Total Project Planning – Case Study 3: *BNCS* Building

Building **N**onstructural **C**omponents & **S**ystems Project

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UC San Diego

December 15, 2015

Outline

- **Motivation**
  - Terminology, Justification
- **Project Overview**
  - Vision, Scope, Resources (human & $$), Timeline
- **Specifics**
  - Design, Construction, Instrumentation, Test Planning & Sequencing, Execution Guidance
- **A Few Important Findings**
  - (there are many)
- **Project Accolades**

What is an NCS?

- **Nonstructural Components & Systems = NCS = common short name adopted in a number of building design codes. Visual elements around us in finished structures…**
- ***Supported* by primary structural system – not *contributing* to primary structural system load bearing needs**
- ***Lightweight* & *low stiffness*, compared with supporting structure**
  - Low damping (lack protection from sharp resonant motions)
- **Designed for *functionality* – often not considering earthquake loads**
- **Often termed "secondary" systems**
- **Broad classification: 1) MEP (mechanical/electrical/plumbing), 2) Architectural & 3) Contents**

Consequences of NCS damage

Calexico Schools
2010 Baja California EQ

- **Major problem during rescue operations**
- **Loss of functionality, facility downtime**
- **Excessive economic losses**
- **Threat to life**

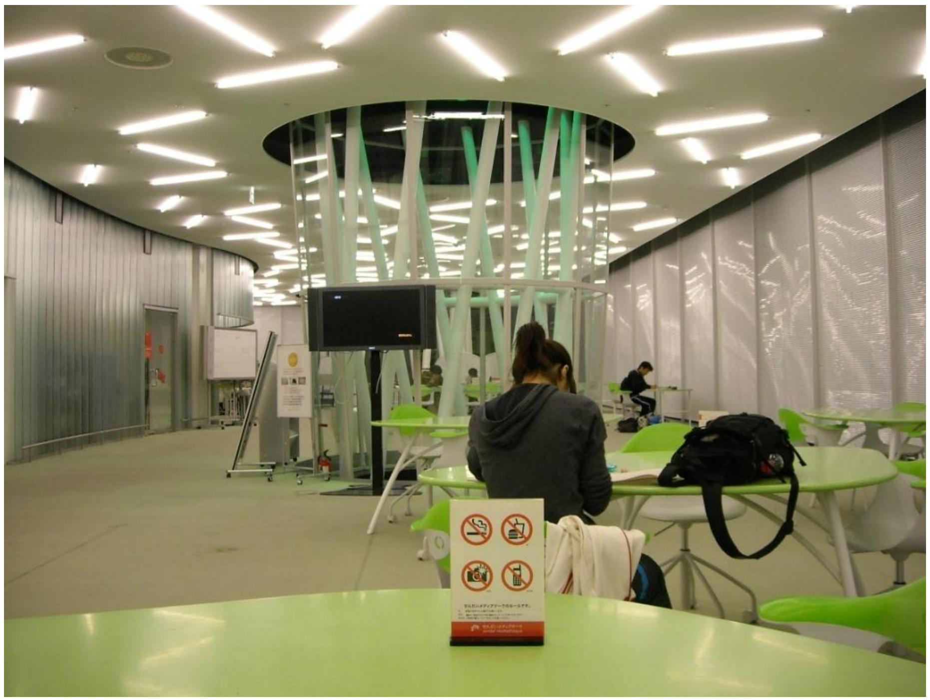
- **Hospitals & other critical facilities: post-earthquake operability of NCSs are *essential* (life saving equipment)**
- **Numerous NCSs play a critical role in minimizing *post-earthquake fire impacts – fire protection NCSs***

Project Motivation:
2011 Tohoku Earthquake, Japan

Sendai Mediatheque (library, constructed 2000)

Plaster board ceiling

Sprinkler head



Before the earthquake

After the earthquake

Courtesy of Shojiro Motoyui

Vision, Scope, Resources, Timeline

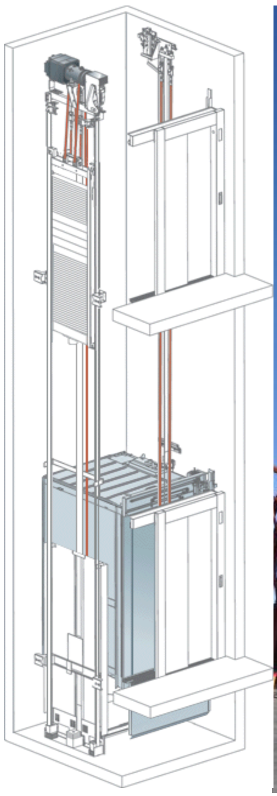
PROJECT OVERVIEW

Project Vision

- To make breakthrough advances in the understanding of <u>total building systems</u> performance (structural *and* nonstructural systems) under moderate and extreme seismic conditions through full-scale testing.
- Obtain data, which are sorely needed to characterize the earthquake performance of structural and nonstructural building systems, including nonstructural systems with protective measures.
- Use this data to validate nonlinear simulation tools, which in turn can be used for higher-performance code design and performance-based seismic design of nonstructural and building systems.
- Infuse findings into seismic design guidelines and codes
  - Validate current code assumptions
  - Advance current code guidelines

Project Overview

➢ **Three-phased full-scale test program conducted on a 5-story building-NCS system (“total building system”)**



Summary of Major NCSs:

- Egress systems:
  - Operable Elevator
  - Stairs
- Facades:
  - Concrete cladding
  - Balloon framing
- Hospital equipment
- Roof mounted equipment
- Sprinkler and riser systems
- Ceilings
- Interior partition walls

HVAC

Facades

Hospital Floor

Testing Scope & Project Resources

- **Three Test Phases**
  1. Base isolated building-nonstructural system
  2. Fixed base building-nonstructural system
  3. Controlled live fire tests
- **~5M US$, multi-organizational 4 year project (2010-2014)**
  - NSF-NEES core research project - $1.2M
  - Englekirk Advisory Board - $1.5M (est)
  - Charles Pankow Foundation - $250k
  - California Seismic Safety Commission (hospitals) - $360k
  - Industry consortium - remainder $ resources, materials, equipment, technical expertise, etc.

Large, Multi-disciplinary Team

- **Core Project Team (>20 faculty, students, engineers)**
  - UCSD, SDSU, Worcester Polytechnic & Howard University
- **Advisory Boards**
  - Industry steering committee (ISC) (>40 companies)
    - ✓ Manufacturers, Sponsors, Technical Advisors
  - Engineering & regulatory advisory committee (ERAC) (10)
    - ✓ Technical oversight (code-perspective)
  - Academic/international liaison group (AILG) (10)
    - ✓ Technical oversight (academic perspective)
  - Englekirk Advisory Board (EAB)
    - ✓ Building (skeleton) design & funding
- **Federal & state partners, foundations**
  - NSF-NEESR, California Seismic Safety Commission, California Hospital Authority, Charles Pankow Foundation, FEMA

More than 300 individuals interacting within this project!

Core Team

Name	Affiliation
Tara Hutchinson (PI)	UC San Diego
José Restrepo (Co-PI)	UC San Diego
Joel Co	
Ken Wa	
Claudia	
Robert	
Brian M	
Matt Ho	
Robert Englekirk	UC San Diego / Englekirk & Sabol Consulting S.E., inc.
Mahmoud Faghihi	Englekirk & Sabol Consulting Structural Engineers, inc.

Name	Affiliation
Consuelo Aranda	San Diego State University
	ate University
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Partners

NEES

Funded by the National Science Foundation under Grant no.: CMMI-0936505

- Academic: University of California, San Diego (UCSD), Worcester Polytechnic Institute (WPI), San Diego State University (SDSU), and Howard University (HU)
- Broad stakeholder participation (industry and government)

Government & Foundations

FEMA

State of California Seismic Safety Commission (SSC)

SFPE

CHARLES PANKOW FOUNDATION
Building Innovation through Research

Design

ARUP

PCI

Brandow & Johnston Associates Structural Engineers

sirve Seismic Protection Technologies

Insurance Evolved FM Global

SIE inc. Seismic Isolation Engineering

MACTEC

Klausbruckner and Associates

Englekirk

Industry Partners

REGAL INDUSTRIES, INC.

AB&I FOUNDRY

WATTS

DELCO SALES
Hawaii California Nevada

PACIFIC STAIR CORPORATION

USG

STATE FARM INSURANCE
Auto Life Fire

B.A.C.

QUAKE HOLD! INDUSTRIAL

WESTERN FIRE PROTECTION

IBM

HILTI

MASON INDUSTRIES

SQUARE D
by Schneider Electric

sto

CEMCO
Steel Framing and Metal Lath

SURE-BOARD

AGI
Seismic Products

RUSKIN

MMFX TECHNOLOGIES CORP

MORLEY BUILDERS

OmegaFlex

HRC

BauGrid

Armstrong

WEHR MINERALS

Schindler

CLARK PACIFIC
Precast. Building for Life.

LAWRENCE DOORS

WILLIS CONSTRUCTION CO. INC.
PRE-CAST CONCRETE PRODUCTS

DASMA
Door & Access Systems Manufacturers Association International

Hill-Rom
Enhancing Outcomes for Patients and Their Caregivers.

Responder Systems Corporation
LOS ANGELES

STANLEY
Healthcare Solutions

HELMER

BIAMP SYSTEMS

stryker

MODULAR SERVICES COMPANY

TANNOY

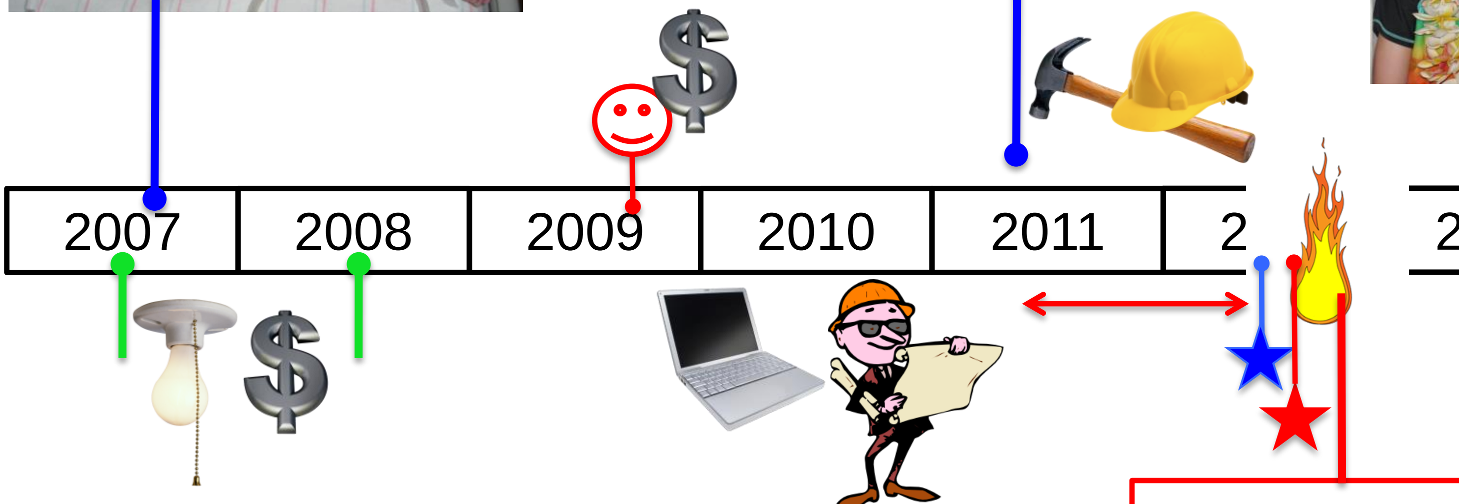
besam

Rauland

e.g. Hilti Team (32 individuals >10%!)

