Seismic Performance of Nonstructural of Systems Subjected to Full-scale Floor Motions

Gilberto Mosqueda
Assistant Professor
Department of Civil, Structural and Environmental Engineering
University at Buffalo

Research Collaborators

- Professor Andre Filiatrault
- Professor Andrei Reinhorn
- Dr. Rodrigo Retamales
- Ryan Davies, Graduate Student

2

Overview

- Definition and importance of nonstructural components and systems in seismic events
- Current code requirements
- UB Nonstructural Component Simulator (UB-NCS)
- New loading protocols for seismic qualification and fragility assessment of nonstructural components
- Seismic performance assessment of a full-scale hospital emergency room

Nonstructural Components

- Systems and elements in a building that are not part of the load-bearing structural system
- Architectural
  - Cladding, glazing
  - Ceilings, partition walls
- Mechanical and Electrical
  - Distribution systems - piping
  - HVAC ducts and equipment
- Contents
  - Free-standing and anchored medical equipment, computers, shelves, etc.

Investment in Nonstructural Components and Content

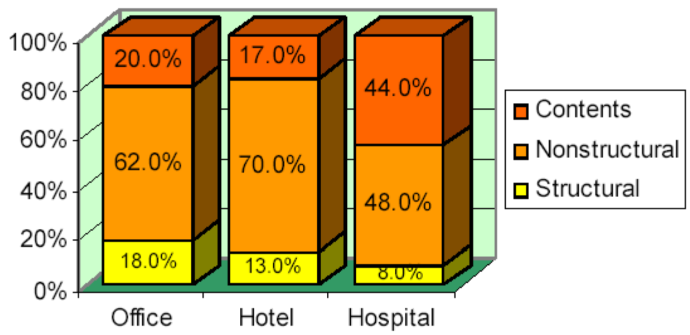


Figure 1. Typical investments in building construction (after E. Miranda)

Role of Nonstructural Components in Earthquakes

- Hospital emergency room immediately after the 1994 Northridge earthquake

Role of Nonstructural Components in Earthquakes

- 2001 Nisqually Earthquake (Filiatrault)






Role of Nonstructural Components in Earthquakes

- In order for a building or facility to remain operational after an earthquake, both structural and nonstructural systems must remain intact
- In past earthquakes
  - many hospitals and other facilities have survived earthquakes without structural damage, but lost functionality due to nonstructural damage
  - 50% of $18 Billion in building damage following 1994 Northridge earthquake was due to nonstructural damage (Kircher 2003)
- In addition to structural response, compatible seismic performance of nonstructural components is essential to achieve global performance objectives

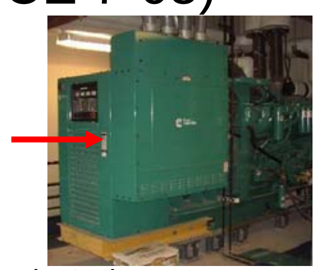
Code Requirements (ASCE 7-05)

International Building Code references ASCE 7-05
Nonstructural design requirements depend on:

- Seismic Design Category of structure
  - A-F, depending on occupancy category and site spectral accelerations at short (S_{DS}) and long period (S_{D1})
- Occupancy Category of structure
  - I – low hazard to human life (storage)
  - II – regular buildings
  - III – high hazard to human life (schools, meeting rooms)
  - IV – essential facilities (hospitals, emergency response center)
- Nonstructural Importance Factor I_P = 1 or 1.5
  - I_P =1.5 if component (a) is essential for life-safety; (b) contains hazardous materials; or (c) is required for functionality of Cat. IV structure

9

Code Requirements (ASCE 7-05)



- Equivalent Static Design Force

$$F_p = \frac{0.4 a_p S_{DS} W_p}{R_p / I_p}\left(1 + 2\frac{z}{h}\right)$$

  - a_p = component amplification factor (1-2.5)
  - I_p = component importance factor (1-1.5)
  - R_p = component response modification factor (1-12)
  - S_{DS} = short period spectral acceleration
  - W_p = component weight
  - z/h = normalized height of component in building

10

Code Requirements (ASCE 7-05)

- **Special Certification Requirements for Designated Seismic Systems** (I_P =1.5 in Seismic Category C-F)
  - Active mechanical and electrical equipment that must remain operable following design earthquake shall be certified by supplier as operable
  - Components with hazardous contents shall be certified by supplier as maintaining containment
- Must be demonstrated by
  - Analysis
  - Testing (shake table testing using accepted protocol)
    - AC-156
  - Experience Data

11

California Hospitals Requirements

- SB-1953 Hospital Seismic Retrofit Program
  - Evaluate current hospital building stock
  - Meet nonstructural performance standards by 2002
  - Meet structural performance standards for collapse prevention by 2008 (possible extension to 2013)
  - Buildings capable of continued operation after design level event by 2030
- ASCE 7-05 Seismic Qualification Requirements apply for mechanical and electrical equipment

12

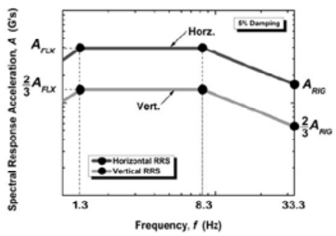
Testing Protocols for Seismic Qualification of Equipment

