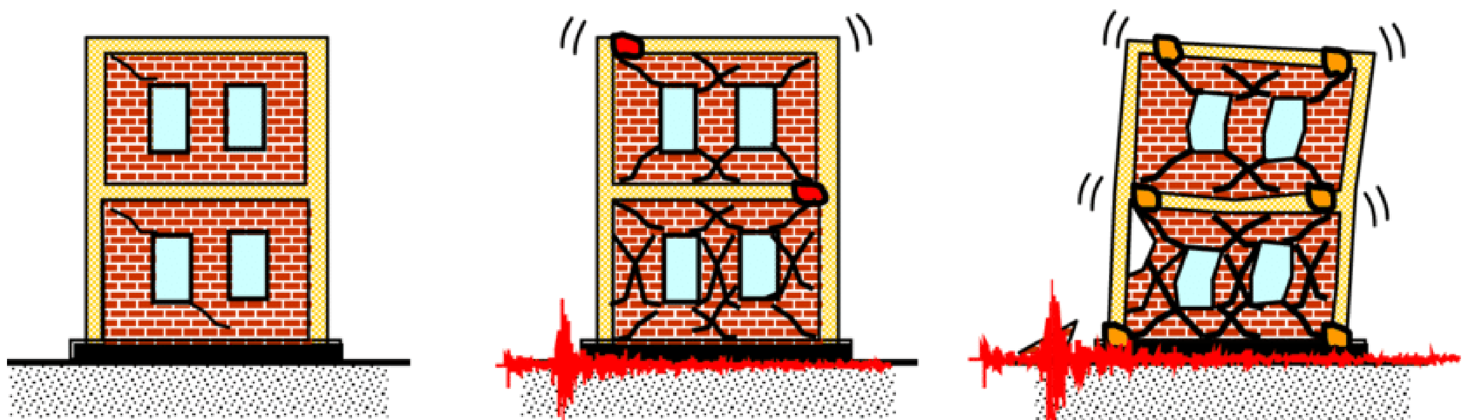
$$x(t) = m \cdot \ddot{x}(t) + c \cdot \dot{x}(t) + k \cdot x(t)$$

$$x(t) = m \cdot \ddot{x}(t) + (c + c_1) \cdot \dot{x}(t) + (k + k_1) \cdot x(t)$$

- Passive and Active dissipating devices → Passive Devices in Buildings

1. Introduction

- State of the art in conventional design: No Collapse



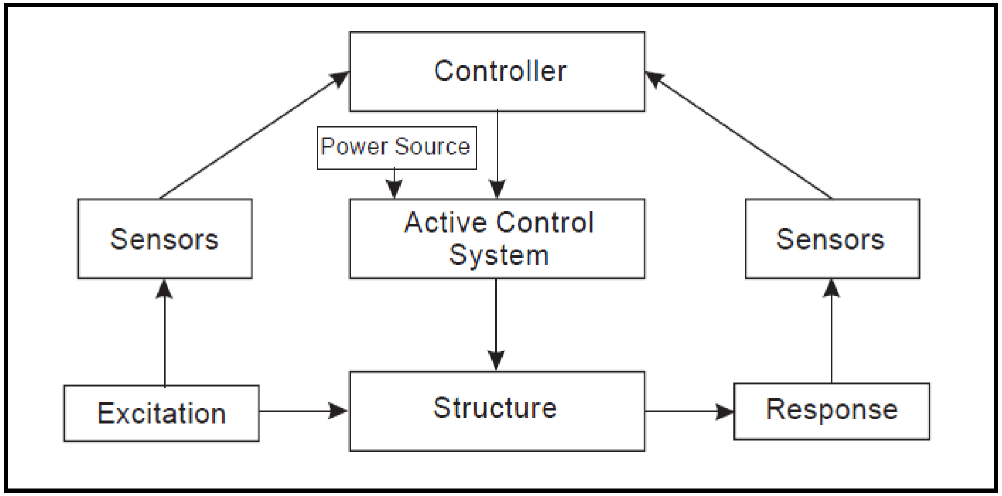
Minor Earthquake | Moderate Earthquake | Strong Earthquake

- Effects of dampers in design:

  - Damage reduction (+)
  - Cheaper structure (+)
  - Devices cost (-)

→ Overall: (+)

2. Active Devices



Elements of an Active Control System (Michael C. Constantinou et al., 1998)

- Active control system
- Semi-active controlled systems
- Hybrid control system

Electricity dependent systems, not the focus of this research.

