Seismic Safety of Nonstructural Components and Systems in Medical Facilities

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Research Collaborators

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- Rodrigo Retamales, PhD Candidate
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Overview

- Definition and importance of nonstructural components and systems in seismic events
- Current code requirements
- UB Nonstructural Component Simulator (UB-NCS)
  - Capabilities and limitations of new testing apparatus dedicated for testing nonstructural components
- Proposed protocol for testing with UB-NCS
- Recent experiments of composite hospital room to examine seismic safety of medical equipment

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

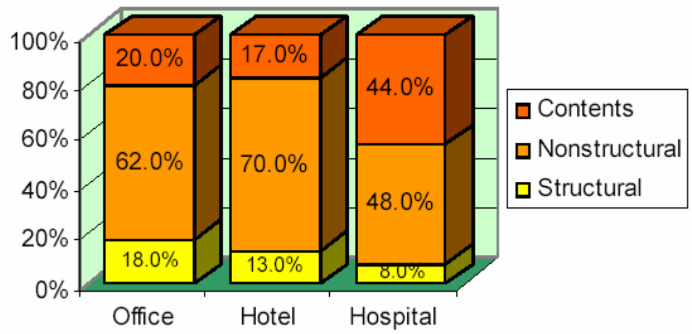


Figure 1. Typical investments in building construction (after E. Miranda)

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

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

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

Special Requirements for Hospitals in California

- 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

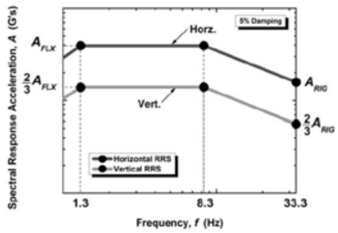
Testing protocols for experimental seismic qualification of equipment

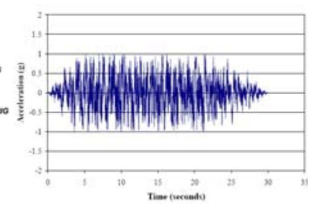
- ICC-ES AC156 shake table testing protocol
  - Test under non-stationary random excitations matching target floor response spectrum

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

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

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

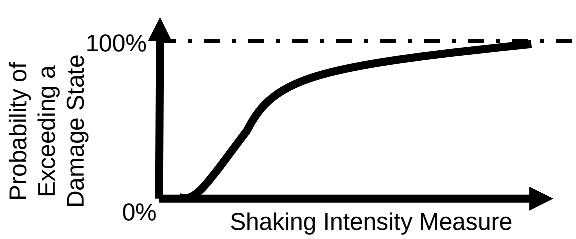




  - Force levels consistent with static design force F_P
  - Test unit should remain functional after testing

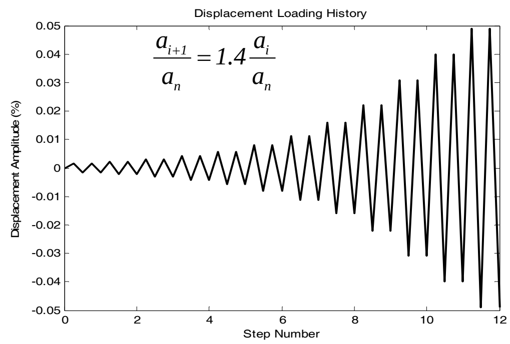
Testing protocols for seismic fragility assessment

- 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



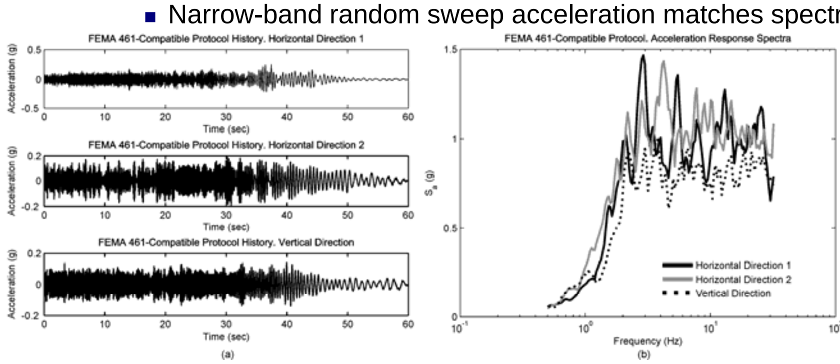
Testing protocols for seismic fragility assessment