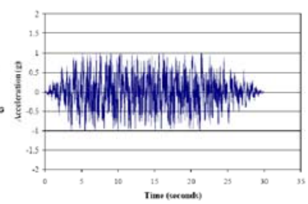
- ICC-ES AC156 shake table testing protocol
  - Test under non-stationary random excitations matching target floor response spectrum

$$A_{FLX} = S_{DS}\left(1+2\frac{z}{h}\right)$$

$$A_{FLX} \le 1.6 S_{DS}$$

$$A_{RIG} = 0.4 S_{DS}\left(1+2\frac{z}{h}\right)$$

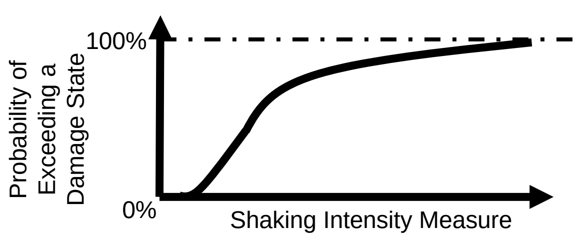




  - Force levels consistent with static design force F_P
  - Test unit should remain functional after testing

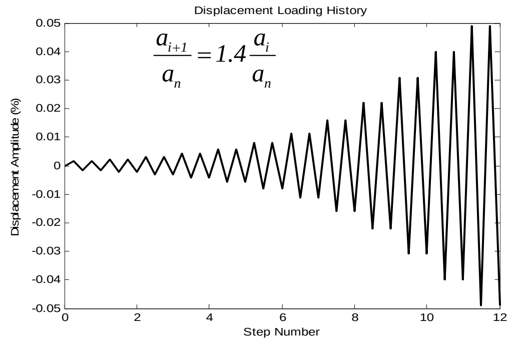
Testing Protocols for Seismic Fragility Assessment

- FEMA 461 testing protocols:
  - Racking (quasi-static) test for displacement (drift) sensitive nonstructural components
  - Shake table tests for acceleration sensitive components
  - Objective is to determine mean loading conditions triggering different damage levels



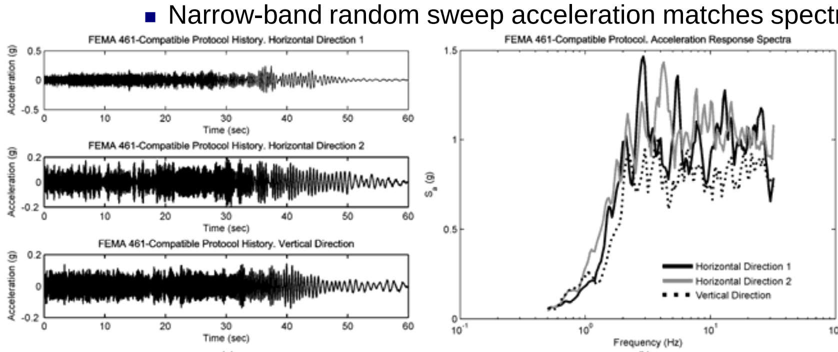
Testing Protocols for Seismic Fragility Assessment

- FEMA 461 testing protocols
  - Racking protocol: low rate cyclic displacements and/or forces selected to match 'rainflow cycles' for expected seismic response of buildings



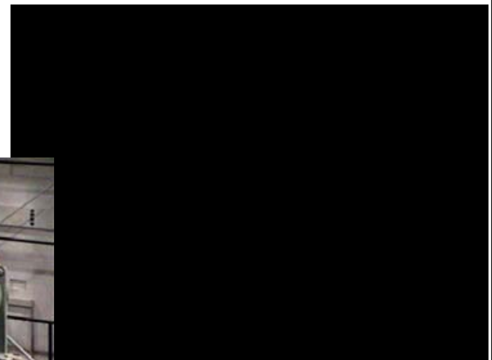
Testing Protocols for Seismic Fragility Assessment

- FEMA 461 testing protocols
  - Shake table protocol:
    - Simulated scaled floor motions to evaluate the response of acceleration sensitive systems (single attachment point)
    - Narrow-band random sweep acceleration matches spectra



Application of Testing Protocol

HVAC Equipment Mounted on Vibration Isolation/Restraint Systems



PI: A. Filiatrault
Sponsor: MCEER/ASHRAE
Industry Partner: ASHRAE

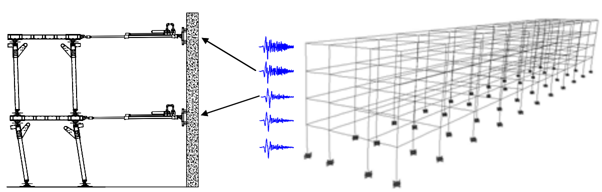
Research Objectives

- Improve experimental testing capabilities for more realistic seismic performance assessment of nonstructural components, systems and equipment located within multistory buildings
  - Develop a new testing facility capable of subjecting NSC's to realistic full-scale floor motions
  - Develop a testing protocol suitable for qualification and fragility assessment of nonstructural components
  - Demonstrate performance of equipment and protocol through seismic testing of a composite hospital room

