Investigation of the Seismic Performance of Steel Structures with Nonlinear Viscous Dampers using Large-scale Real-time Hybrid Simulation

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Research Overview

Background

- Supplemental damping devices can enhance seismic performance of structural systems.
- Existing design procedures do not adequately integrate the design of passive damping systems into the design of building structures.
- Lack of large-scale experimental evaluation of design procedures for buildings with damping system.

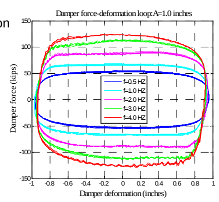
Scope of Work

- Characterization and modeling of large-scale nonlinear viscous dampers
- Development of simplified design procedure (SDP) for design of steel buildings with nonlinear viscous dampers
- Validation of SDP using real-time hybrid simulation of a three-story structure with nonlinear viscous dampers

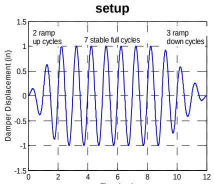
Nonlinear Viscous Damper

Characterization Tests

- Large-scale damper characterization tests at various frequencies, displacement amplitudes, and ambient temperatures.

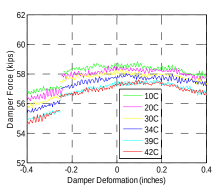


Damper characterization test setup



Displacement loading history

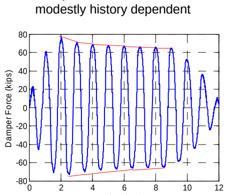
- Damper behavior is insensitive to ambient temperature

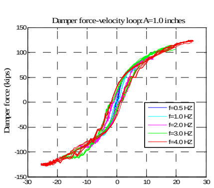


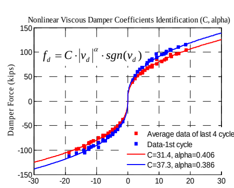
Chamber for temperature control

- Damper behavior is not purely nonlinear viscous, and exhibits a slight amount of storage stiffness

- Damper coefficients are modestly history dependent







Nonlinear 'Maxwell' model

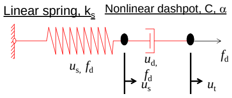
- Nonlinear dashpot

$$f_d = C \cdot |v_d|^{\alpha} \cdot sgn(v_d)$$

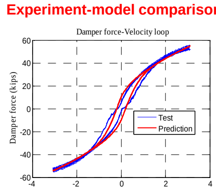
C, α are damping coefficients, v_d is the damper velocity, and f_d is the damper force.

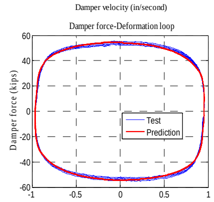
- Nonlinear spring to model damper body flexibility

$$f_d = k \cdot u_s$$

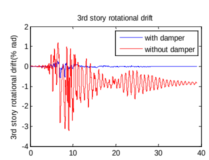


Experiment-model comparison





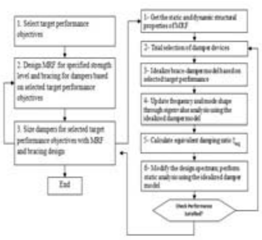
Damper application



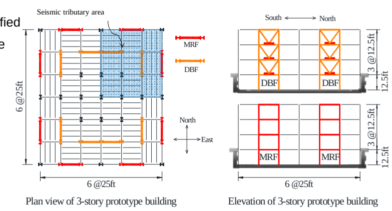
Performance-based Design Procedure and Design of Prototype Building

Simplified Design Procedure

- Multi-level of performance objectives are specified
- Damper model are idealized for design purpose
- Seismic response prediction with simplified analysis method

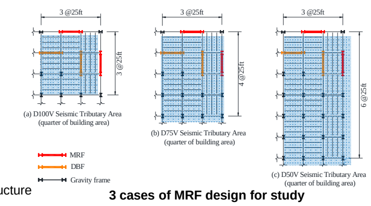


Design procedure for building with nonlinear viscous dampers



Plan view of 3-story prototype building

Elevation of 3-story prototype building



3 cases of MRF design for study

Prototype Building

- Office building
- Site class D
- Seismic group I (IE=1.0)
- Seismic category D,
- SDS=1.0g, SD1=0.6g

Test Structure

- 0.6 scale of prototype structure
- Moment resisting frame (MRF) with RBS fuse design
- MRF satisfy weak beam and strong column requirement
- Brace frame with dampers (DBF)