- 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

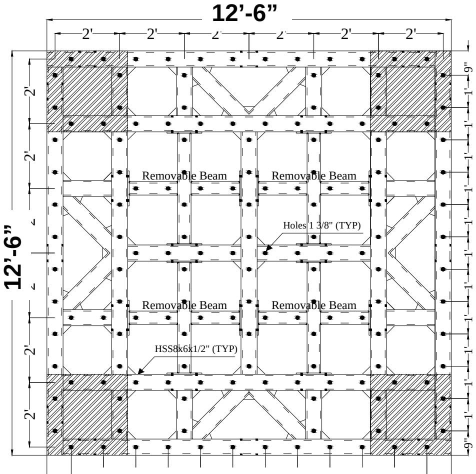
HVAC Equipment Mounted on Vibration Isolation/Restraint Systems

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

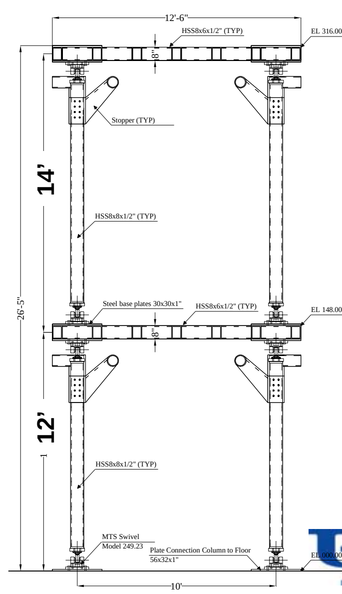
University at Buffalo Nonstructural Component Simulator (UB-NCS)

Modular and versatile two-level platform for experimental seismic performance evaluation of full scale acceleration and displacement sensitive nonstructural components under realistic full scale floor motions

UB-NCS Geometry



Plan view & elevation



UB-NCS Properties

- General properties
  - Capable of 2 horizontal DOF (+ 1 vertical when mounted on shaking table)
  - Max. specimen weight: 6 kips/level (27 kN/level)
  - Operating frequency range: up to 5.0 Hz
- Activated by 4 high performance dynamic actuators
  - Force per actuator: 22 kips (100 kN)
  - Peak displacement: ± 40 in (1 m)
  - Peak velocity: 100 in/s (2.5 m/s)
  - Peak acceleration: up to 3g's

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 and white noise tests
  - Sine sweep tests
  - Transient floor motions
  - New protocols under development

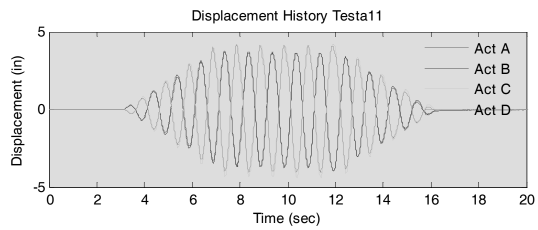
Performance Evaluation of UB-NCS

- 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

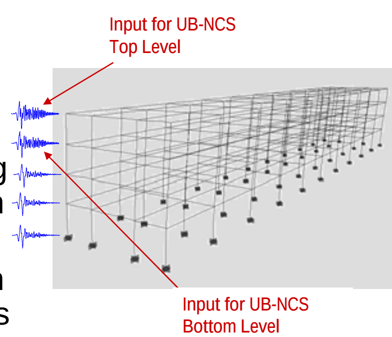
- Tapered sinusoidal test examples



Testa11: f=1 Hz, A=±4 in.