19

Nonstructural Component Simulator (UB-NCS)

Modular and versatile two-level platform for experimental seismic performance evaluation of full-scale nonstructural components, systems and equipment under realistic full-scale building floor motions



Characteristics:

Plan dimensions: 12.5'x12.5'
Story height: 14'
Actuator capacity: 22 kips
Payload capacity: 5 kips/level

Displacements: ± 40 in
Velocities: 100 in/s
Accelerations: up to 3g
Frequency range: 0.2-5 Hz

UB-NCS Testing Capabilities

- Replicate recorded or simulated floor motions at upper levels of multi-story buildings
- Replicate full scale near-fault ground motions (including large displacement/velocity pulses)
- Capability to generate data required to better understand behavior of nonstructural components under realistic demands
  - Develop experimental fragility curves
  - Develop effective techniques to protect equipment in buildings

Performance Evaluation of UB-NCS

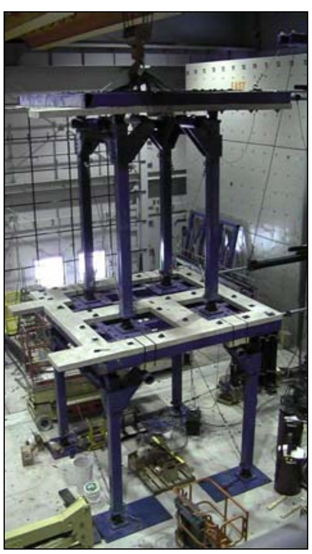
- Objectives:
  - Identify dynamic properties and limitations of UB-NCS
  - Evaluate system fidelity for replicating simulated and recorded full scale floor motions
- Extensive testing including:
  - Hammer impact
  - White noise and sine sweep tests
  - Transient floor motions
  - New protocols under development

Performance Evaluation of UB-NCS

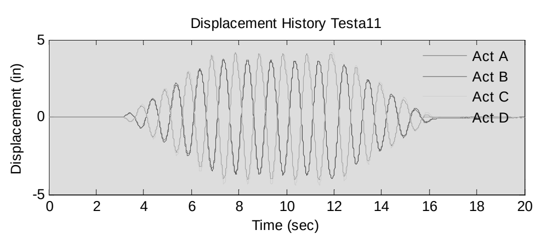
- UB-NCS dynamic properties limit frequency range of operation to 5 Hz

Dynamic property	Frequency (Hz)
Actuator vertical bow-string frequency	8.7-9.2
Actuator horizontal bow-string frequency	6.6
Actuator oil-column frequency	12.3-13.6
Frame transverse direction frequency	38.9-39.3
Platform dish mode frequency	19.1-20.0

Performance Evaluation of UB-NCS



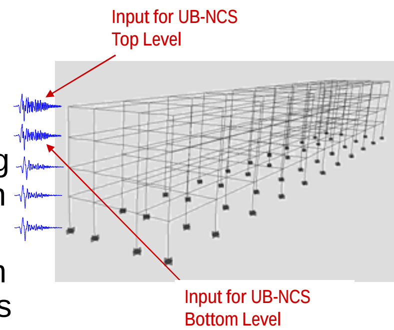
- Tapered sinusoidal test examples



Testa11: f=1 Hz, A=±4 in.

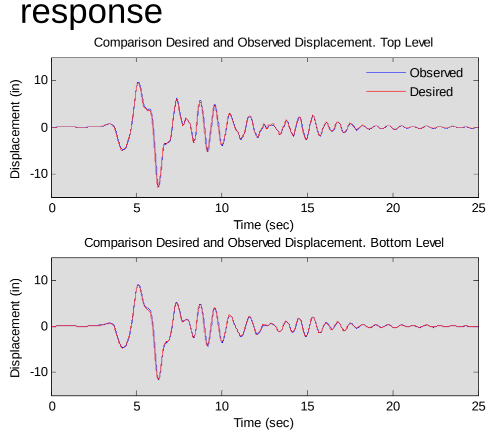
Performance Evaluation of UB-NCS

- Simulated seismic response of building
  - Existing medical facility in the San Fernando Valley, Southern California
  - 4-story steel framed building with non uniform distribution of mass and stiffness
  - Floor motions obtained from nonlinear numerical analysis
  - Synthetic ground motions with seismic hazard of 10%/50yrs