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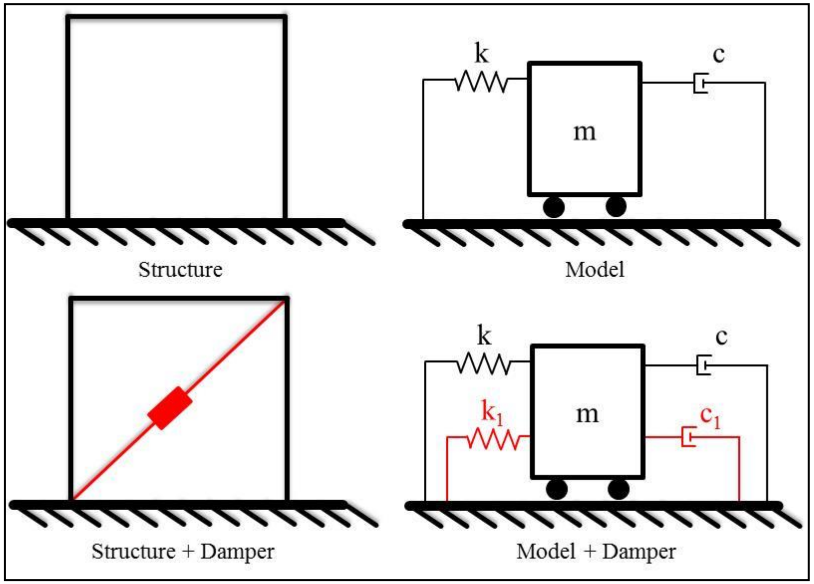
3. Passive Devices

- Definition:



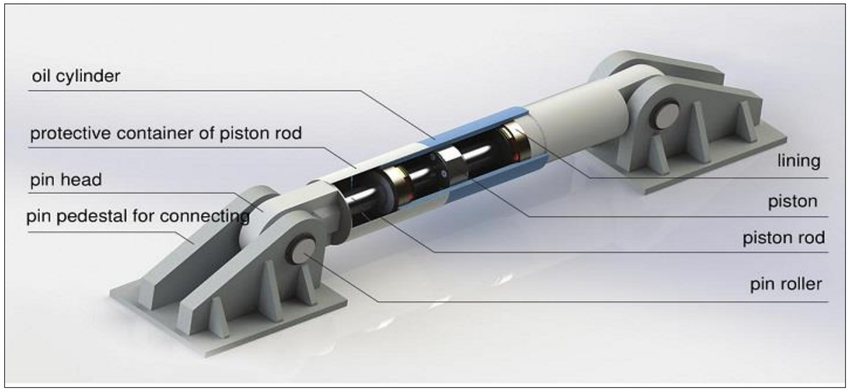
Response according:

$$x(\ddot{t})$$
$$x(\dot{t})$$

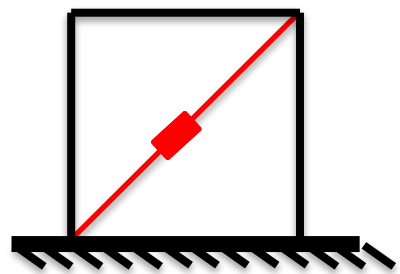
- 4 types have been widely implemented
- For each device type:
  - Working principle
  - Development history
  - Model for describing behaviour

3. Passive Devices

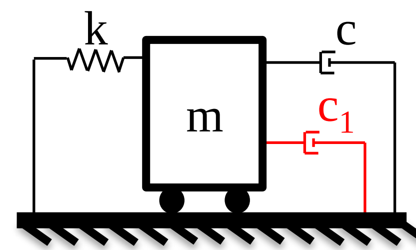
3.1. Viscous Fluid Dampers (VFD):



Double head piston in FVD (ROAD, 2017)