MRF and DBF Designs

Story level	Frame member section					Predicted Story drift-DBE			
	MRF		DBF			No damper	One damper each story		
	Column	Beam	Column	Beam	Brace	D100V	D100V	D75V	D50V
1	W8x67	W18x46	W8x67	W12x40	HSS 8x6x3/8	1.92%	0.84%	1.03%	1.35%
2	W8x67	W14x38	W8x67	W12x40	HSS 8x6x3/8	2.24%	0.97%	1.21%	1.61%
3	W8x67	W10x17	W8x67	W12x40	HSS 8x6x3/8	2.12%	0.89%	1.14%	1.54%

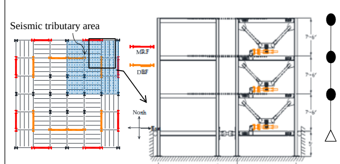
Real-time Hybrid Simulation of Structure with Dampers

Objectives

- Validate the analytical damper model
- Validate the simplified design procedure (SDP)
- Evaluate performance of the structural system with nonlinear viscous dampers

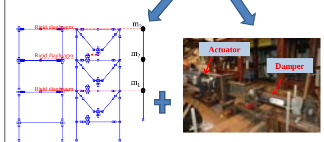
Application of real-time hybrid simulation

- Simulations performed at Lehigh NEES RTMD facility
- Test methodology comprises physical testing and numerical simulation by dividing the structure into experimental and analytical substructures
- Explicit unconditional stable CR integration algorithm
- Hydraulic actuator delay compensation



Discretized equations of motion

$$\mathbf{M}\ddot{\mathbf{X}}_{i+1} + \mathbf{C}\dot{\mathbf{X}}_{i+1} + \mathbf{K}\mathbf{X}_{i+1} = \mathbf{F}_{i+1}$$



Analytical substructure (MRF, DBF, gravity system, seismic mass)

Experimental substructure (Damper)

Substructures for Real-time hybrid simulations

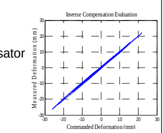
Actuator delay control

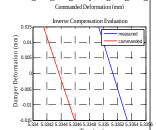
- Transfer function of Inverse compensator

$$G_C(z) = \frac{X^P(z)}{X^c(z)} = \frac{\alpha \cdot z - (\alpha - 1)}{z}$$

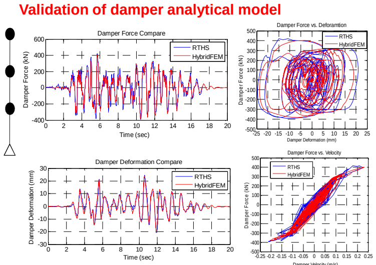
$$\alpha = \frac{\text{observed time delay } \tau}{1/1024} + 1$$

- α=22 was used in the transfer function
- With inverse compensator, only minor time delay between the command and measured actuator displacement exists

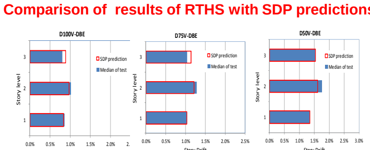




Validation of damper analytical model

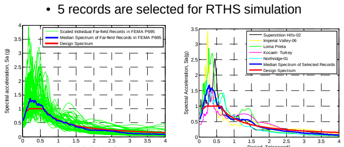


Comparison of results of RTHS with SDP predictions



Ground Motion Selection for Real-time Hybrid Simulation

- FEMA P695 Far-Field records
- Ground motions are scaled to DBE level using the scaling procedure by Somerville (1997)
- Median spectrum of records matches the design spectrum
- 5 records are selected for RTHS simulation



Selected ground motions

Test NO.	EQ. Event	Ground motion record	Scale factor	
			DBE	MCE
1	Superstition Hills-02	B-POE270	1.716	2.574
2	Imperial Valley-06	H-E11140	1.649	2.474
3	Loma Prieta	CAP000	1.361	2.041
4	Kocaeli- Turkey	DZC270	1.127	1.690
5	Northridge-01	LOS270	1.104	1.656

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Summary and Conclusions

- Large-scale nonlinear viscous dampers were characterized and nonlinear 'Maxwell' material damper model was validated
- A simplified design procedure (SDP) for steel buildings with nonlinear viscous dampers was developed
- Prototype building and structures were designed using the SDP
- The application of real-time hybrid simulation to a structure with nonlinear viscous dampers works well
- The nonlinear 'Maxwell' model is validated for numerical simulation involving seismic loading conditions
- The SDP was validated through real-time hybrid simulation with one experimental damper in the 3rd story and analytical dampers in the 1st and 2nd story

Acknowledgements

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