Project gy

Temus: March 31, 2011



- **Pre-proposal workshop**
- **NEESR Funding & Kick-off meeting**
- **Construction (~9m)**
- **Seismic Testing Phases (~1m)**
- **Live Fire Testing (~0.5m)**

Design & Construction

SPECIFICS

Shake Table Specimen Design Questions

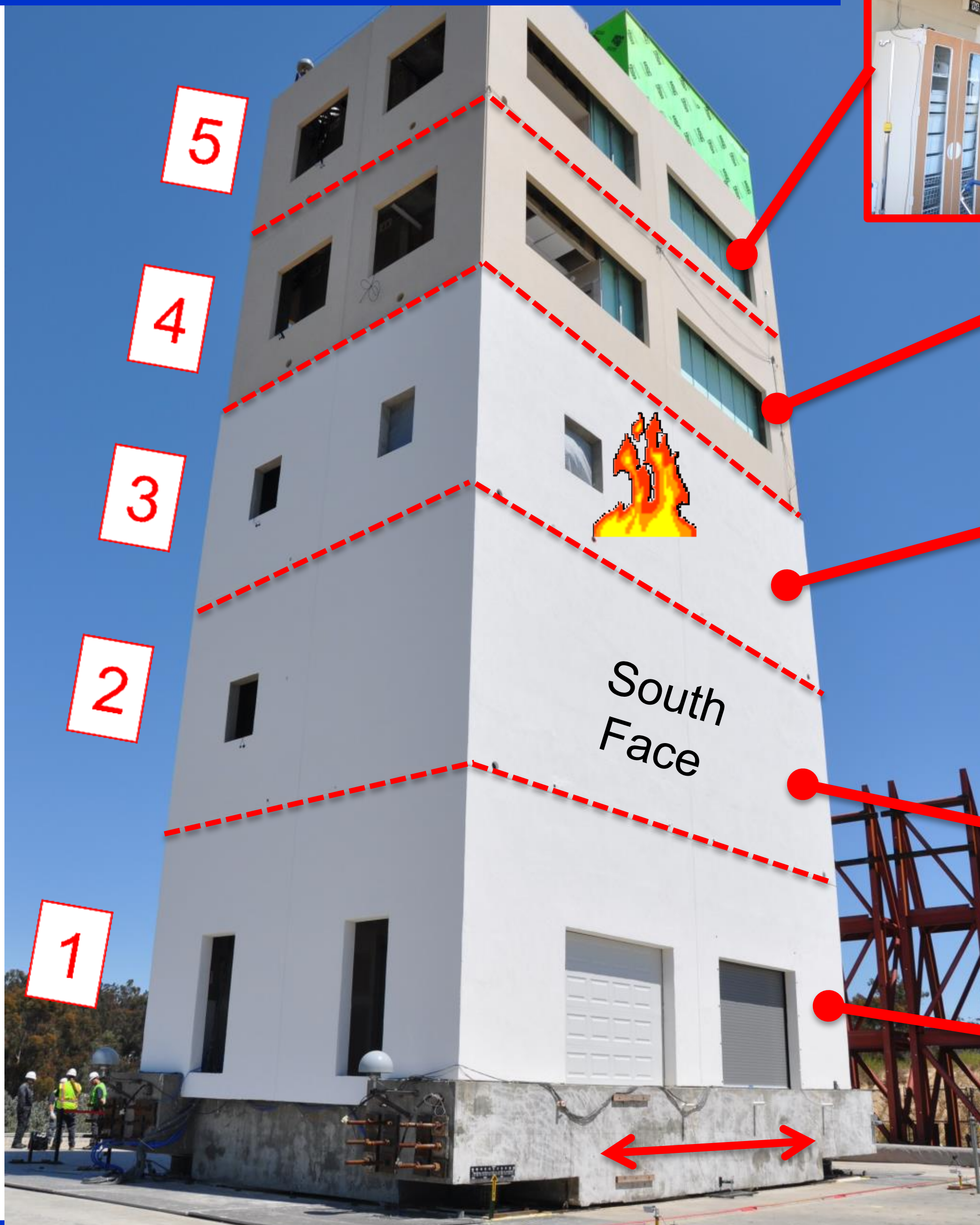
- **What type of structural skeleton is needed?**
  - Structural skeleton role: provide a vehicle for delivering demands to NCSs (accelerations & deformations)
  - Many iterative discussions, options…
    - ✧ Flexible steel frame-braced structure
    - ✧ Stiff steel braced structure
    - ✧ Podium-style (lower concrete wall & upper flexible frame)
    - ✓ Reinforced concrete frame-braced
  - Decisive aspects: cost (design team), balance between benefits of flexible frame (expect large lower floor drifts) & nominally large accelerations (upper floors); shake table platen size
- **What types of nonstructural components are essential?**
  - Secure the key “bad actors” (or those lacking data!) early on prior to NEESR proposal submission e.g. (egress, façade, passive & active fire systems)
  - “If we build it they will come”

Structural System

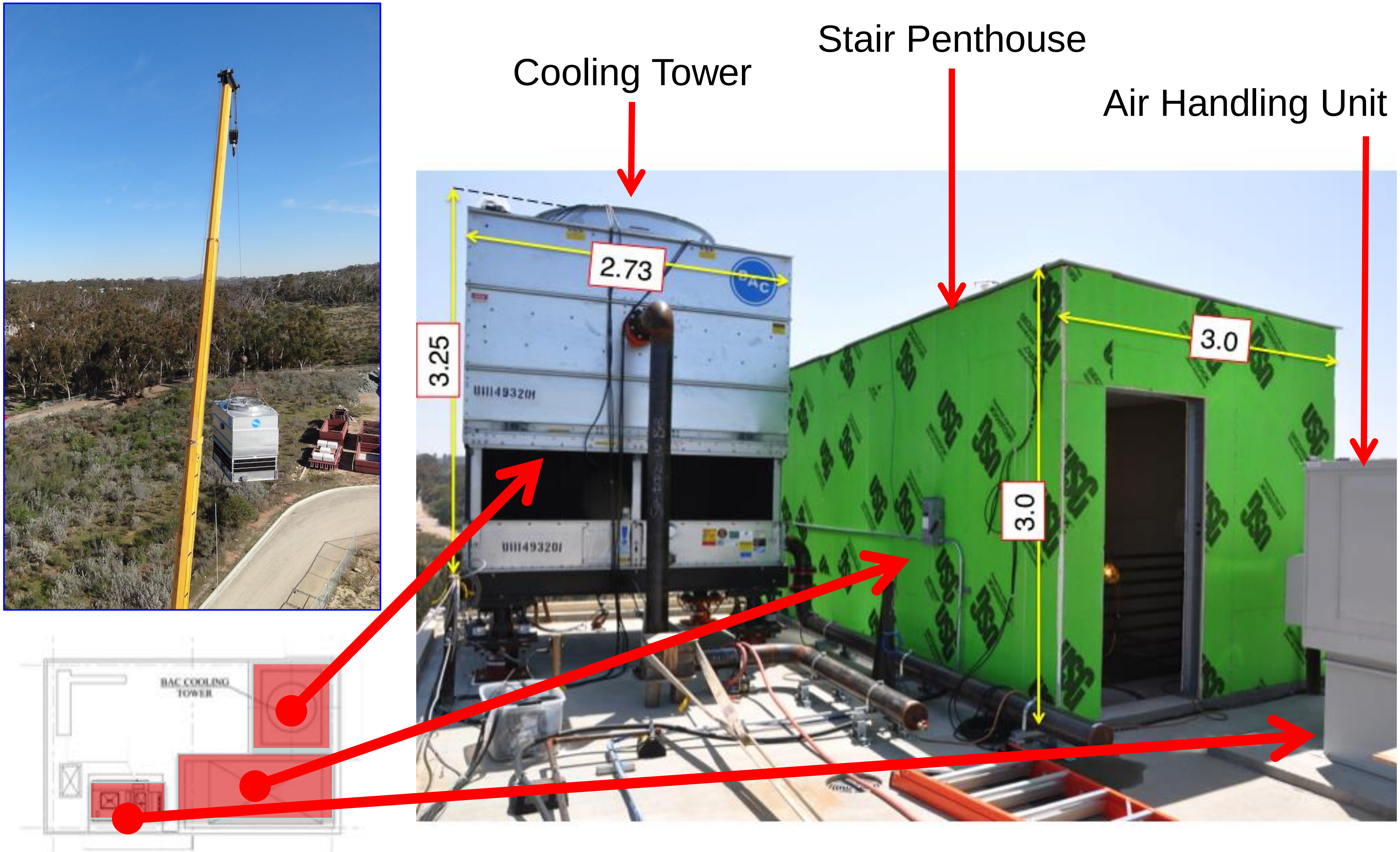
- Design (criteria – community decision):
  - Downtown LA (site class D; 7 MCE motions, 3 service motions; 2-2.5% design interstory drift ratio, peak ~0.7-0.8g floor acceleration)
- Poured-in-place concrete
- 2 bay x 1 bay; pair of SMRF (shaking direction)
- 4.2m story heights; 5 floors; 21.3m + 1.5m foundation + 4m tower = 26.8m (tallest on UCSD table)
- Elevator shaft and stairway openings at floor diaphragms
- 10.4m x 6.1m c/c footprint
- ~ 1 sec longitudinal (fixed base)
- ~2.5 sec longitudinal (base isolated)

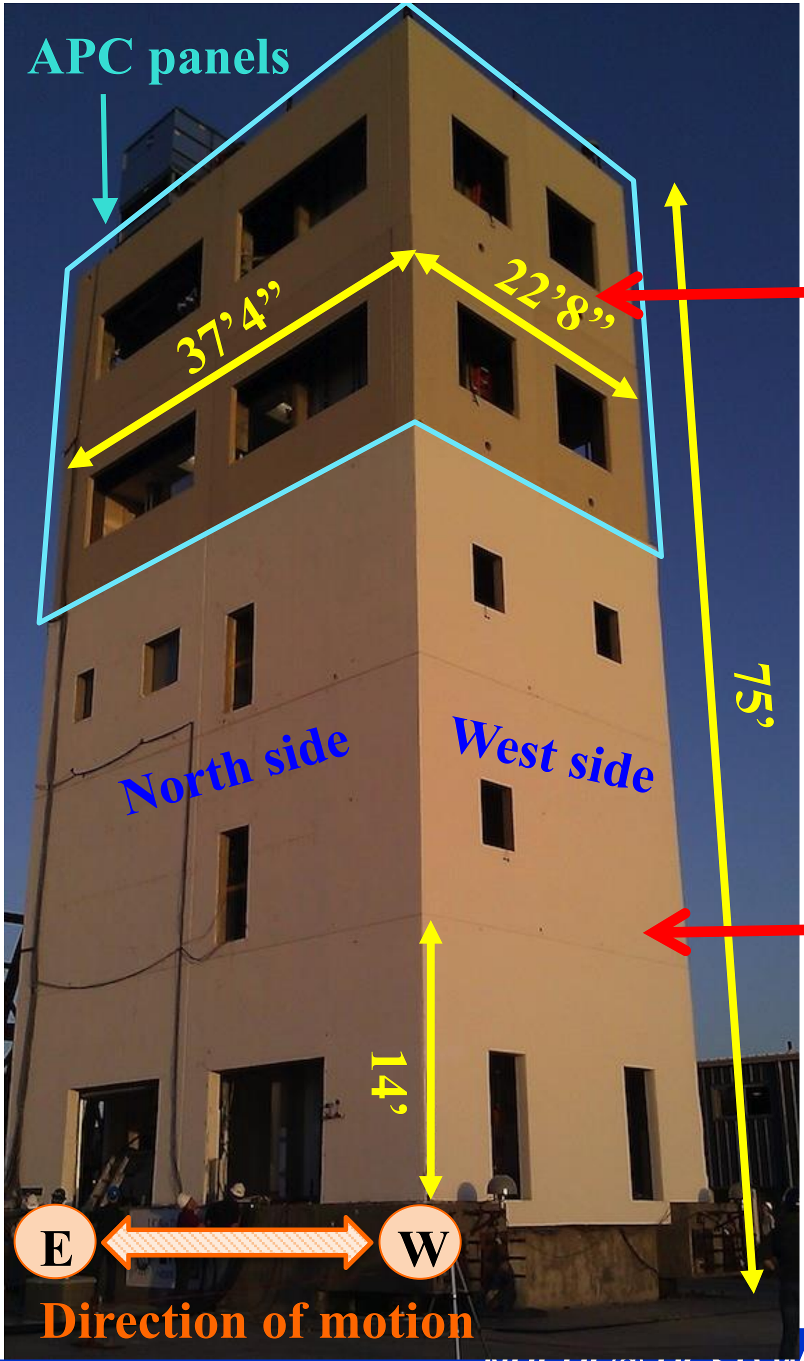
- **Bare structure: ~4900kN**
- **Building+NCSs: ~6300kN**
- **(Foundation = 1870kN)**