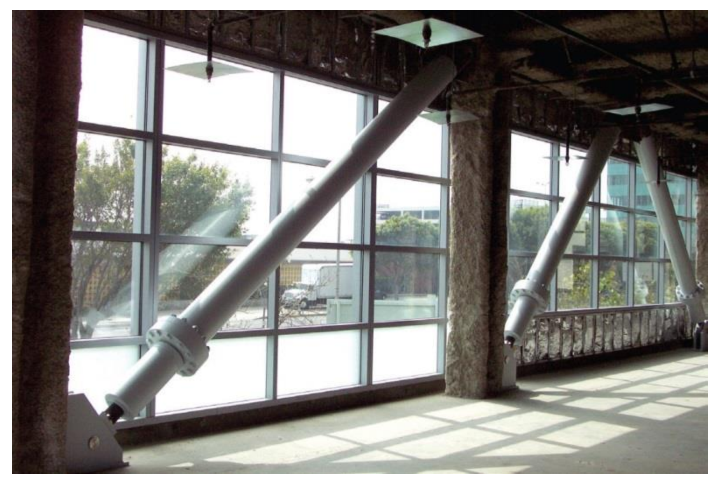
Structure + VFD



Model + VFD

$$x(t) = m * \ddot{x}(t) + (c + c_1) * \dot{x}(t) + k * x(t)$$

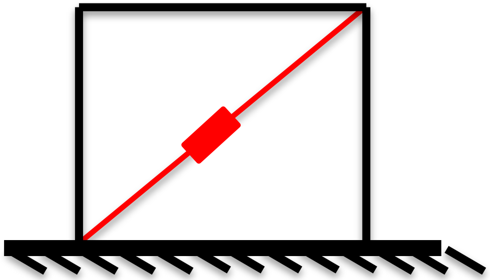
Car shock absorber (Wayalife LLC, 2020)

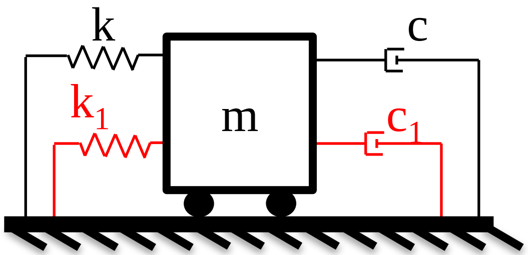


Diagonal and Chevron Bracing with Dampers (Taylor Devices Inc, 2020)

3. Passive Devices

3.2. Viscous Solid Dampers (VSD):





$$x(t) = m \cdot \ddot{x}(t) + (c + c_1) \cdot \dot{x}(t) + (k + k_1) \cdot x(t)$$

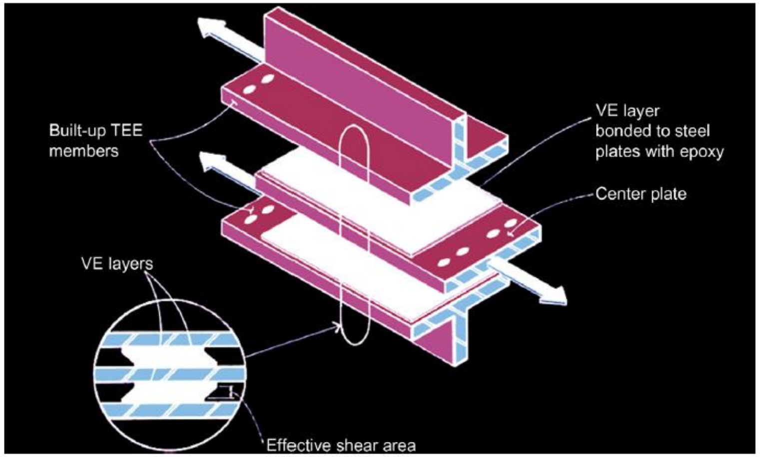


FIGURE 8.6
Columbia Center: VE damper typical scheme.

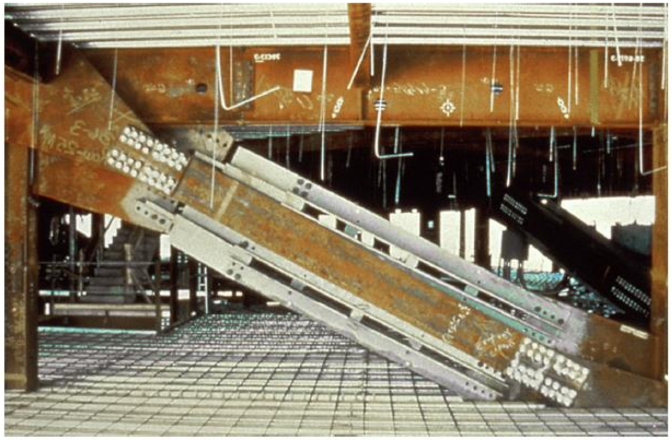


FIGURE 8.7
Columbia Center: VE damper installed in the building.