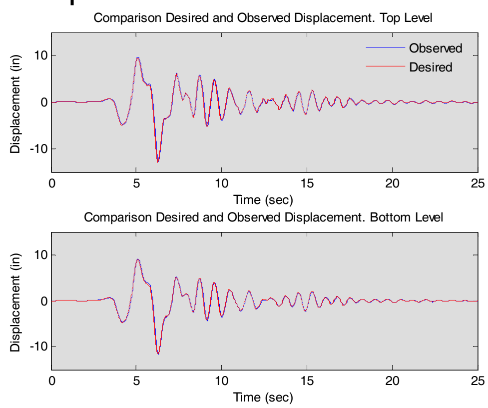
Performance Evaluation of UB-NCS

- 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



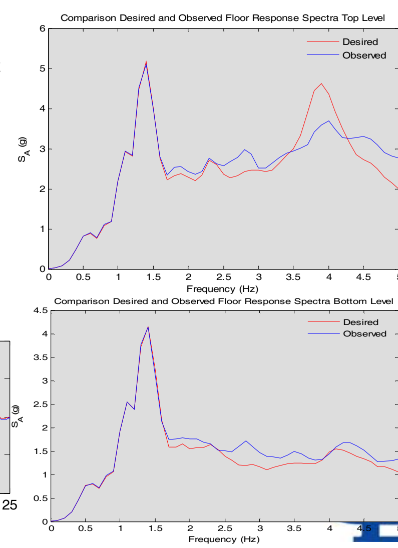
Performance Evaluation of UB-NCS

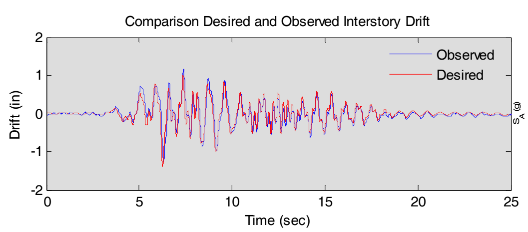
- Simulated building seismic response



Performance Evaluation of UB-NCS

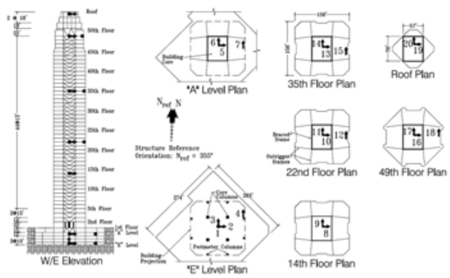
- Simulated building seismic response
- Accuracy of test machine measured by comparing
  - Response spectrum
  - Interstory drift history





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



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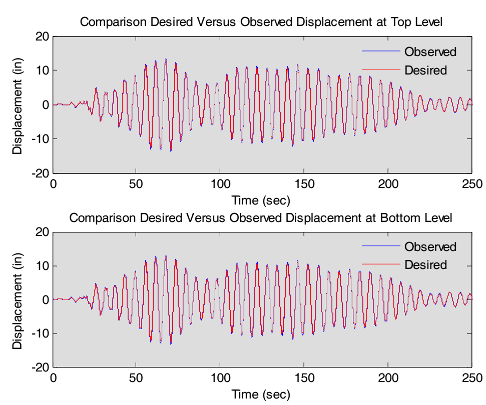
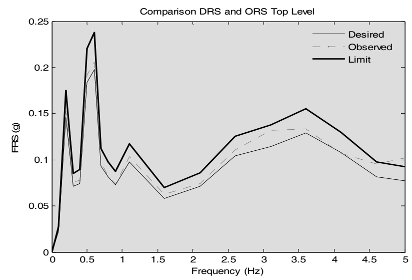
Performance Evaluation of UB-NCS

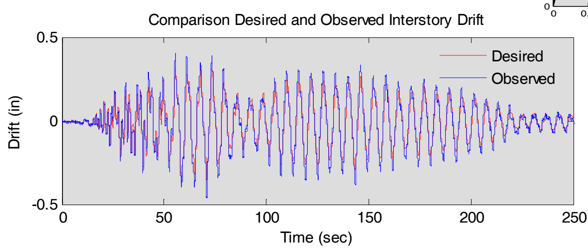
- Reproduction of recorded seismic response