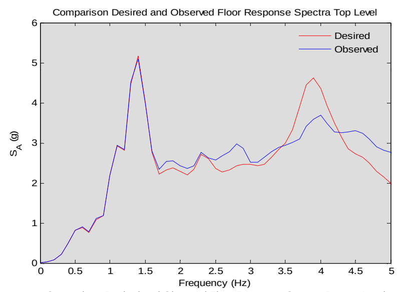
Performance Evaluation of UB-NCS

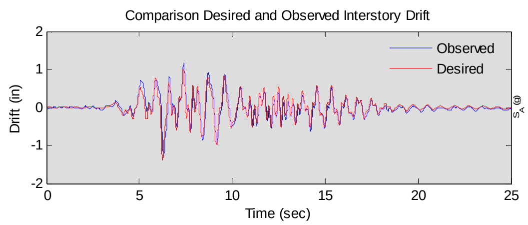
- Simulated building seismic response

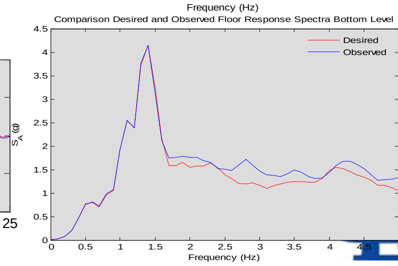


Performance Evaluation of UB-NCS

- Simulated building seismic response
- Accuracy of test machine measured by comparing
  - Response spectrum
  - Interstory drift history

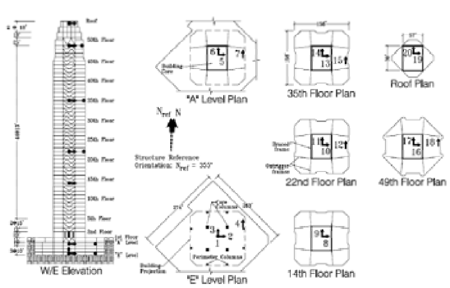






Performance Evaluation of UB-NCS

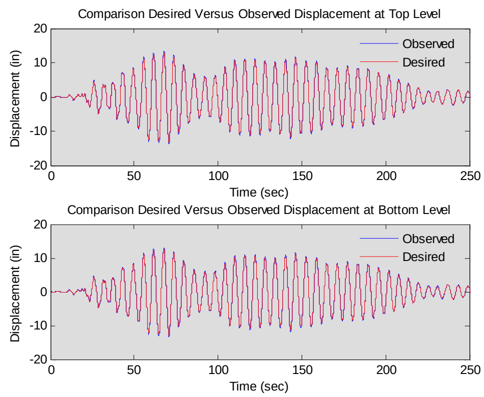
- Recorded building seismic response, 1992 Landers M_w=7.4
  - 52-story office building in LA
  - Concentrically braced steel frame core with outrigger moment frames



(CSMIP)

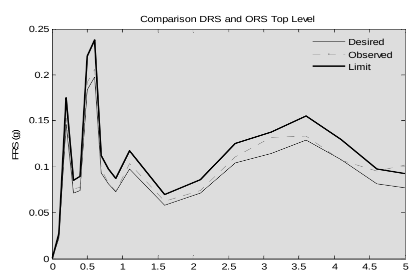
Performance Evaluation of UB-NCS

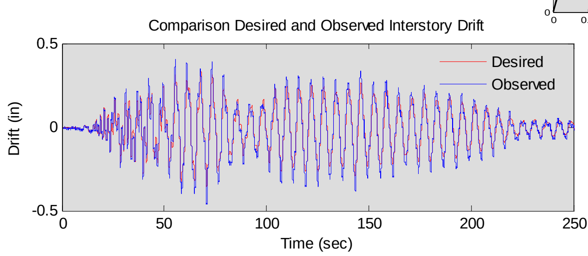
- Reproduction of recorded seismic response



Performance Evaluation of UB-NCS

- Applied iterative corrections to input in order to match
  - desired response spectrum
  - Interstory drift





Testing Protocol for UB-NCS

- Current testing protocols focus either on displacement or acceleration sensitive nonstructural components (NSC's):
  - Nonstructural systems may be sensitive to both
- Proposed Protocol
  - Replicate seismic demands expected on distributed nonstructural systems in multistory buildings
  - Pair of displacement histories for bottom and top levels of UB-NCS that simultaneously match:
    - (i) target floor acceleration response spectrum (FRS)
    - ii) inter-story drift spectrum

31

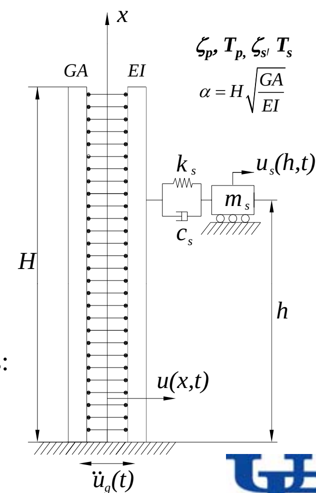
Testing Protocol for UB-NCS

- Allows testing of systems with multiple attachment points and sensitive to both displacements and accelerations (e.g. piping systems)
- Different versions for seismic qualification and fragility assessment
- Provides code compatible loading
  - Considers location along building height h/H
  - Imposes seismic demands compatible with ASCE7 (characterized by spectral parameters S_{DS} and S_{D1}) and FEMA450 Floor spectra
- Simple loading patterns given by a set of closed-form equations