(Lago et al., 2019)

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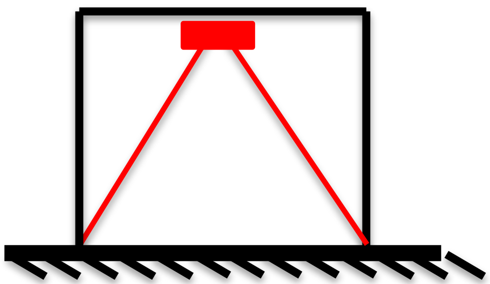
3. Passive Devices

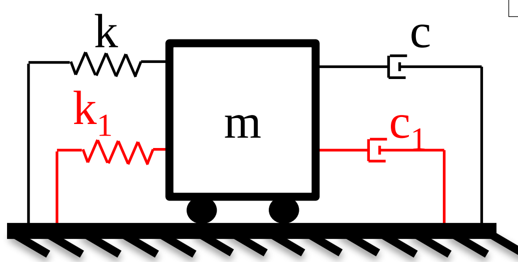
3.3. Metallic Damper (MD):

$$x(t) = m * \ddot{x}(t) + (c + c_1) * \dot{x}(t) + (k + k_1) * x(t)$$

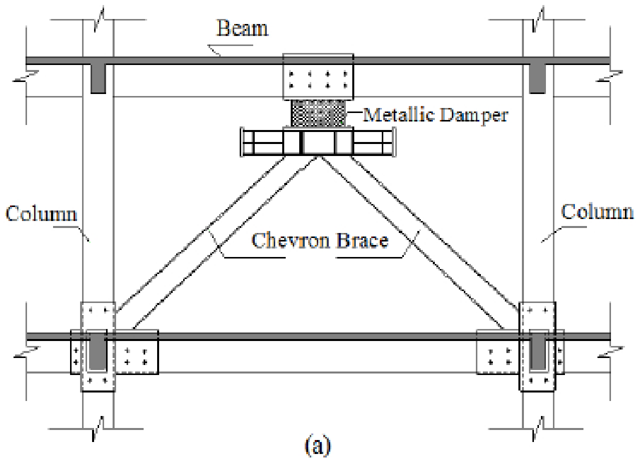
$$E_I = E_S + E_K + E_D + E_H$$



Structure + MD



Model + MD



Round hole and Double X-shaped devices (Li et al., 2014)

Metallic damper with chevron brace (Zhang et al., 2015)

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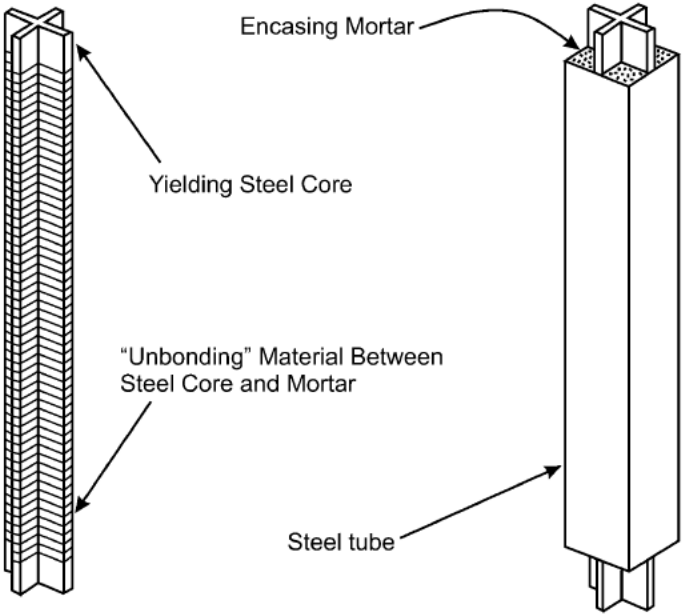
3. Passive Devices