Performance Evaluation of UB-NCS

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



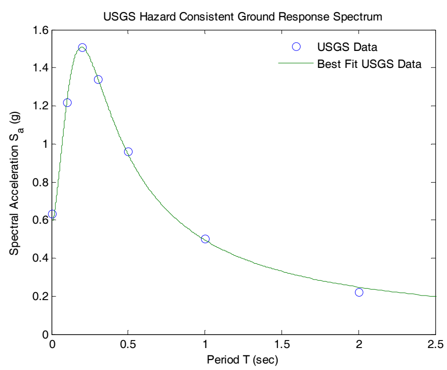


UB-NCS Testing Protocol

- New protocol is being developed to
  - Simultaneously apply displacement and acceleration demands similar to those expected in real buildings
  - Test systems with multiple attachment points at different floor levels (e.g. piping systems) and sensitive to both displacements and accelerations
- Motions for bottoms and top level are determined for a given *z/h* ratio to match:
  - Target floor acceleration response spectrum
  - Inter-story drift spectrum

UB-NCS Testing Protocol

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

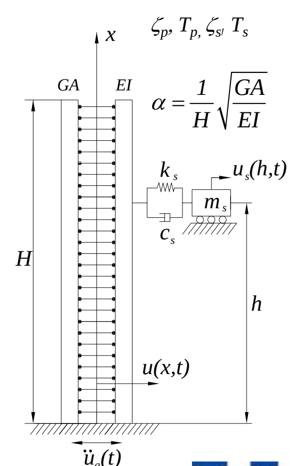


USGS Spectral Acceleration Amplitudes for a SH with PE 10%/50yrs

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	

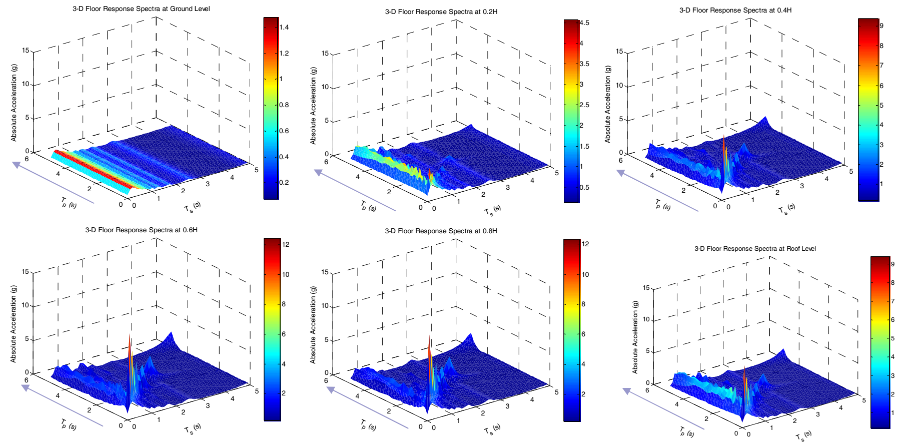
UB-NCS Testing Protocol

- Power Spectral Density consistent with seismic hazards is used as input for building model
- Floor motion demands computed by considering shear-flexural model with secondary system
  - 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 α=0, 5 and 10



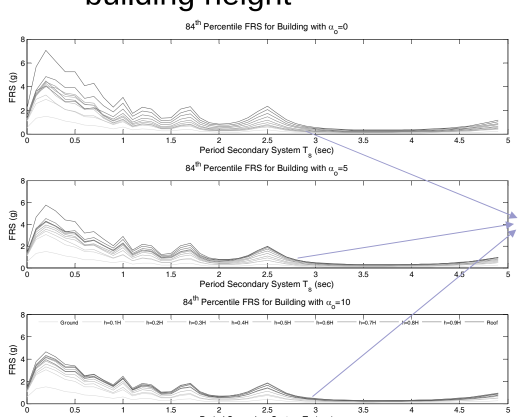
UB-NCS Testing Protocol

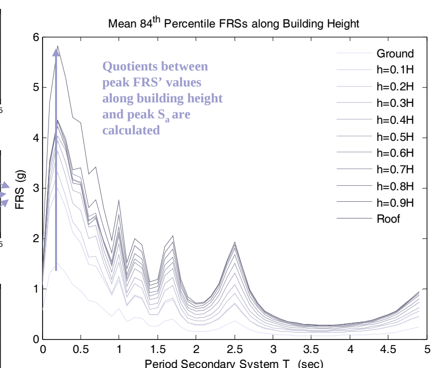
Resulting three dimensional Floor Response Spectra (FRS) for α=5 as a function of Tp and Ts