32

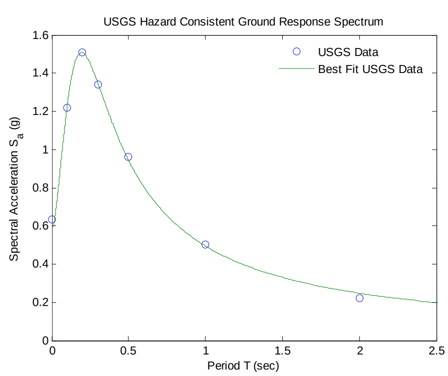
Testing Protocol Model

- Input characterized by hazard consistent power spectral density function
- Continuous beam model and Random Vibration Theory (RVT) considered for estimating:
  - Absolute accelerations along building height
  - Generalized drifts along building height
- Parameters for building model:
  - Primary system periods: T_p=0.1-5 sec
  - Secondary system periods: T_s=0-5 sec
  - Damping for primary and secondary systems: $\zeta_p = \zeta_s$ =5%
  - Parameter controlling building deformation pattern: α=0, 5 and 10



Testing Protocol Input

- Example Probabilistic Seismic Hazard with a probability of exceedance of 10% in 50 (USGS)

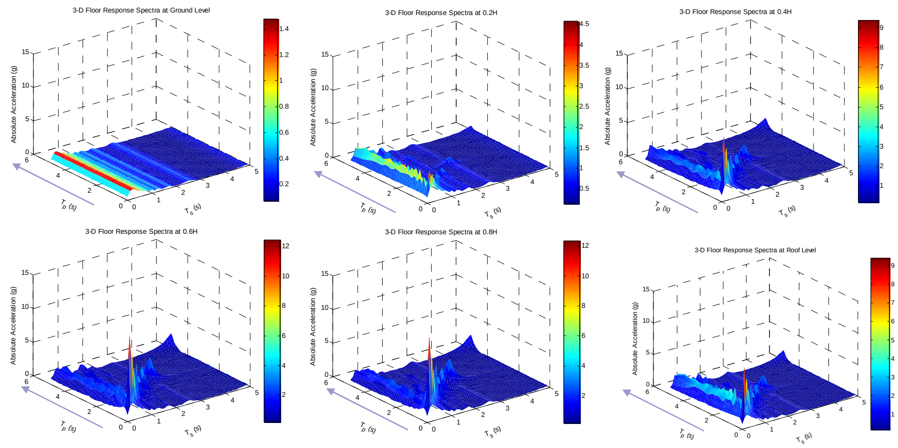


USGS Spectral Acceleration Amplitudes for a SH with PE 10%/50yrs

Period T (sec)	Spectral Amplitude (g)	
0.0	0.63	
0.1	1.22	
0.2	1.51	← S_{DS}
0.3	1.34	
0.5	0.96	
1.0	0.50	← S_{D1}
2.0	0.22	

Testing Protocol Demands

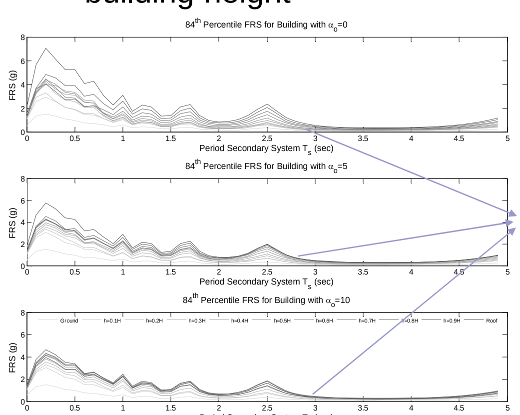
Resulting three dimensional Floor Response Spectra (FRS) for α=5 as a function of Tp and Ts

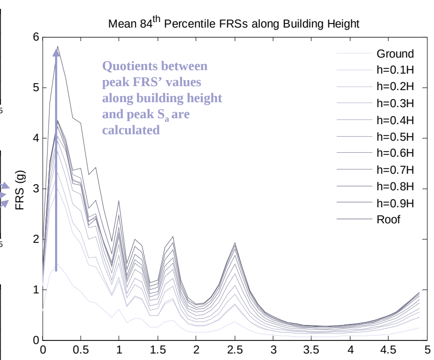


35

Testing Protocol Demands

84th percentile FRS's and mean 84th percentile FRS along building height

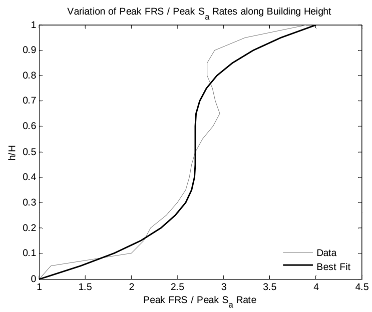




36

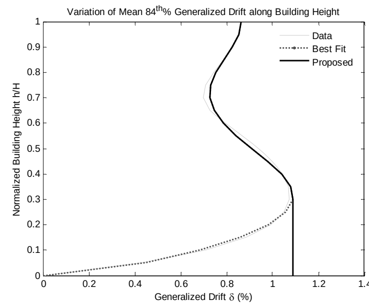
Distribution of Seismic Demands along Building Height

Variation of peak mean 84th % FRS's along building height



$$FRS_{Factor}\left(\frac{h}{H}\right) = 1 + 10\frac{h}{H} - 19.4\left(\frac{h}{H}\right)^2 + 12.4\left(\frac{h}{H}\right)^3$$