Architectural (NCS) Design



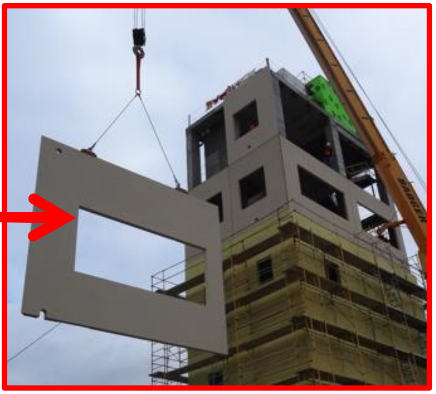

Roof Mounted Equipment





Exterior Facades

Architectural Precast Concrete Cladding



Balloon-framed metal stud+EIFS

NW View

Construction Management

- **During construction, such a complex project needed careful planning. For this effort, SDSU led a comprehensive construction management effort**
  - Coordinating all superstructure construction phasing
  - Coordinating all nonstructural installation phasing
  - Documenting on-site deliveries
  - Dealing with construction delays (reorganizing subs)
  - We held multiple planning meetings (2009, 2010, 2011) with all industry partners & researchers

Prof Ken Walsh (SDSU)

Construction (Superstructure)

ROOF SLAB:
September 21st,2011

FIFTH FLOOR SLAB:
September 6th,2011

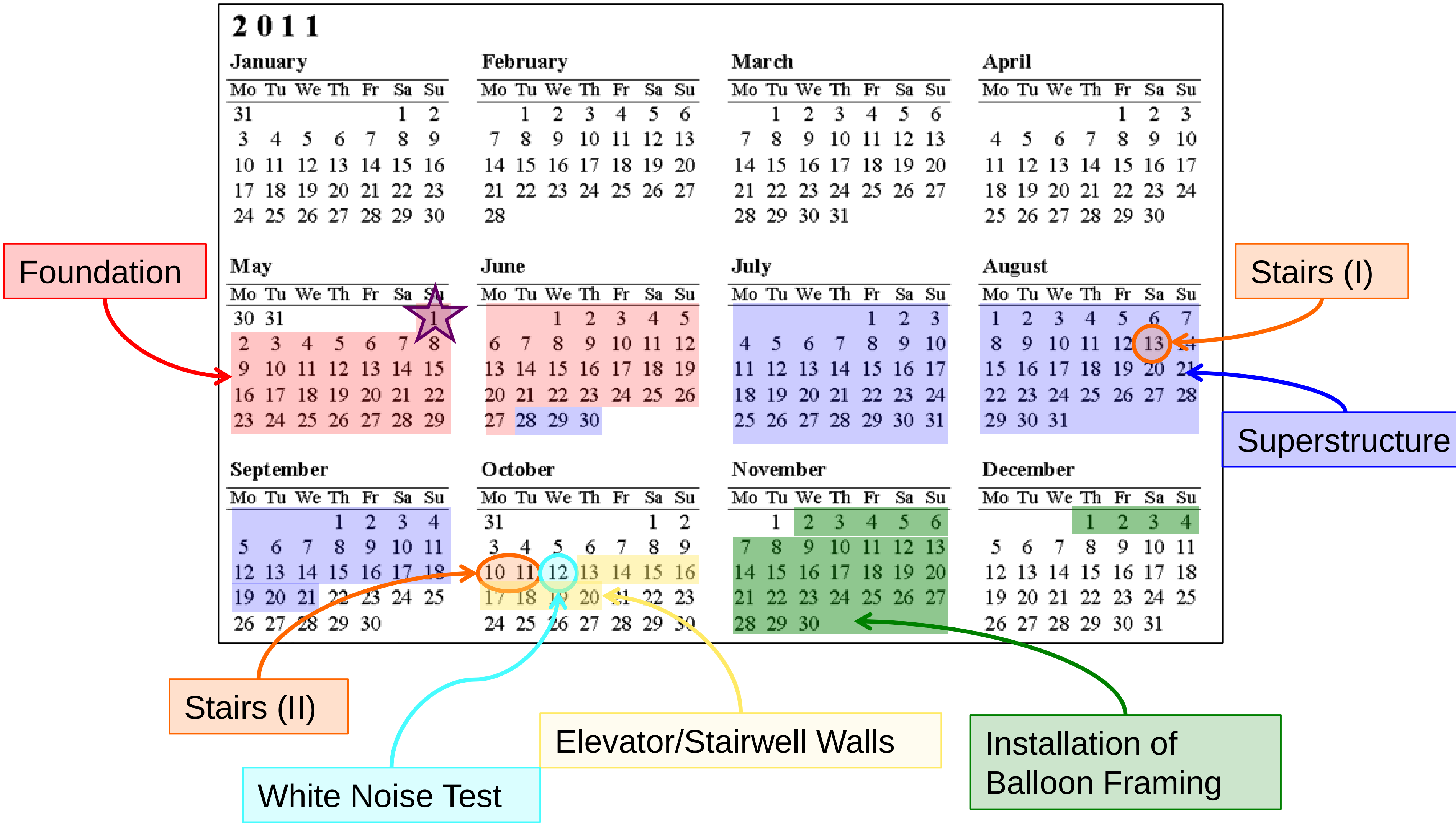
FOURTH FLOOR SLAB:
August 19th,2011

THIRD FLOOR SLAB:
August 3rd,2011

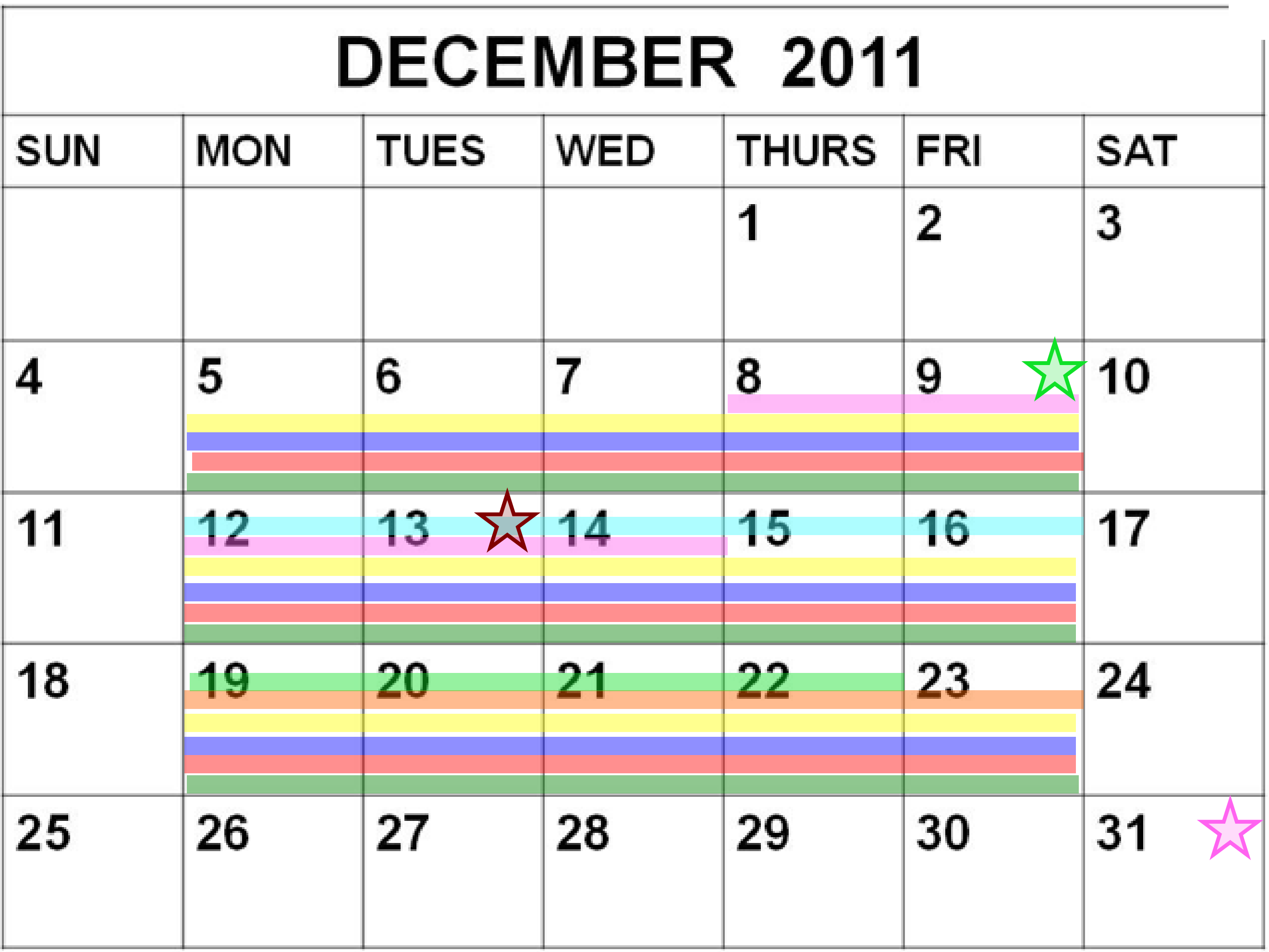
SECOND FLOOR SLAB:
July 15th,2011

FOUNDATION:
June 27th,2011

Construction (Nonstructural)