UB-NCS Testing Protocol

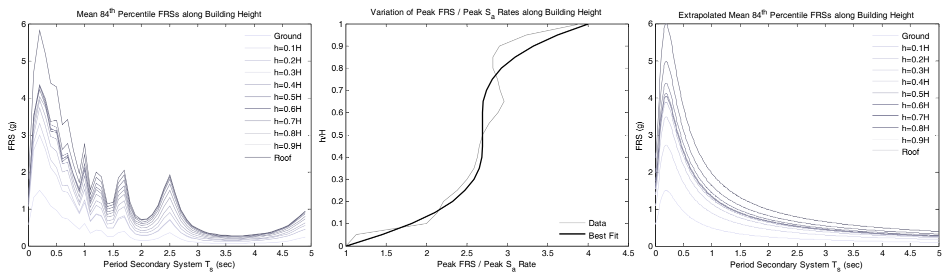
84^{th} percentile FRS's and mean 84^{th} percentile FRS along building height





UB-NCS Testing Protocol

Extrapolated mean 84th percentile FRS along building height



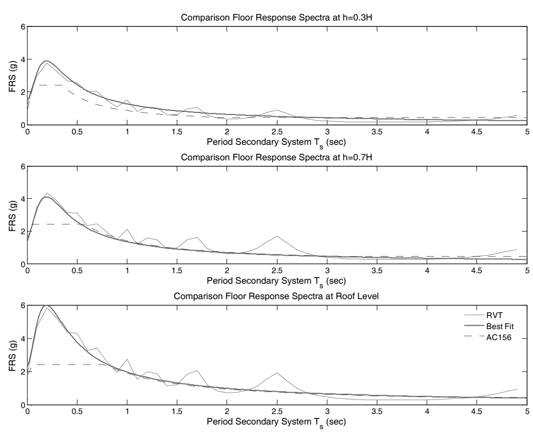
$$FRS_{Factor}\left(\frac{h}{H}\right)=1+10\frac{h}{H}-19.4\left(\frac{h}{H}\right)^2+12.4\left(\frac{h}{H}\right)^3$$

$$FRS_{Factor}\left(\frac{h}{H}=0.3\right)=2.59$$

$$FRS\left(T_s,\xi,\frac{h}{H}\right)=FRS_{Factor}\left(\frac{h}{H}\right)S_a\left(T_s,\xi\right)$$

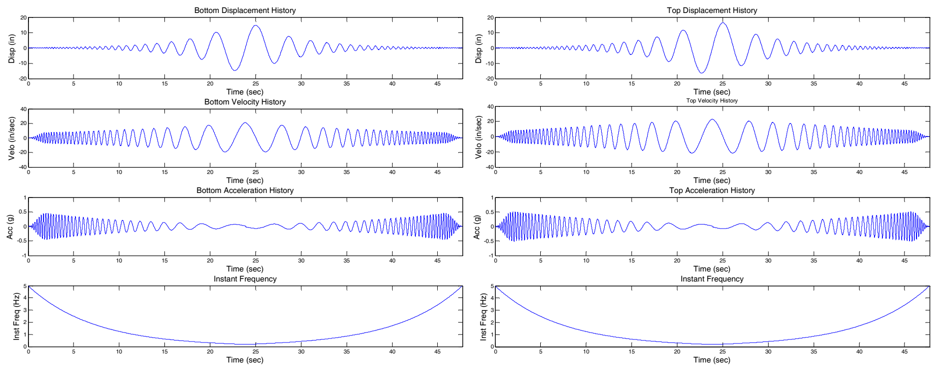
UB-NCS Testing Protocol

Mean 84th percentile FRS along building height



UB-NCS Testing Protocol

- Resulting protocol histories (*h/H*=0.3)