3.3. Metallic Damper (MD):

$$x(t) = m * \ddot{x}(t) + (c + c_1) * \dot{x}(t) + (k + k_1) * x(t)$$

$$E_I = E_S + E_K + E_D + E_H$$

Wallace F. Bennett Federal Building(Symans et al., 2008)



Buckling restrained brace, BRB (Soong and Spencer, 2002)

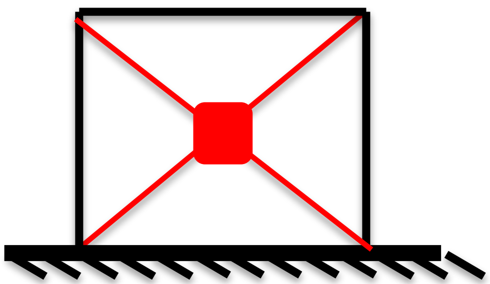
Santa Clara Medical Center (Symans et al., 2008)

3. Passive Devices

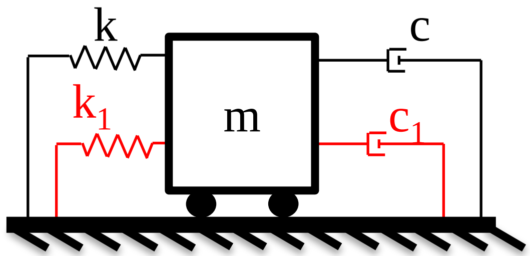
3.4. Friction Damper (FD):

$$x(t) = m * \ddot{x}(t) + (c + c_1) * \dot{x}(t) + (k + k_1) * x(t)$$

$$E_I = E_S + E_K + E_D + E_H$$

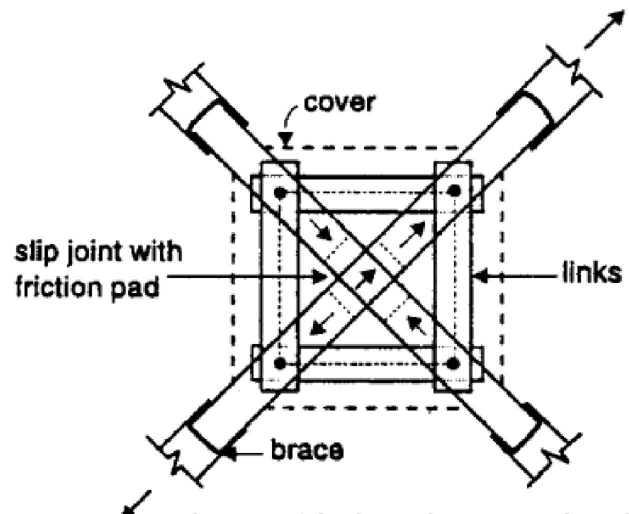


Structure + FD



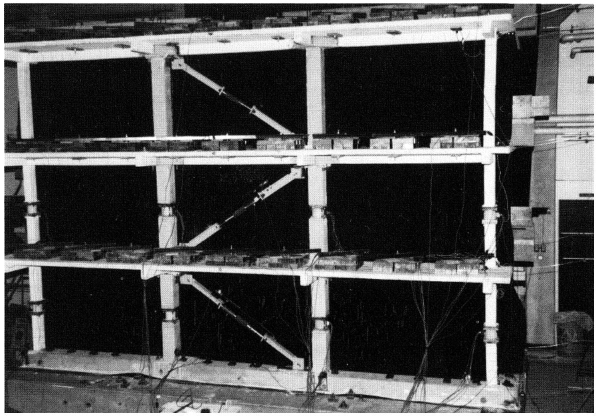
Model + FD

Monterey County Government Center (Chang et al., 2008)

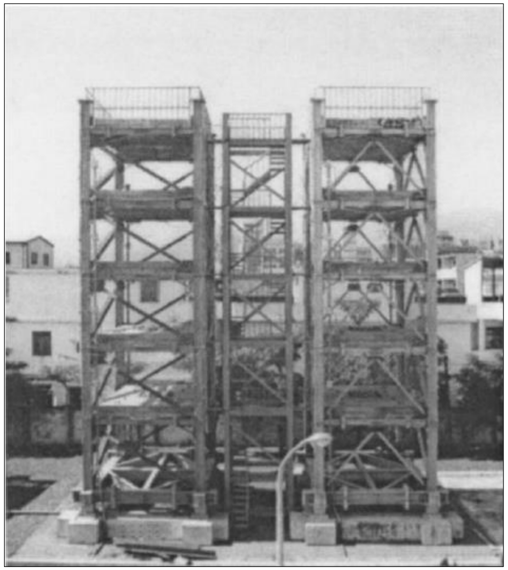


Cross-brace friction damper detail (Soong and Spencer., 2002)