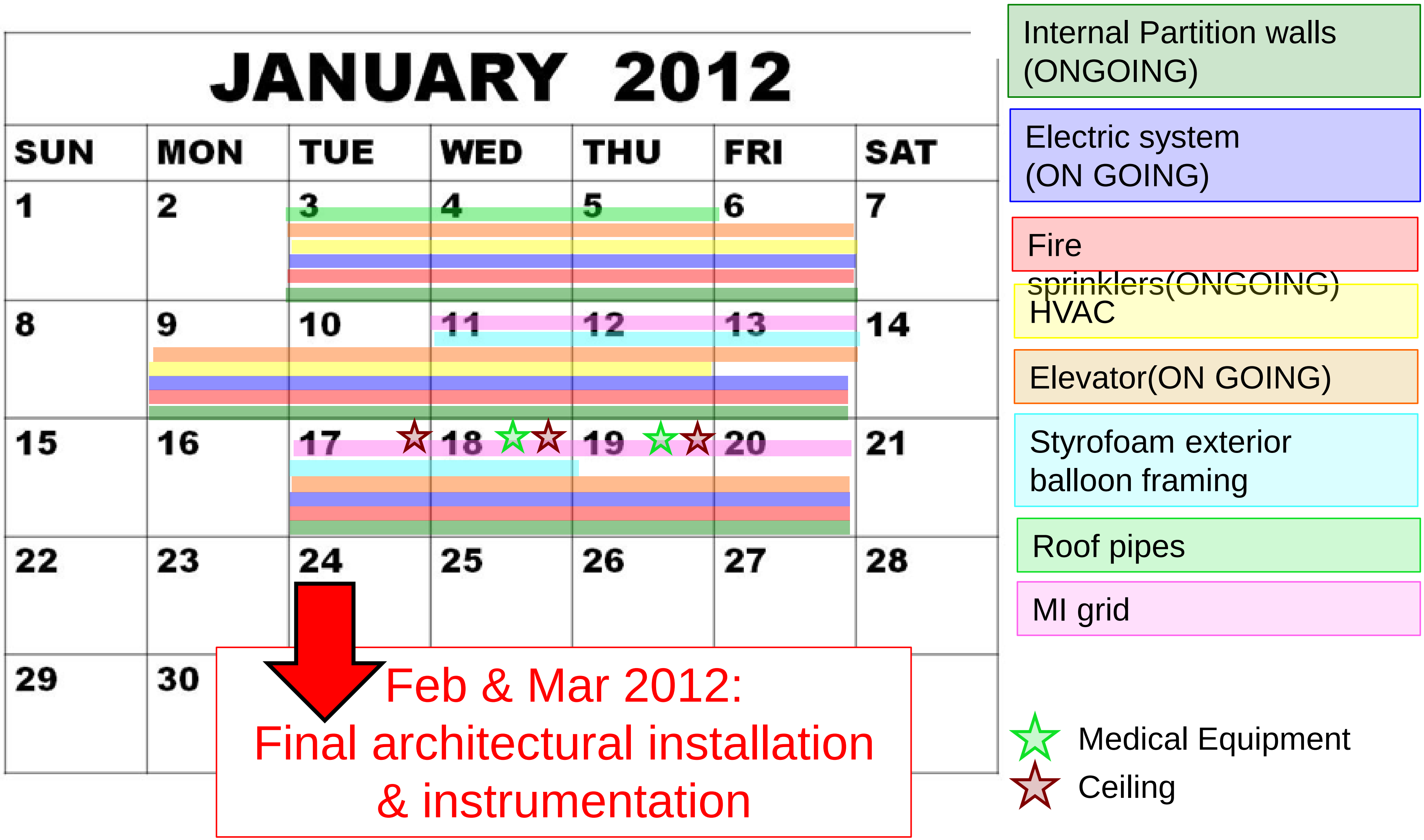


Construction (Nonstructural)



- Internal Partition walls (ONGOING)
- Electrical system (ONGOING)
- Fire sprinklers (ONGOING)
- HVAC
- Gas Pipes
- Elevator
- Waterproofing paint on balloon framing
- Precast concrete cladding
- Cooling Tower
- AHU
- Isolators arrived on site

Construction (Nonstructural)



Research Activities (pre-test)

- **During construction, research team needed to multi-task**
  - Conduct pre-test simulations (guide motion selection, instrumentation layout)
  - Watch, document, & take part in (as feasible) construction
  - Create instrumentation drawings
  - Watch, document, & take part in (as feasible) construction
    - ✓ We created a weekly construction log documenting all key construction activities digitally & disseminating them during a weekly team meeting

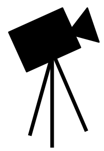
Instrumentation, Test Planning & Sequencing

SPECIFICS

Instrumentation

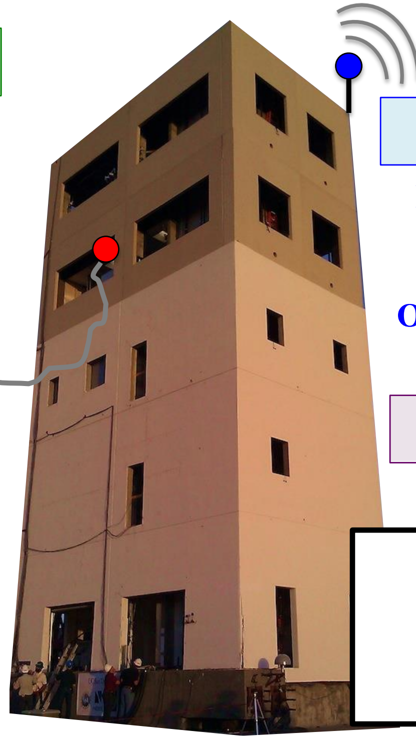
VIDEO CAMERAS

Provided by industry partners and by NEES@UCSD



ANALOG SENSORS

Three DAQs provided by NEES@UCSD and NEES@UCLA (UCLA1 and UCLA2)



GPS

Provided by the Scripps Institute of Oceanography

STILL CAMERAS

High resolution digital

We produced an entire 200pg report summarizing the instrumentation (cameras & analog sensor details)

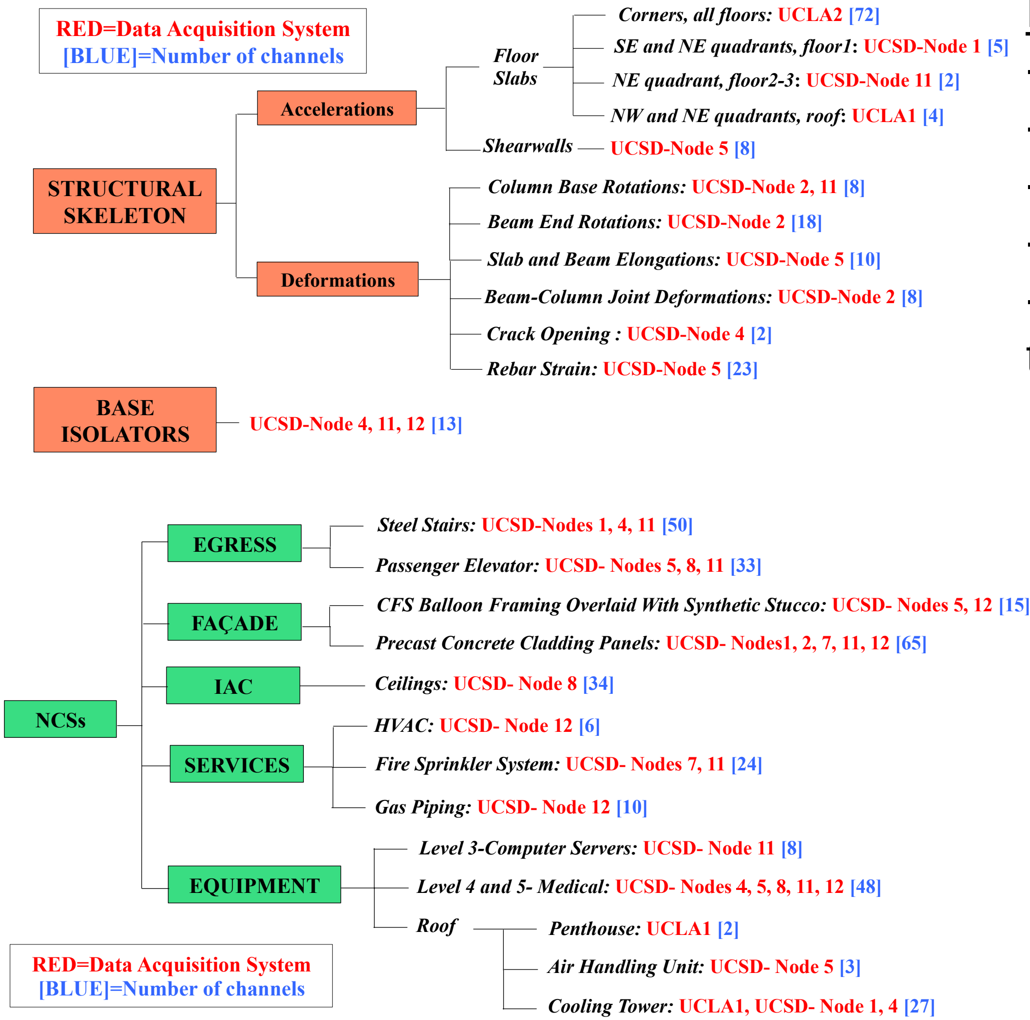
Analog:

420 channels: NEES@UCSD + 90 channels: NEES@UCLA

= 510 channels

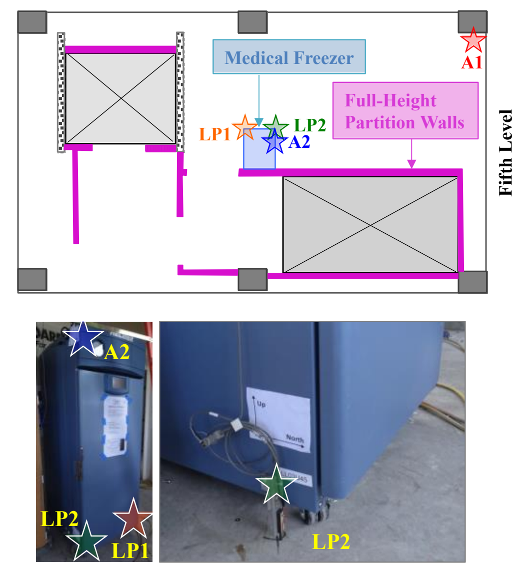
Structure (~1/3) + NCSs (~2/3)

Analog Sensors



<u>Every sensor was:</u>

-Physically attached to the structure
-Provided a unique name
-Cable-based connected to the DAQ
-Connected to a NODE
-Visually & digitally documented (during testing as well!)



<u>Medical freezer: Level 5</u>

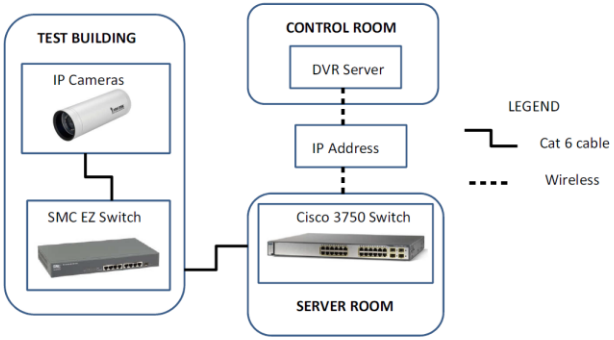
Video Imagery

➢ **The importance of high quality video cannot be understated**

Table 1. Cameras used during seismic test phase.

Camera Type	Typical Image of Camera	Number of Cameras	Uncut Data Collected (GB)	Sample Snapshot of Camera View
IP		56	~140	
Coax		16	~43	
HD Camcorder		8	~215	
GoPro HD HERO2		7	~200	

*Note: Not all cameras were used for each earthquake motion.