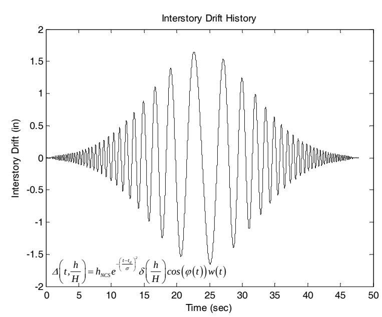


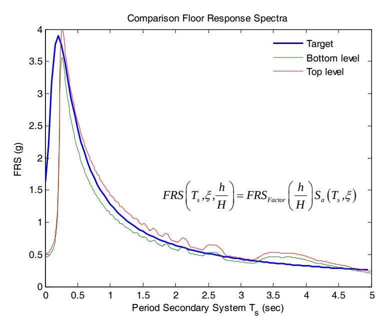
$$x_{Bottom}\left(t,\frac{h}{H}\right)=\bar{\alpha}\, f(t)^{\beta}\cos(\varphi(t))\,w(t)\,FRS_{Factor}\left(\frac{h}{H}\right)$$

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

UB-NCS Testing Protocol

- Protocol histories (*h/H*=0.3)



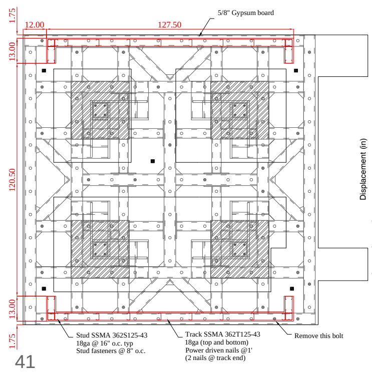


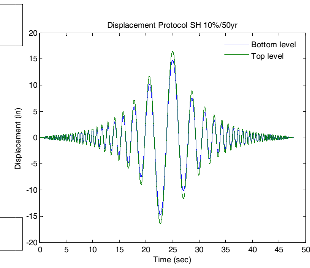
Envelope floor motions testing protocol h/H =0.3.

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)
14.8	16.4	1.65	1.09	21.2	23.2	0.45	0.51

UB-NCS Testing Protocol

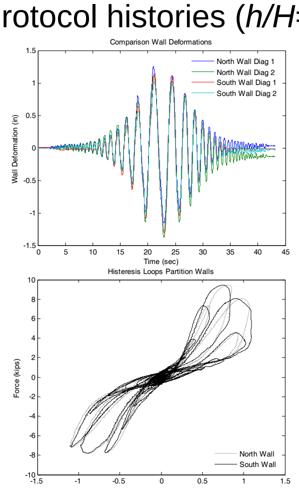
- Protocol histories (*h/H*=0.3) used to assess the seismic performance of two identical steel studded gypsum partition walls





UB-NCS Testing Protocol

- Protocol histories (*h/H*=0.3)



Drift (%)		Damage observed
0.47	**:**	**Raised areas and small cracks around screws at and near bottom and top tracks.** **Vertical "cracks" at top and bottom ends of corner beads.**
0.52	**:**	**Initial pop-out of screws at and near bottom and top tracks.** **Cracks along tape covering sheetrock panel joints.** **Vertical "cracks" at top and bottom ends of corner beads are propagated.** **Incipient crushing of wall corners.**
1.10	**:**	**Widespread pop-out of screws in the interior of sheetrock panels.** **Cracks along most of tape covering sheetrock panel joints.** **Permanent gaps (~1/16-1/8") in joints between sheetrock panels.** **Increased crushing of wall corners.**
1.64	**:**	**Widespread pop-out of screws in the whole wall.** **Edges of sheetrock panels crushed.** **Small dimension sheetrock panels become loose.** **Permanent gaps (~1/8-1/4") in most joints between sheetrock panels.** **Increased crushing of wall corners.**
2.21	**:**	**Widespread pop-out of screws in the whole wall.** **Screws in all edges of all panels are disconnected.** **Edges of sheetrock panels continue crushing.** **Small dimension sheetrock panels totally loose.** **Permanent gaps (~1/4-1/2") in most joints between sheetrock panels.**
3.31	**:**	**All edges of sheetrock panels crushed.** **All panels became loose or unstable.** **Permanent gaps (~1/2-3/4") in all joints between sheetrock panels.**