4. Experimental Evaluation



VFD (Reinhorn et al., 1995)



VSD (K.-C. Chang & Lin, 2004)

MD (Guerrero et al., 2016)

FD (Park et al., 2012)

4. Experimental Evaluation (Products)

Title: Experimental Study on the Seismic Behavior of a Steel-Concrete Hybrid Structure with Buckling Restrained Braces

Author(s): Liang Li, Guoqiang Li and Tianhua Zhou

Year of publication: 2020 | Reference: (L. Li et al., 2020)

Type of device considered: Metallic Damper (MD)

Objective of the Publication:

It is known that the usual damage on a concrete wall, caused by a strong earthquake, happens at the base of such wall; this being a great safety threat and a difficult post-earthquake reparation work for steel-concrete hybrid structures. This paper aims to study the dynamic response, seismic response and failure process of a hybrid structure equipped with buckling restrained braces (BRB). First, static reciprocating loads were applied to determine the mechanical properties of the dampers and later seismic motion records were considered to determine the dynamic properties and seismic response of the studied structure equipped with the metallic dampers.

Experimental setup:
A 10-story 1/10 scaled steel-concrete hybrid structure (based on an actual office building) equipped with BRB (on an inverted V-bracing configuration) was tested in a shake-table.
The mechanical properties of the dampers were previously obtained via a static reciprocating load test. The hybrid structure was loaded with a specific arrangement of vertical loads (resembling the loads applied in the actual building).
Three ground motion records were used to measure the seismic response of the tested structure: El Centro, Shanghai and Tianjin). *Figure 9.19* shows the tested structure.

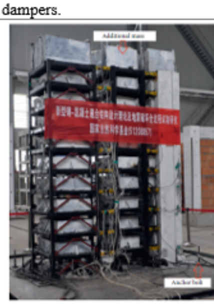


Figure 9.19

Publication conclusions:

- Two recommended values for the damping ratio of the hybrid structure are provided.
- All cracks observed are microcracks under the action of severe earthquakes (while cracks being widely distributed along the different floors, meaning a global failure mode intead of the usual local failure mode); additionally, the ductility of the BRB-equipped structure is very good.
- Both, the steel frame and the braced frame remain elastic even after severe earthquakes. These frame can then perform as a second defense line.
- None of the BRB devices were damaged during the tests and the plates connecting the structure to the dampers remained also in good condition after the tests.

Experimental bibliographic references catalog

Device	Section / Reference	Structure: Type	Structure: Description	ξ (%)	Δω(%)	ADC	LRFS State	Energy Distribution: $\sim E_H$ (%)	Energy Distribution: $\sim E_{AD}$ (%)	Damper State
VFD	8.1.1 (Kasai & Matsuda, 2014)	Steel Frame	5 floor full size with dampers in the two plan directions (2x2 bays)	~10%	10% - 15%	50.0%	MN	N. A.		Intact
	8.1.2.1 (M. C. Constantinou & Symans, 1992)	Steel Frame	1 floor scaled with 2 and 4 linear dampers (1x1 bays)	19.3%	9.4%	30.0%	MN	15%	80%	Intact
				37.4%	12.1%		MN	N. A.		Intact
		Steel Frame	3 floors scaled with 2, 4 and 6 linear dampers (1x1 bays)	9.9%	1.5%	45.0%	MN	N. A.		Intact
				17.70%	5.50%	60.0%	MN	N. A.		Intact
				19.40%	1.50%	70.0%	MN	N. A.		Intact
	8.1.2.2 (Reinhorn et al., 1995)	RC Frame	3 floors scaled retroffited with dampers in all floors (3x1 bays)	25.0%	15%	~40%	MN	10%	80%	Intact
	8.1.2.3 (M.C. Constantinou & Seleemah, 1997)	Steel Frame	1 floor scaled with 2 nonlinear dampers (1x1 bays)	22.0%	10.0%	40.0%		13%	85%	Intact
		Steel Frame	3 floors scaled with 2, 4 and 6 nonlinear dampers (1x1 bays)	16.7%	2.5%	50.0%	MN	N. A.		Intact
				26.8%	5.00%	70.0%	MN	N. A.		Intact
				32.5%	8.00%	80.0%	MN	N. A.		Intact
	8.1.2.4 (M. Constantinou et al., 2001)	Steel Frame	1 floor planar scaled with toggle braced damper (1 bays)	16.5%	12.50%	52.6%	MN	N. A.		Intact
	8.1.2.5 (Hwang et al., 2005)	Steel Frame	3 floors scaled with dampers in all floors (2x2 bays). VFD in diagonal and toogle brace system	21.0%	0.00%	35.0%	L	N. A.		Intact
				36.0%	29.03%	47.0%	L	N. A.		Intact
	8.1.2.6 (Hwang et al., 2006)	RC Frame	Two identical 3 floors scaled with one wall (2x2 bays): one with TBD in all floors	N.A.	N.A.	41.9%	N	10%	85%	Intact