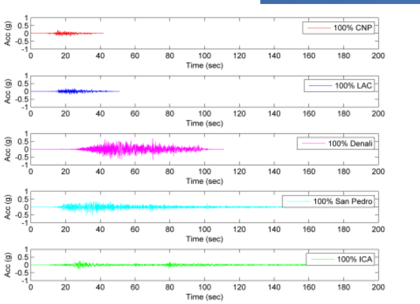


Panoramic Imagery

Third Floor (**before** fire testing)

Third Floor (**after** fire testing)

Phase 1: Base isolated building-nonstructural system



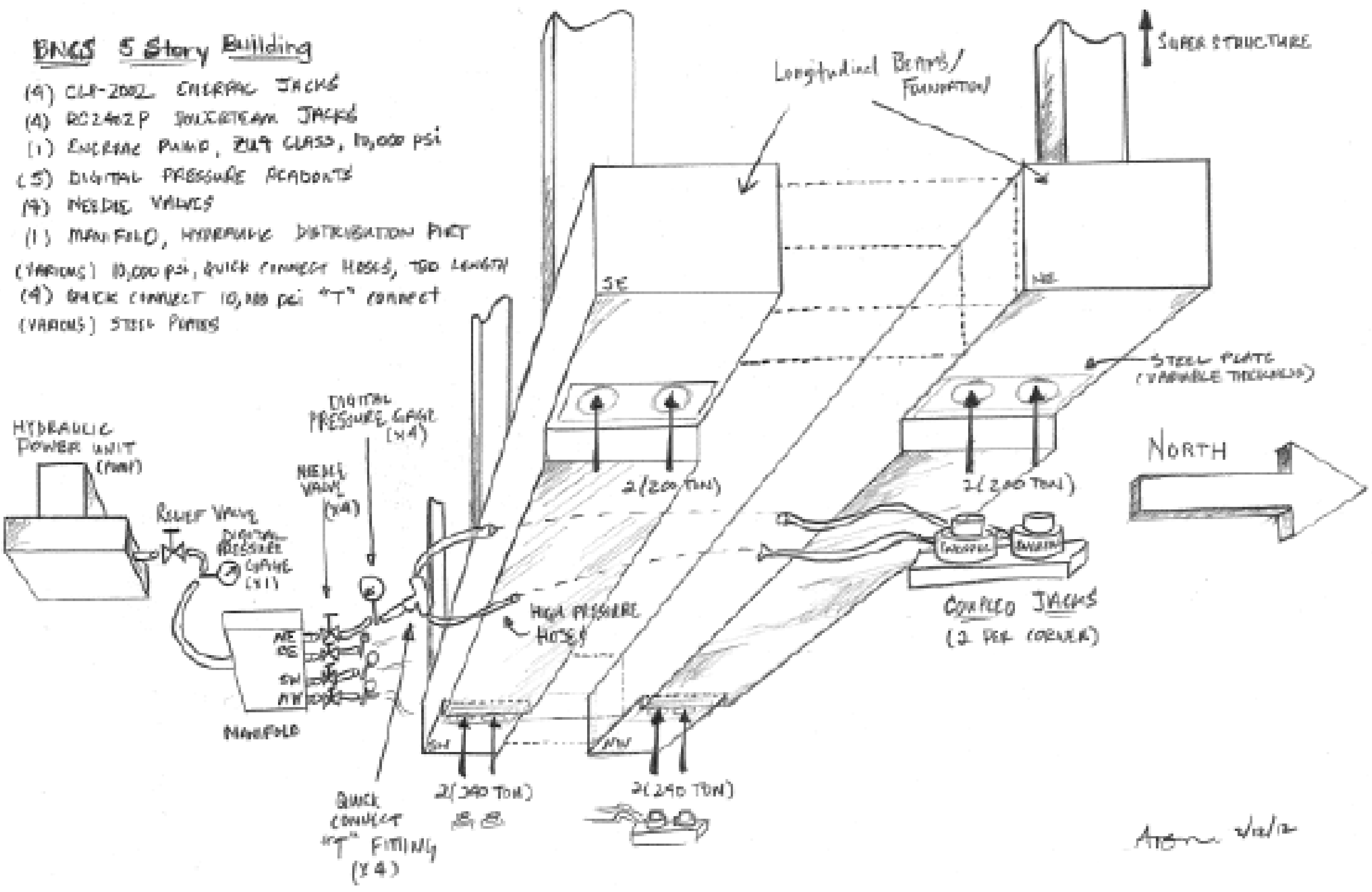
4 days of seismic motion testing (April 16-27, 2012)

1. High damping rubber, cylindrical bearings placed @ each corner of building (4 total)
2. Building elevated from shake table

Building Lift

- **We lifted our ~700 ton building twice (to install & remove isolators)**
  - Building was cast with a 12” pedestal, isolator was 3-1/16” taller, therefore we lifted it 4”
- **Safety was of upmost importance; UCSD Site staff were outstanding in supporting and executing this effort**
- **Process:**
  - Propose a sequence of lift in close consultation site staff
  - Collect materials
    - ✓ Purchase/rent/pickup jacks (we used 8x enerpac pancake jacks, 200 & 240ton@10ksi; we rented 4 of these, site had 4)
    - ✓ Test jacks
  - Un-PT and unbolt vertical rods, unbolt pedestals
  - Install jacks
  - Install linear potentiometers & redundant needle valves
  - Maneuver plates
  - Install isolators (or pedestal for the second lift)

Building Lift (artistic rendering, Gunthardt)

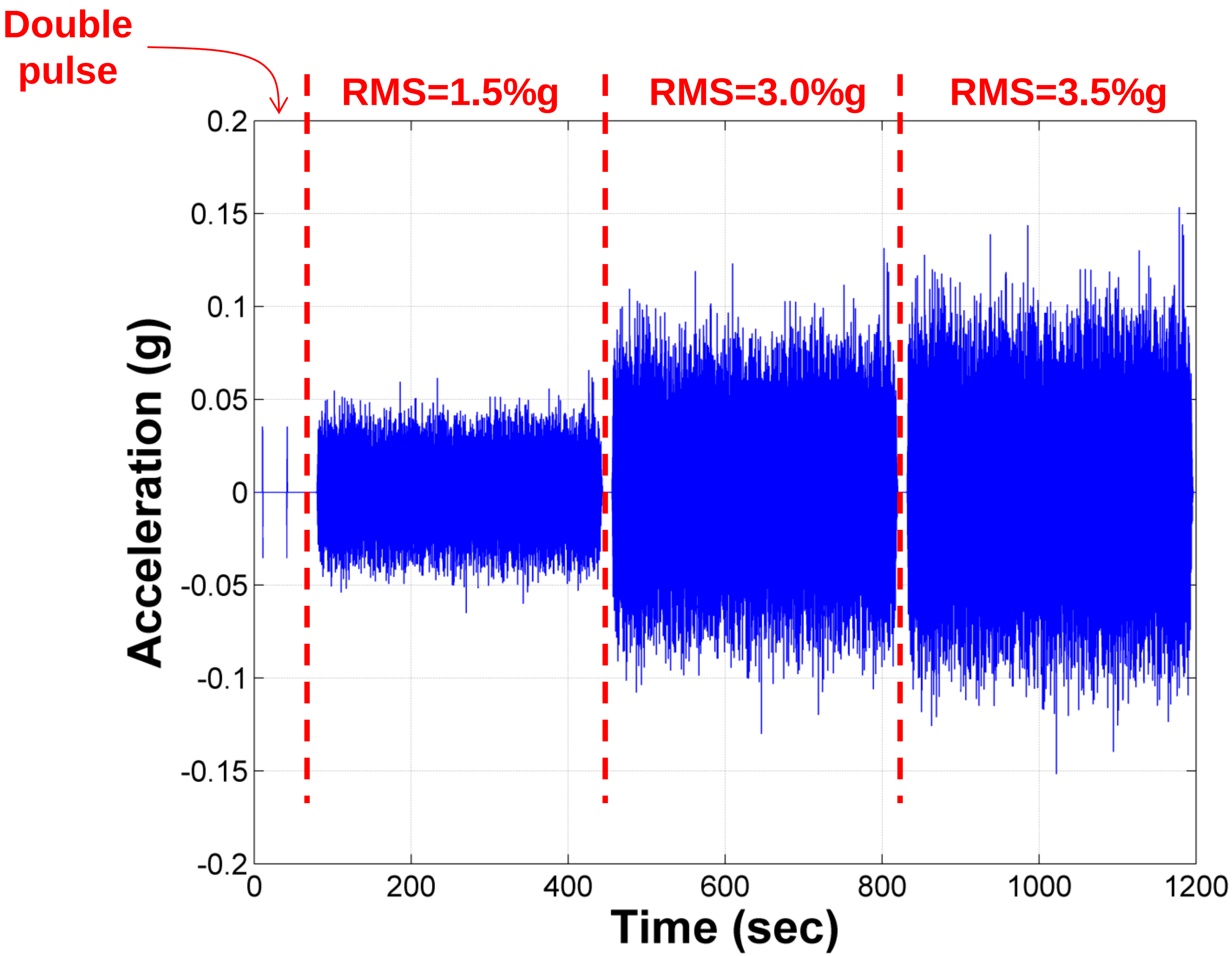


Phase 2: Fixed-base building-nonstructural system

4 days of seismic motion testing (May 7-15, 2012)

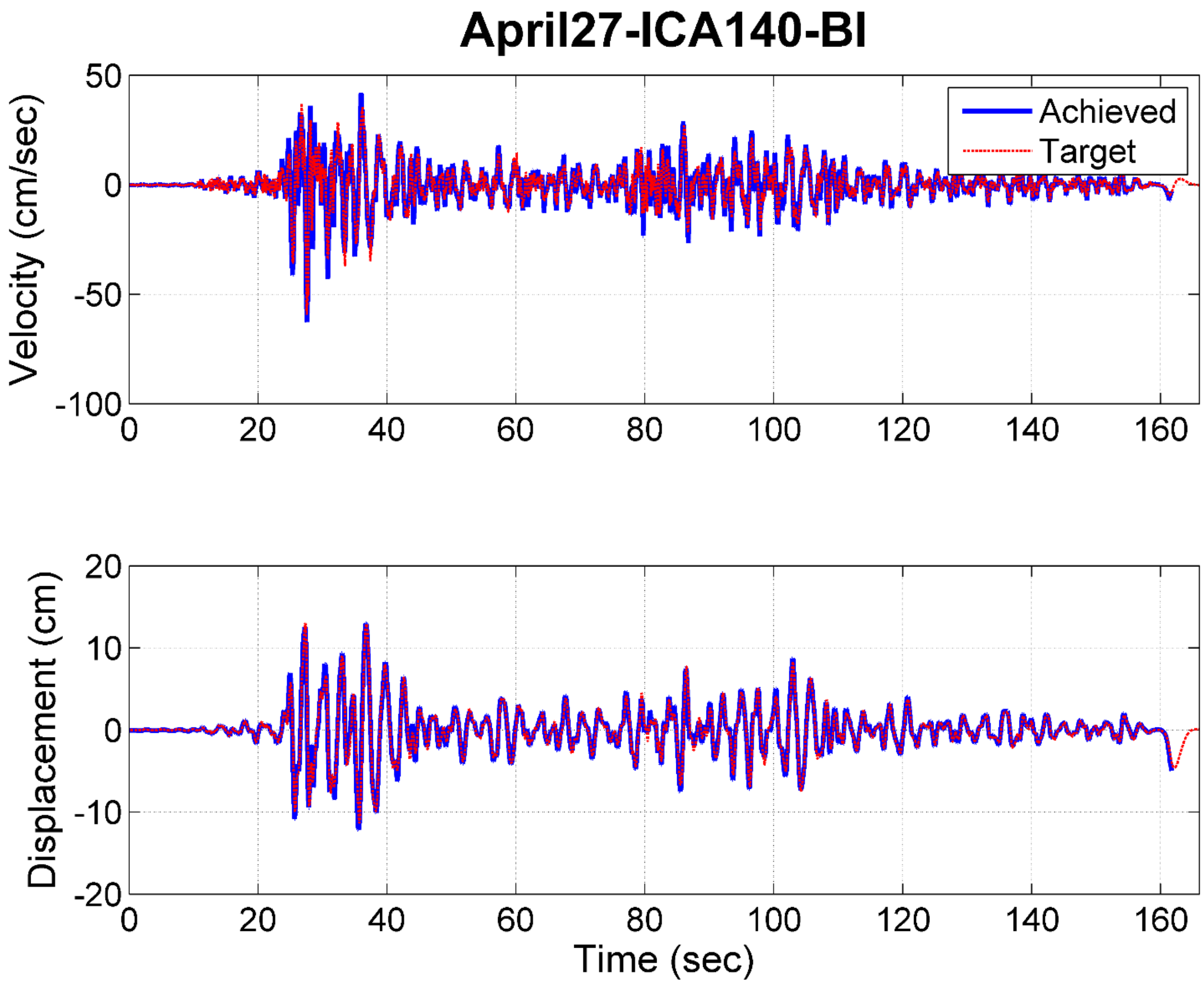
1. Building resting on shake table
2. Post-tensioned at its perimeter