Variation mean 84th % generalized drift along building height

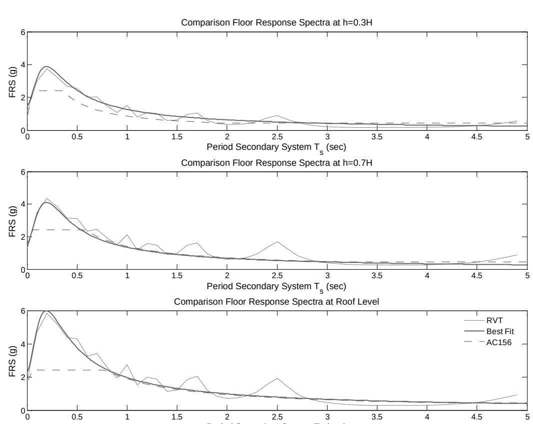


$$\delta\left(\frac{h}{H}\right) = \begin{cases} 1.09 & \frac{h}{H} \le 0.3 \\ \frac{1}{4}\sin\left(7\frac{h}{H}\right) - \frac{6}{5}\left(\frac{h}{H}\right)^2 + 1.9\left(\frac{h}{H}\right)^{0.55} & \frac{h}{H} > 0.3 \end{cases}$$

37

UB-NCS Testing Protocol

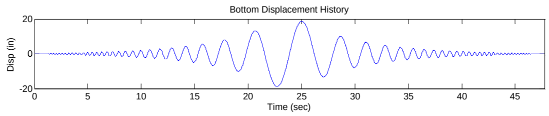
Mean 84th percentile FRS along building height



38

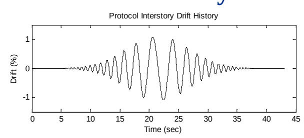
Testing Protocol for Seismic Qualification

- **Closed-form equation for bottom level of UB-NCS:**



$$x_{Bottom}\left(t,\frac{h}{H},S_{DS},S_{D1}\right)=\alpha\left(t,\frac{h}{H},S_{DS},S_{D1}\right)f\left(t\right)^{\beta}\cos\left(\varphi\left(t\right)\right)w\left(t\right)FRS_{Factor}\left(\frac{h}{H}\right)$$

- **Closed-form equation for interstory drift:**



$$\Delta\left(t,\frac{h}{H},S_{D1}\right)=h_{NCS}\frac{S_{D1}}{0.5g}\delta\left(\frac{h}{H}\right)e^{-\left(\frac{t-t_0}{\sigma}\right)^2}\cos\left(\varphi\left(t\right)\right)w\left(t\right)$$

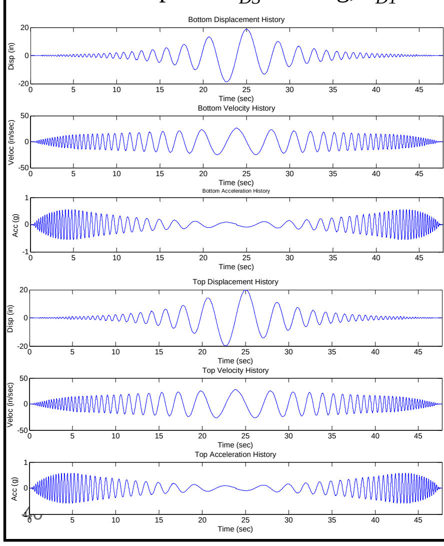
- **Closed-form equation for top level of UB-NCS:**

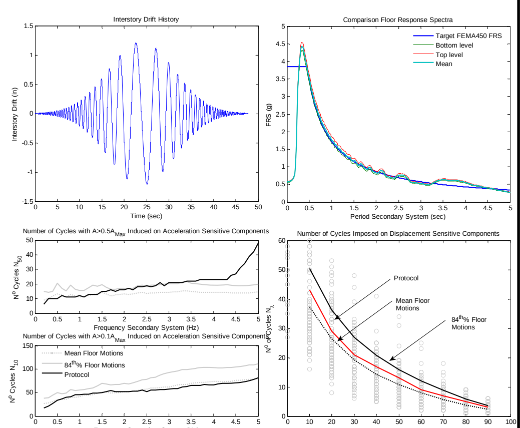
$$x_{Top}\left(t,\frac{h}{H},S_{DS},S_{D1}\right)=x_{Bottom}\left(t,\frac{h}{H},S_{DS},S_{D1}\right)+\Delta\left(t,\frac{h}{H},S_{D1}\right)$$

39

Testing Protocol for Seismic Qualification

- Example 1: S_{DS}=1.283g, S_{D1}=0.461g and *h/H*=1 (Northridge, Soil Class B)





Peak Displacements		Peak Interstory Drift		Peak Velocities		Peak Accelerations	
$D_{Max\ Bot}$ (in)	$D_{Max\ Top}$ (in)	Δ_{Max} (in)	δ_{Max} (%)	$V_{Max\ Bot}$ (in/s)	$V_{Max\ Top}$ (in/s)	$A_{Max\ Bot}$ (g)	$A_{Max\ Top}$ (g)
18.8	20.0	1.21	0.79	26.6	28.0	0.55	0.58