Composite Hospital Room Tests

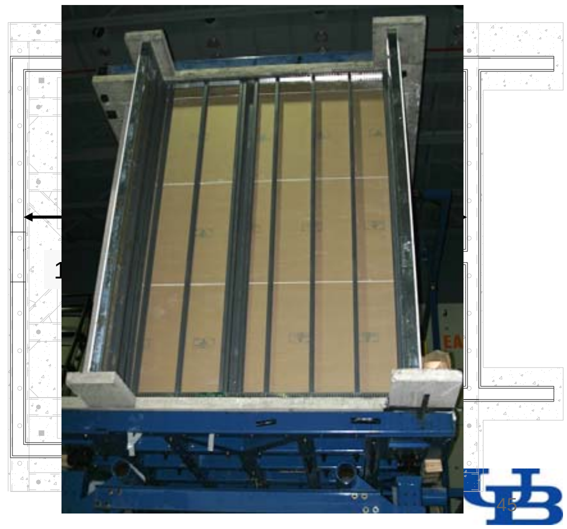
- Demonstrate effects of earthquakes on typical medical equipment and other nonstructural components in hospitals
  - Research emphasis is on partition walls
- Compare loading protocol developed at UB with simulated floor motions
- Verify performance capabilities of UB-NCS with realistic payload

Composite Hospital Room Tests

- 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

Partition wall

- Main emphasis of research
- Gypsum panels on steel stud frame
- Layout based on quasi-static test conducted at UC San Diego

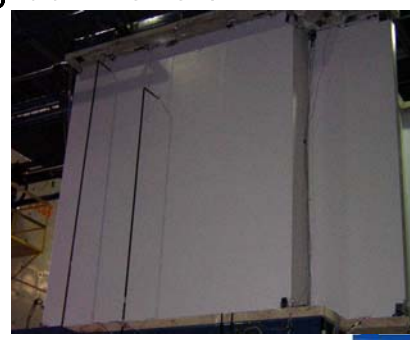


Ceiling system

- Suspended ceiling with lay in tiles, including light and sprinkler

Piping System

- Horizontal U-shaped run at top level with single sprinkler head
- Vertical run connecting both levels



Medical Gas Piping System

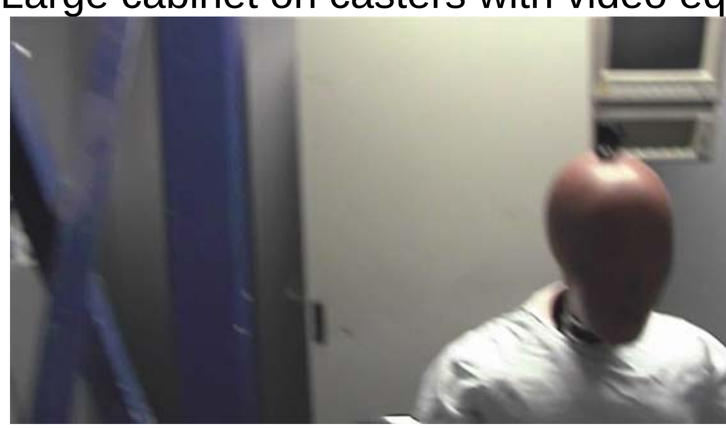
- Two copper lines connected to wall outlets
- Horizontal run supported by trapeze

Medical Equipment - attached

- Wall mounted monitor
  - Anchored to three stud assembly in wall
  - 4 locations including one faulty installation
- Ceiling mounted surgical lamp
  - Supported by steel frame connected to platform

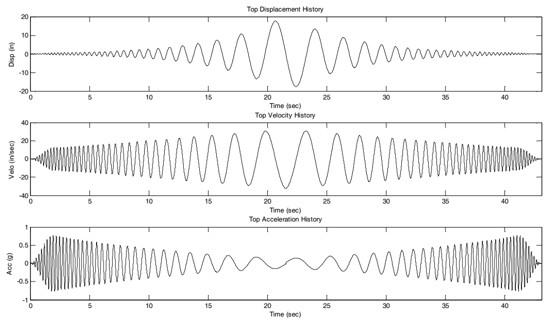
Medical Equipment – free standing

- Gurney with dummy, IV poles with pumps, Large cabinet on casters with video equip.



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%)



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16.3	17.6	1.31	0.87	30.5	32.6	0.73	0.77

Simulation using protocol - MCE

Simulation using protocol - MCE

Simulation using protocol - MCE

Simulation using protocol - DBE

Thank you