White Noise Motions

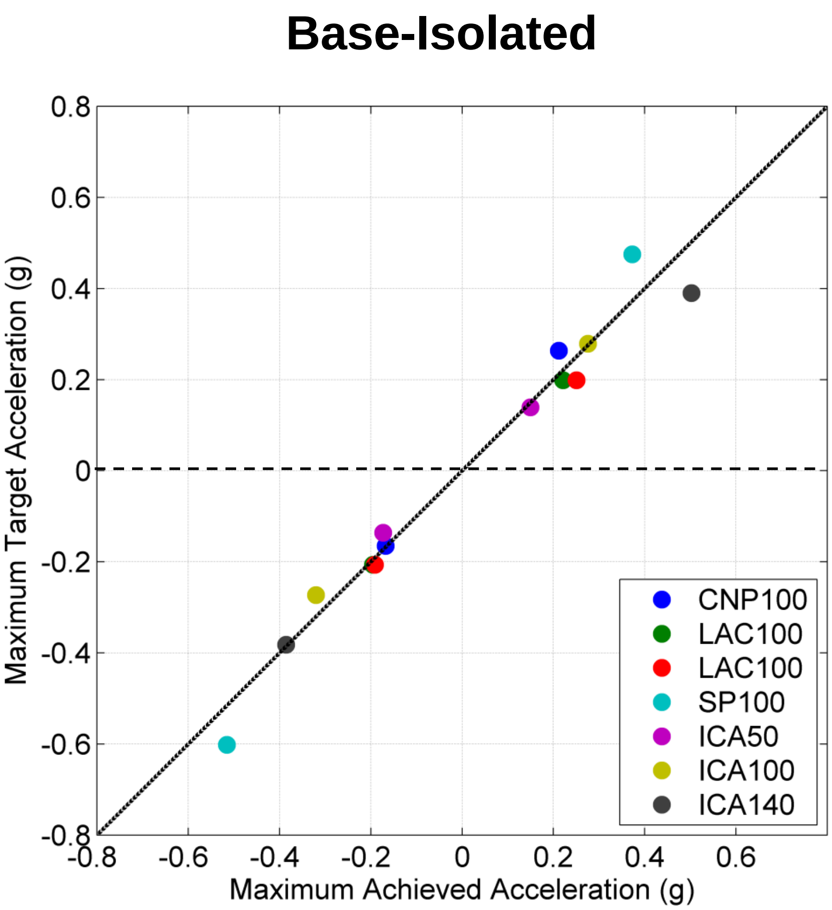


We performed WN before and after seismic tests to asses the state of the structure (SI)

Tracking the Table Performance



Maximum Acceleration



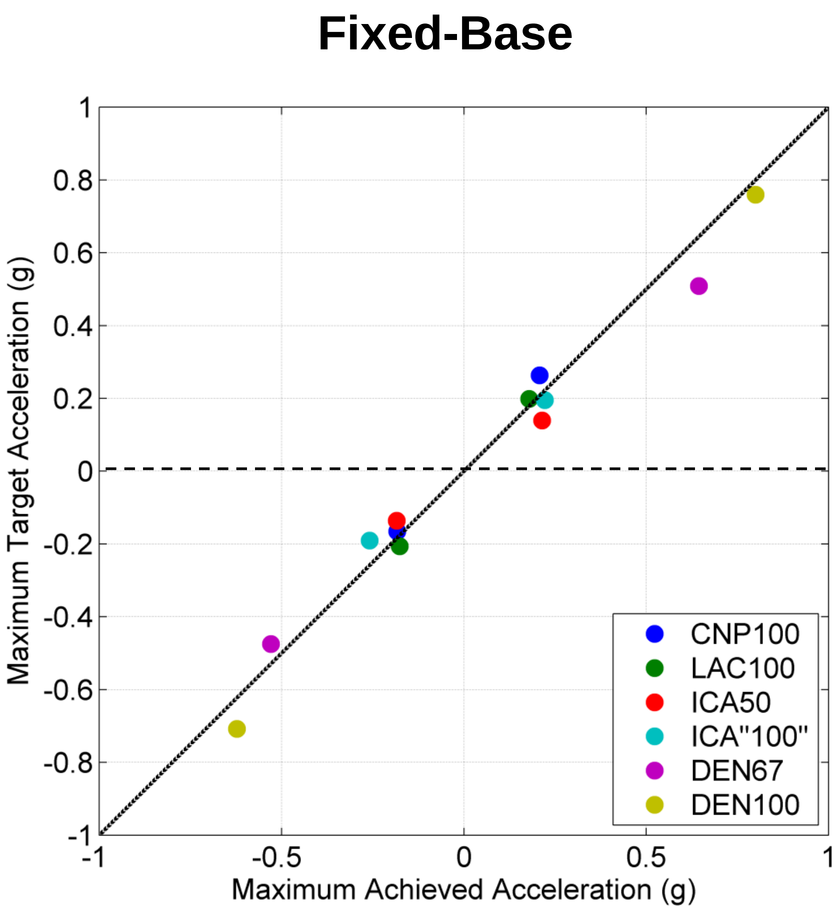
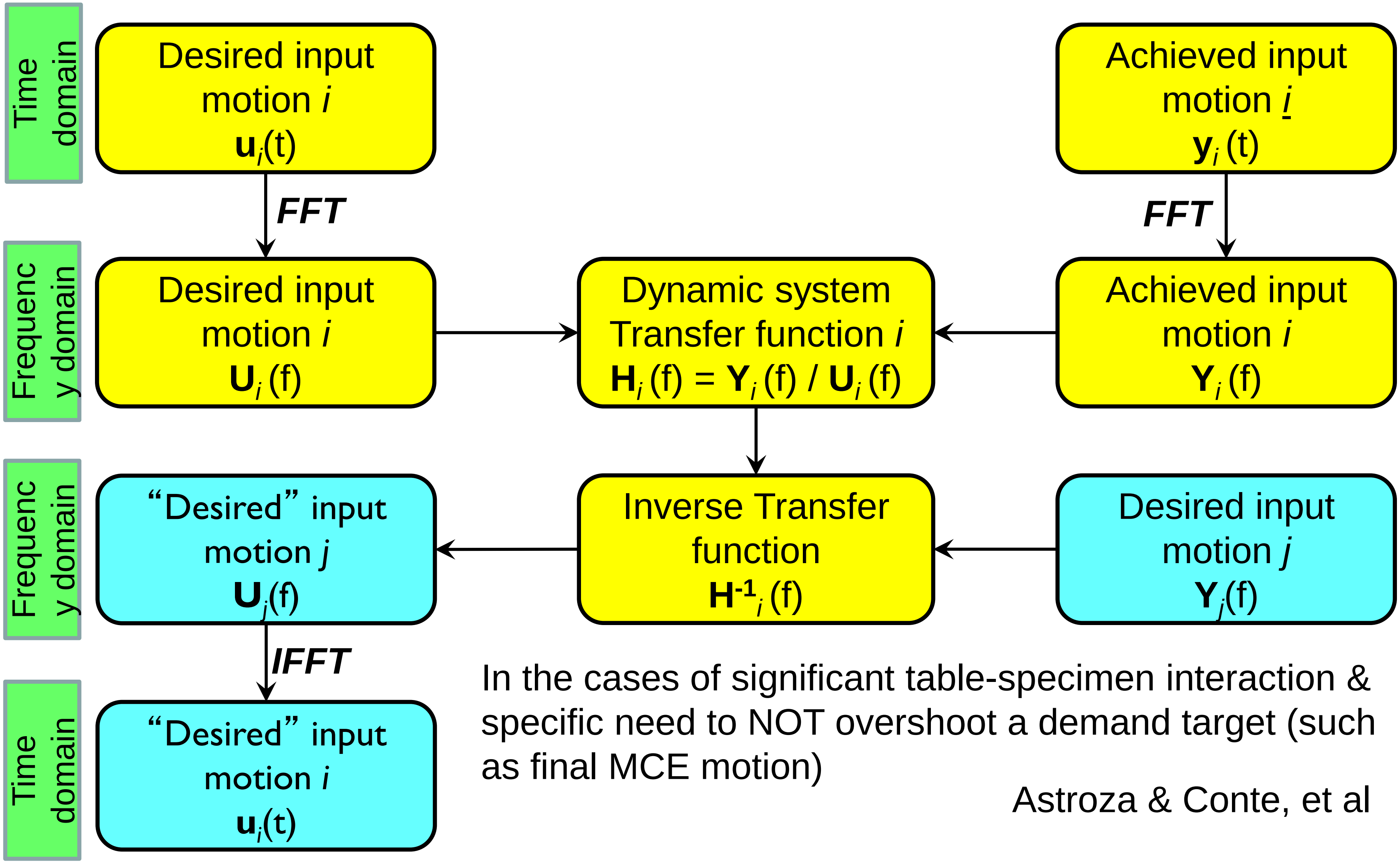