40

Seismic Performance of Emergency Room

- Demonstrate effects of earthquakes on typical medical equipment and other nonstructural components in hospitals
  - Research emphasis is on partition walls and wall mounted patient monitors
- Compare loading protocol developed at UB with simulated floor motions
- Verify performance capabilities of UB-NCS with realistic payload

41

Seismic Performance of Emergency Room

- Nonstructural components include
  - Steel-stud gypsum partition wall
  - Lay-in suspended ceiling system
  - Fire protection sprinkler piping system
  - Medical gas lines
  - Medical equipment
    - Free-standing
    - Anchored

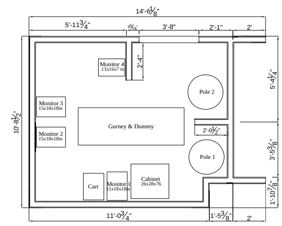
42

Seismic Performance of Emergency Room

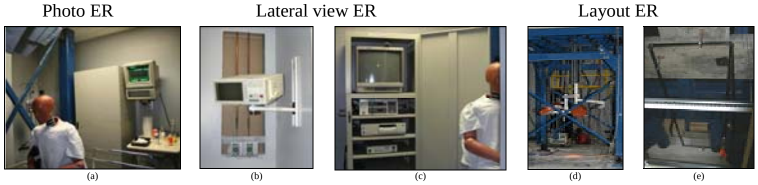
- Experimental seismic performance assessment of full-scale emergency room
  - Testing protocol for S_{DS} = 1.51g, S_{D1} = 0.5g, and *h/H* = 1
  - Simulted Response of 4-story hospital building subjected to 10%/ in 50
  - Detailed performance analysis conducted on partition walls and wall mounted monitors

Photo ER

Lateral view ER



Layout ER

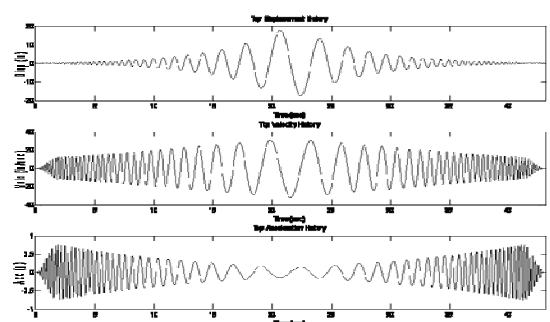


(a) Dummy sitting on gurney, poles with IV pumps, video rack, cart and monitor; (b) Medical gas piping, outlets and monitor; (c) Video rack; (d) Surgical lamp; and (e) Sprinkler runs

gm2

Loading Protocol

- Use protocol developed at UB
  - (*h/H*=1.0)
  - Preliminary tests at 10%, 25% and 50% of design level
  - Design Basis Earthquake DBE (100%)
  - Maximum Considered Earthquake MCE (150%)



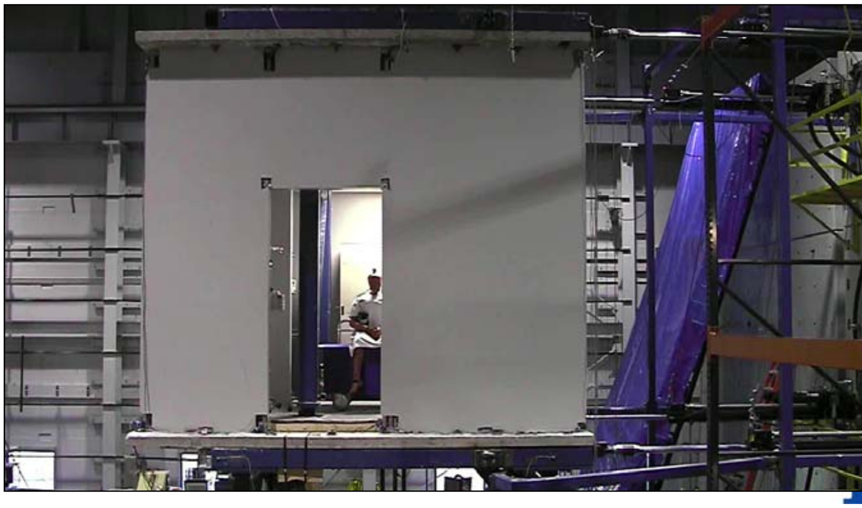
Peak Displacements		Peak Interstory Drift		Peak Velocities		Peak Accelerations	
$D_{Max\ Bot}$ (in)	$D_{Max\ Top}$ (in)	Δ_{Max} (in)	δ_{Max} (%)	$V_{Max\ Bot}$ (in/s)	$V_{Max\ Top}$ (in/s)	$A_{Max\ Bot}$ (g)	$A_{Max\ Top}$ (g)
16.3	17.6	1.31	0.87	30.5	32.6	0.73	0.77