ξ: Damping ratio (bare frame vs damper equipped frame)
Δω: Frequency variation (initial frame vs damper equipped frame)
ACD: Achieved displacement control
LRFS: Lateral resisting force system, initial frame (Lineal, Moderately Nonlineal, Nonlineal)
$\sim E_H$ (%): Energy dissipated by hysteretic mechanism in the LRFS
$\sim E_{AD}$ (%): Energy dissipated by devices

Experimental evaluation summary

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4. Experimental Evaluation (Results overview)

-Revised literature, from 1990 to 2020.

Type	Disp. control	Energy dissipated	Reusability
VFD	30-70%	~80%	High
VSD	30-80%	~80%	High
MD	30-90%	40-90%	Low
FD	up to 80%	20-90%	Low

-Displacement control shows in general a great variability amongst all types.
-Energy dissipation shows greater consistency in VFD and VSD.
-MD and FD are damaged after large energy inputs.

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5. Application Examples

- Objectives:
  - To collect an extensive amount of damper application examples
  - To draw a comparison
  - Versatility description: to see the range of applications

- Identified Application Types (in Buildings)

  - Seismic Retrofitting (S-R)

  - Wind Retrofitting (S-R)

  - Ambient Vibration Control (AVC)

  - Seismic Design (S-D)

  - Wind Design (W-D)

  - In structures different that buildings

5. Application Examples

- Catalogue of application cases:

9.2 Catalogue of application cases

Name Reference	Type	City, Country	Year	Building Use	Floors/ Height (m)	Structural System	I. T.	Devices Location	D. Q.	Target
Pacific Bell North - Area Operation Center (Constantinou et al., 1998)	VFD	Sacramento, USA	1995	Special Building	3/12m	S-Braced Frame	S-D	VFD in chevron bracing along all the height	62	To provide enough additional damping to keep the structure elastic during a maximum level earthquake
County Medical Center (Constantinou et al., 1998)	VFD	San Bernardino, USA	1996	Hospital	5/ 18m	S-MF	S-D	At level foundation, in parallel with the seismic isolation system	184	VFD used to enhance energy dissipation in rubber bearing isolation systems
Science Building II (Constantinou et al., 1998)	VFD	Sacramento, USA	1996	Education	N.A.	N.A.	S-D	Along all the height of the building	40	Provide energy dissipation system to limit actions in LRFS
Langenbach House (Constantinou et al., 1998)	VFD	Oakland, USA	1996	Residential	3/ 12m	Masonry	S-D	At foundation level	4	New construction with base isolation that includes VFD to diminish costs
The Money Store										

- Versatility description: Broad – Existent – Non Existent

Device	Retrofitting			Design		In structures different than Buildings
	Seismic (S-R)	Wind (W-R)	Ambient Vibration (AV-R)	Seismic (S-D)	Wind (S-D)	
VFD	Broad	Existent	Existent	Broad	Broad	Broad
VSD	Broad	N.E.	N.E.	Broad	Broad	N.E.
MD	Existent	N.E.	N.E.	Broad	N.E.	N.E.
FD	Broad	N.E.	N.E.	Existent	N.E.	N.E.