Table Performance: Guidance for Subsequent Motions



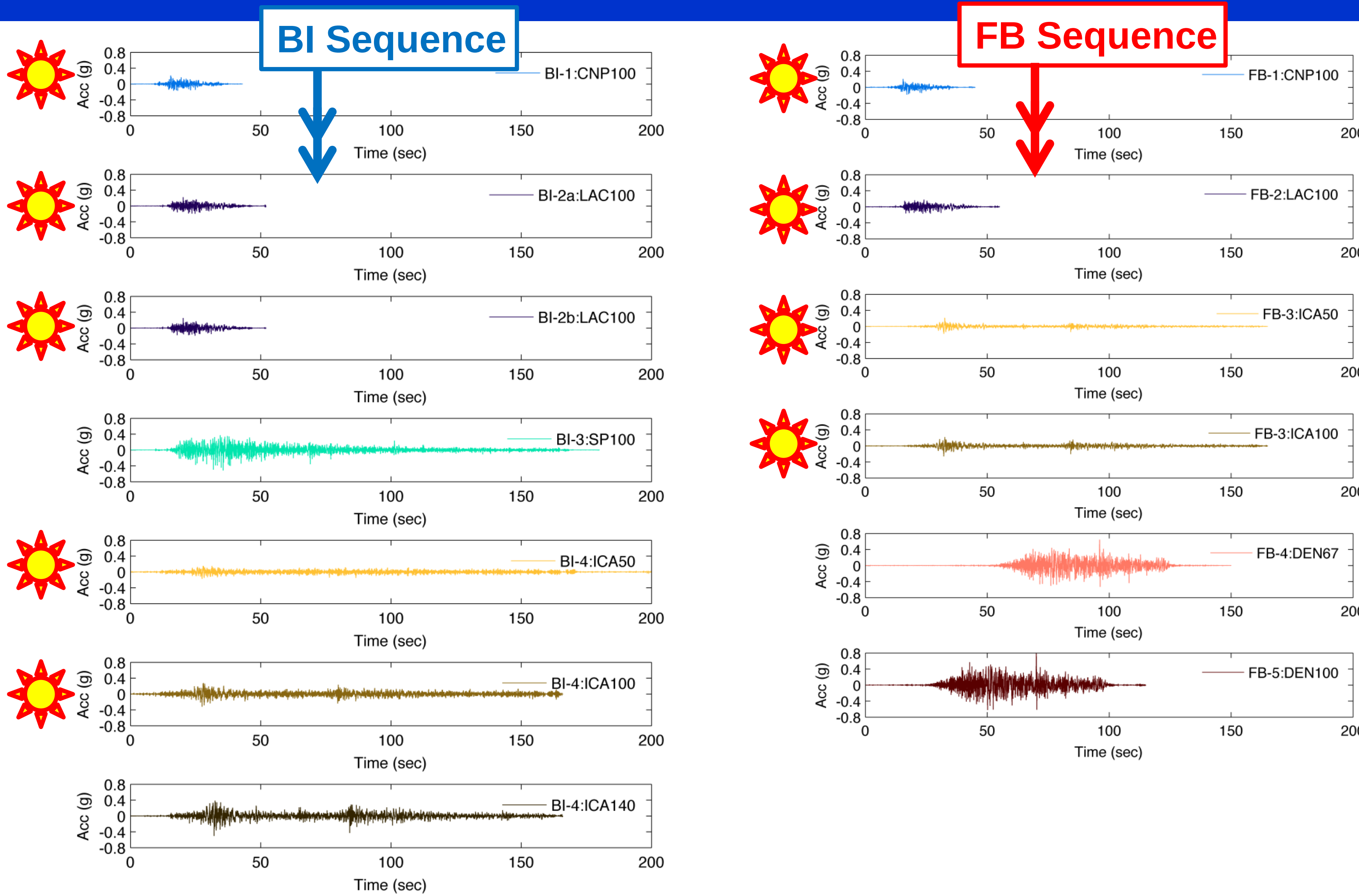
In the cases of significant table-specimen interaction & specific need to NOT overshoot a demand target (such as final MCE motion)

Astroza & Conte, et al

Motion selection, sequencing & scaling strategy

- **Overlap between portion of BI & FB motions**
- **< 0.5% Peak Interstory drift ratio (IDR) BI Phase**
  - Service level hazards (~43yr event)
  - Preserve structure for FB phase
- **Motions with varied characteristics**
  - Motion from CA/West coast US
  - Long duration of shaking
- **Achieve design performance objectives in building (FB)**
  - 2-2.5% Peak IDR
  - 0.8g or so PFA
  - ~Design earthquake event
- **Achieve well above design demands**

Seismic Motions: Achieved



Phase 3: Controlled live fire, pressurization & smoke tests

3 days of live fire testing
(May 23-25, 2012)

Test Execution, some informal guidance

SPECIFICS

Plan well in advance “between-motion activities”

- **Safety inspection – site staff – NO ENTRANCE into test specimen**
- **Tier 1 video & data analysis**
  - Rapid review of individual data channels
  - Safety & subsystem integrity checks
- **Tier 2 video & data analysis**
  - Specific components, subsystems
- **Tier 3 video & data analysis**
  - More detailed analysis (as time allowed)
- **Physical inspection – research team**
  - 2-3 research (core team) members were teamed with ALL invited industry partners (no industry partners were allowed to freely roam the building

Continued….

- **Functionality checks**
- **Compartment pressurization tests (WPI)**
- **Replenish water cooling tower**
- **Replace push-pull rods at PCC connections**
- **Replace damaged ceiling tiles**
- **Replace sensors, reposition cameras**
- **Reposition equipment, replace component of a subsystem as needed**
- ***QuakeHold* – free BI; strapped FB**
- **…**

Media Exposure

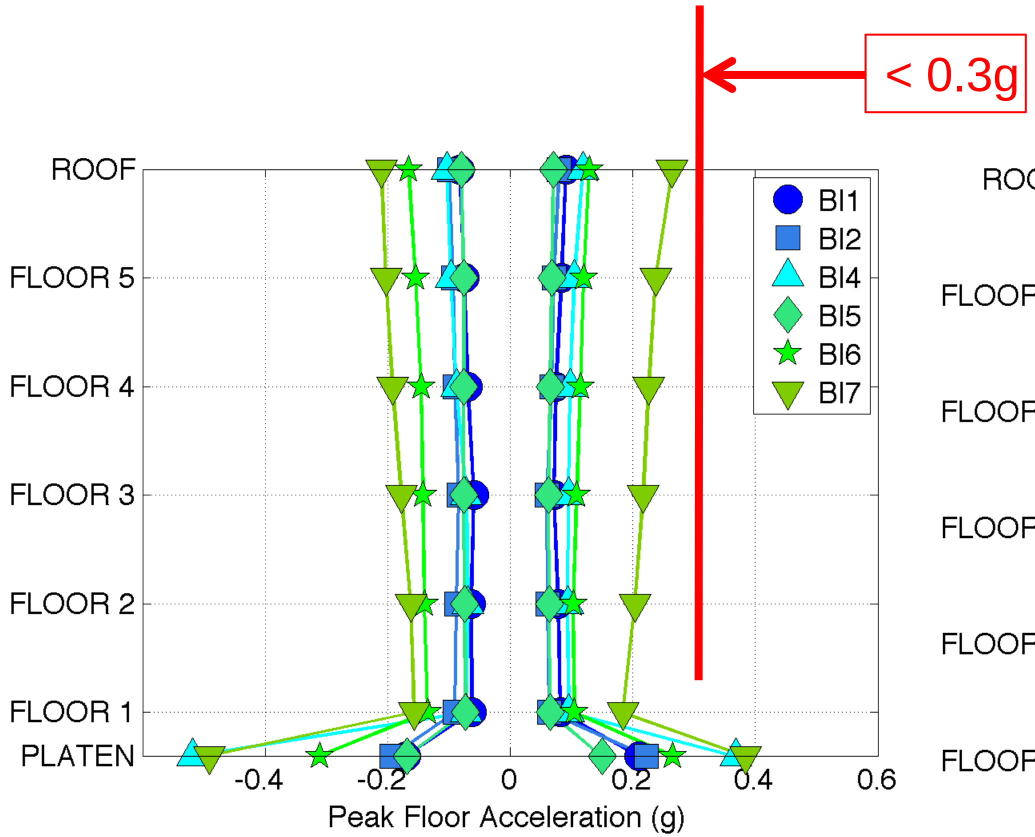
- **Large-scale tests are a terrific opportunity to provide visibility to our efforts as a research community**
  - Video documenting the entire process (construction, testing, demolition)
- **Look for help/suggestions/media teams to provide support and help document all aspects**
- **We held three key "media days"**
  - UCSD-JSOE advertised (sent out media advisories & coordinated all incoming media groups)
  - All major national news channels were allowed on-site, several international media channels; interviewed project PIs & industry sponsors
  - Within one of these hosted an NSF-Live Science Webcast with Dr. Joy Pauschke (answering questions live between tests)

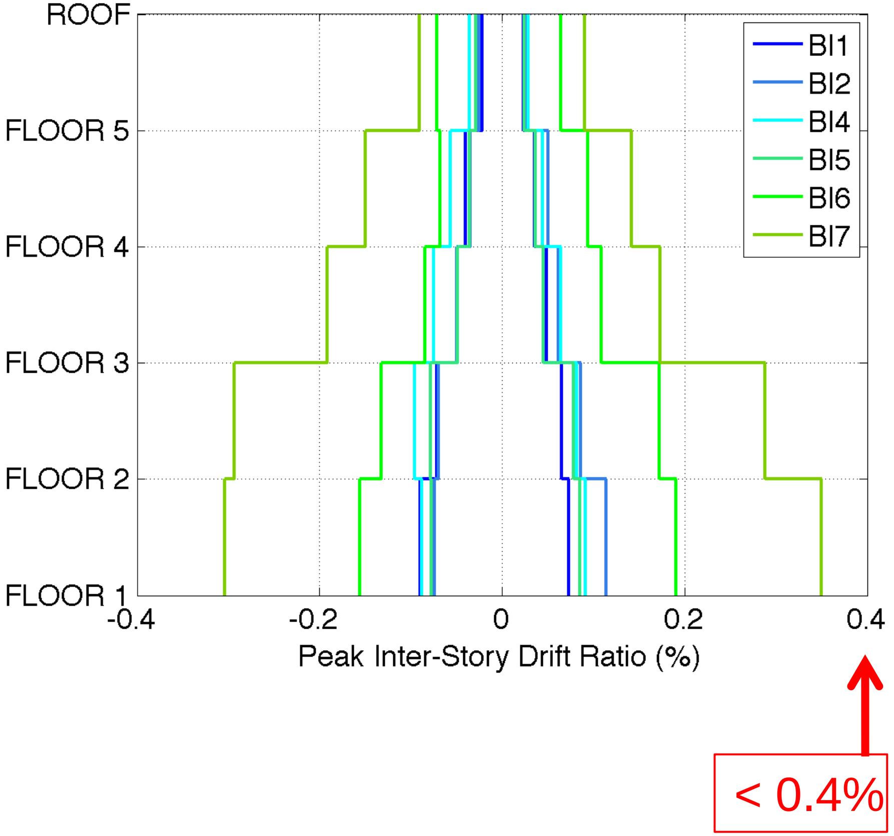
Media Exposure = Society Awareness

(there are many)