Slide 44

gm2 Inseert table by Rodriog on peak drifts
Gilberto Mosqueda, 10/11/2007

Seismic Performance of Emergency Room

Protocol loading histories – Design Level

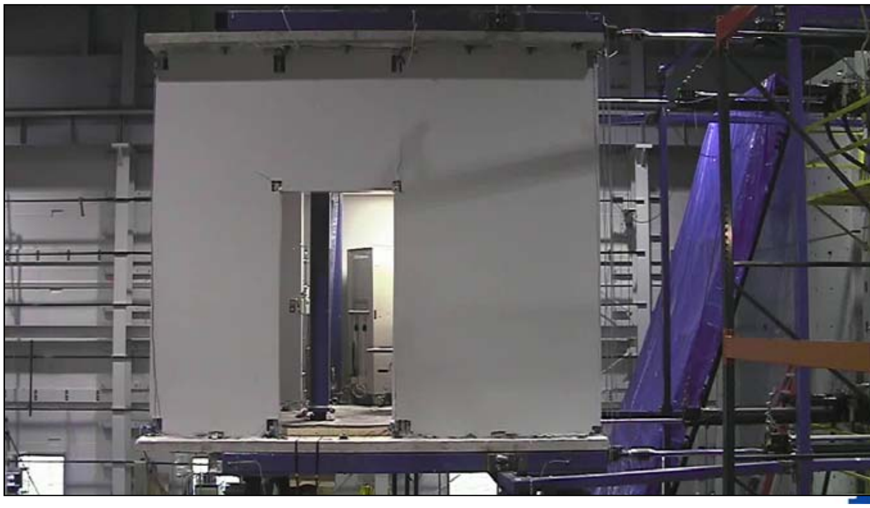


Seismic Performance of Emergency Room

Protocol loading histories – Design Level

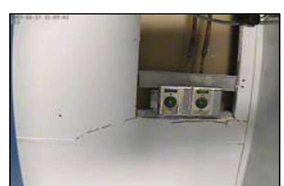
Seismic Performance of Emergency Room

Simulated building floor motions



Seismic Performance of Emergency Room

Simulated building floor motions

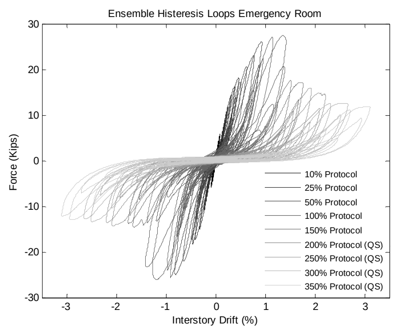


Seismic Performance of Emergency Room

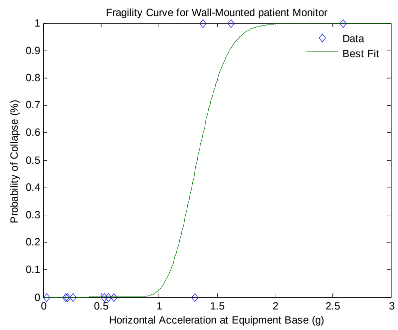
Seismic Performance of Partition Walls

Drift Ratio (%)		Observed Damage
0.09	:	No visible damage in specimen
0.23	:	Minimum level of damage observed Incipient hairline cracks along base of cornerbeads and gypsum panel joints
0.47	:	Raised areas and small cracks around screws near bottom and top tracks Hairline cracks all along of corner beads Vertical cracks $t \leq 1/16''$ along wall boundary panel joints Small hairline cracks around door fenestration
1.42	:	Widespread pop-out of screws around wall boundaries Tape covering vertical wall boundaries completely damaged Permanent gaps $1/16'' \leq t \leq 1/4''$ along cornerbeads, some horizontal gypsum panel joints, and door fenestration
1.77	:	Widespread pop-out of screws in the whole specimen Tape covering vertical wall boundaries completely damaged Permanent gaps $1/16'' \leq t \leq 1/4''$ along cornerbeads, horizontal gypsum panel joints, and door fenestration Some permanent gaps $t \geq 1/4''$ along cornerbeads Initiated gypsum panel detachment from steel studded frame
2.22	:	Generalized pop-out of screws in the whole specimen Tape covering vertical wall boundaries completely damaged Permanent gaps $t \geq 1/4''$ and crushing of joint compound along cornerbeads, horizontal gypsum panel joints, and door fenestration Gypsum panel detached from steel studded frame
2.67	:	Damage total of specimen Most of gypsum panels are detached of steel studded frame Extensive crushing of gypsum along panel joints and cornerbeads

Seismic Performance of Partition Walls and Fragility of Patient Monitors



Damage Measure	Damage State Associated	Best Fit Parameter for Monitor Base Acceleration (g)	
		θ	β
Peak acceleration at base of monitor	Monitor's supporting device failure	1.35	0.20



Conclusions

- A Nonstructural Component Simulator (UB-NCS) has been commissioned to subject nonstructural components to realistic full-scale building floor motions
- The UB-NCS provides improved experimental capabilities for seismic qualification and fragility assessment of nonstructural components and building contents
- Nonstructural systems with multiple attachments sensitive to acceleration and/or drifts can be rigorously evaluated under realistic loading conditions
- The experimental program verified the capabilities of the UB-NCS to reproduce full-scale floor motions and loading protocols imposing similar demands.
- The experimental methods presented can be used for the seismic qualification or fragility assessment of nonstructural components

Thank You!

Questions?