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6. Comparison

Description		VFD	VSD	MD	FD
Experimental	Advantages	-Damper properties and modeling are virtually frequency and temperature independent -Device's behavior near pure viscous damper. Minimal restoring force -Simple modeling -No replacement needed after design earthquake -Can cover a wide range of excitation frequencies	-Device can be activated without trigger displacement -Highly effective at high frequency solicitations -Provides restoring force -Recently new developed application and potential for further improvements	-Stable hysteretic behavior -Properties are frequency and temperature independent -Material and behavior commonly used by structural engineers -In the BRB case, provide linear damping as well as hysteretic damping and adaptability as a structural system, besides the application as additional dissipating device	-Large energy dissipation per cycle -Properties are frequency and temperature independent
	Disadvantages		-Damper properties and modeling are highly frequency and temperature dependent. Thus, modeling implies several assumptions	-Device damaged after providing hysteretic damping energy dissipation requires replacement. -Large trigger displacement for activating hysteretic damping	-Reliability concern about the conditions of the sliding interface: deteriorating with time -Device damaged after providing hysteretic damping energy dissipation. Requires replacement -Large trigger displacement for activating hysteretic damping
Versatility in Applications		1st	3rd	2nd	4th

7. Design Considerations

- Objectives:
  - Review of the most important provisions for structures with dampers
  - Review of Design Procedures
  - State-of-the art in investigation in design of structures with such devices

7.1. Minimum Requirements

7.1.1. ASCE – 41
7.1.2. EN 1998-1-2:2020

7.2. Design Procedures

- Summary for two procedures

7.3. Availability of devices

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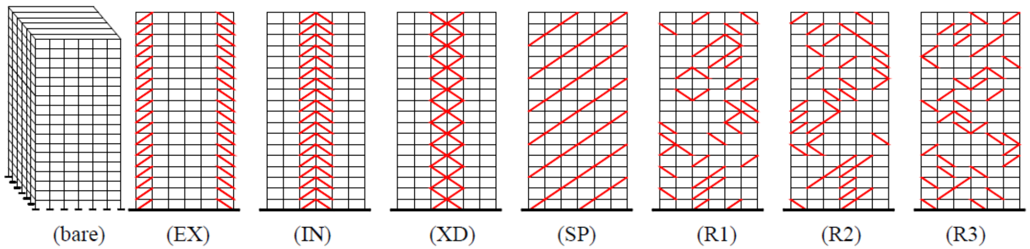
7. Design Considerations

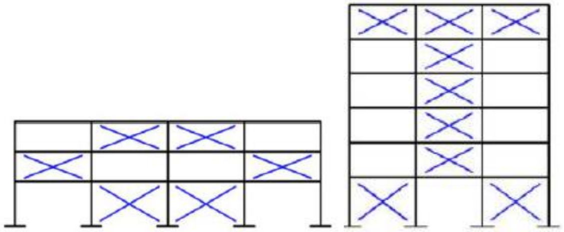
7.4. State of the art of latest investigation

7.4.1. Distribution of damping in height

7.4.2. Devices spatial location



Considered spatial location in (Mezzi, 2010)



Optimal Arrangements in (Apostolakis and Dargush 2010)

7.4.3. Minimum requirements for structures with added damping

- Provisions in Section 7.1. do not provide lower probabilities of collapse in comparison to conventionally designed buildings

- (Kitayama & Constantinou, 2018) provide modified minimum requirements

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8. Conclusions

-The behavior and modelling of passive energy dissipating devices, as well as the effects when applied to buildings, can be satisfactory predicted thanks to the extensive study and testings being done all over the world, regarding this type of devices.

-Each type of damper have its own set of advantages and disadvantages. The use of a specific type of damper will depend on the particular requirements of the target structure.

-Further research is needed regarding design procedures as well as minimum requirement for structures with passive dampers, in order to complement the available information as well as to standardize it.

-At present, there are several specialized manufacturers that can provide ready-to-install damper devices. Even though in the case of VSD, the design of the device itself must be done by those directly involved in the design and/or construction of the target structure.

-The connecting elements between the energy dissipating devices and the main structural system, must remain elastic and provide the required rigidity to guarantee an adequate force transfer.

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