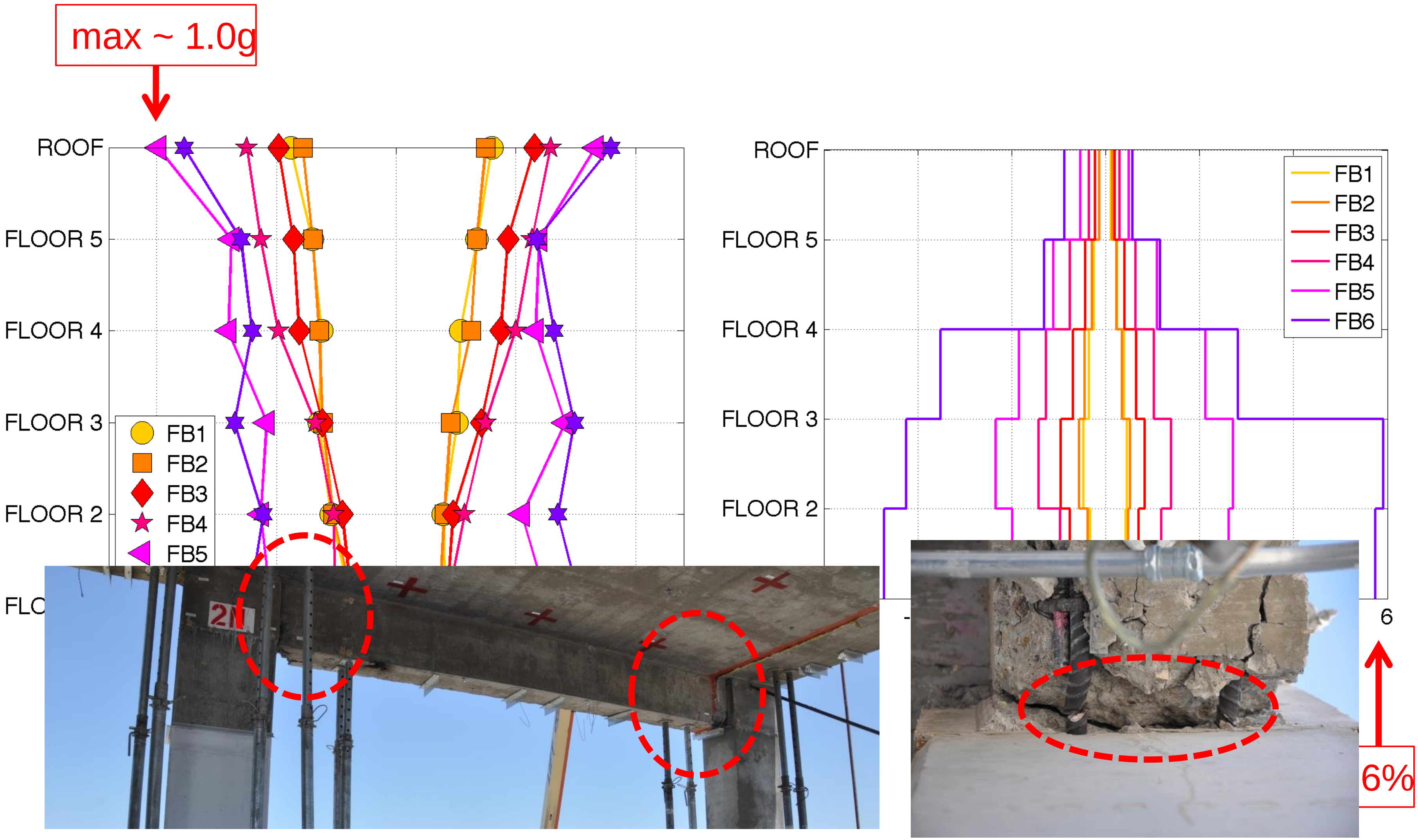
A FEW IMPORTANT FINDINGS

Phase 1: Base isolated building-NCS system



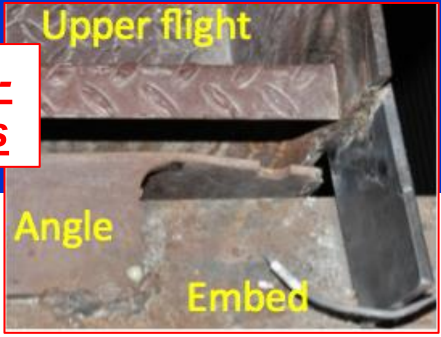


Phase 2: Fixed base building-NCS system

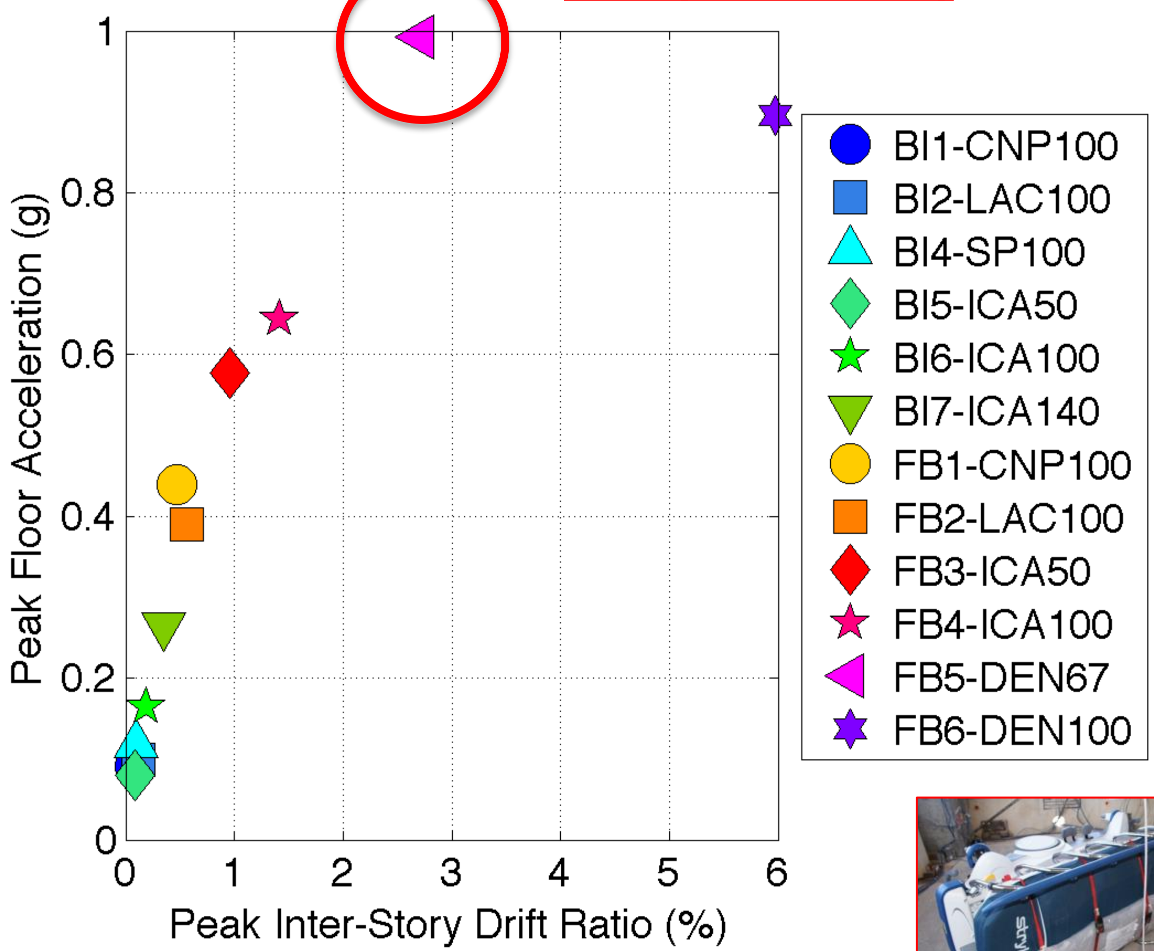


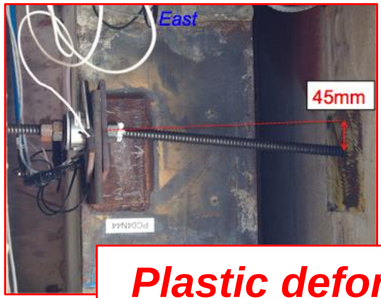
Peak Res

Failure of Stair Flight-Landing Connections



~DE (FB5-Den67)



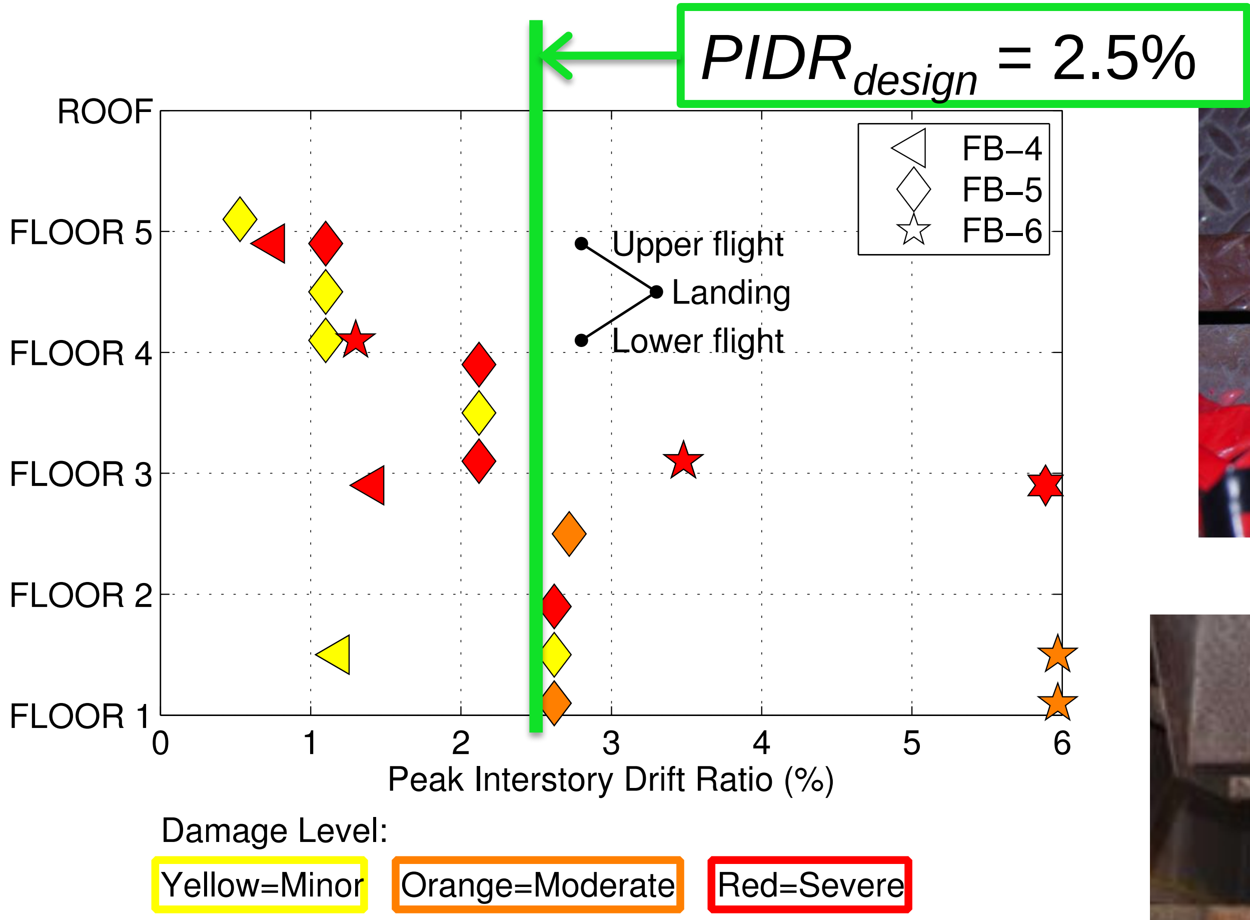


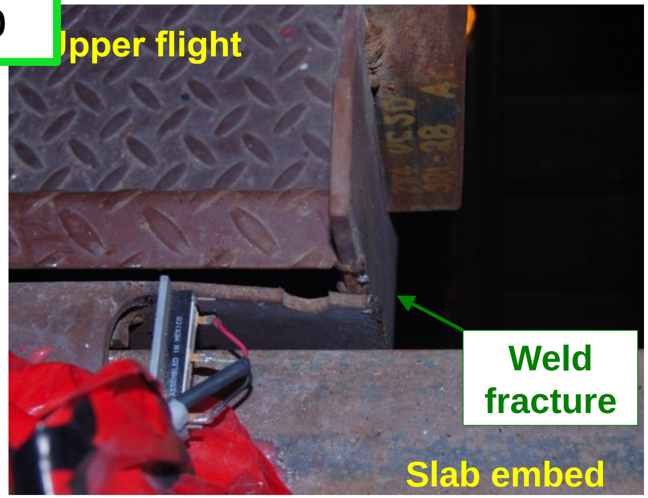
Plastic deformation in APC connections

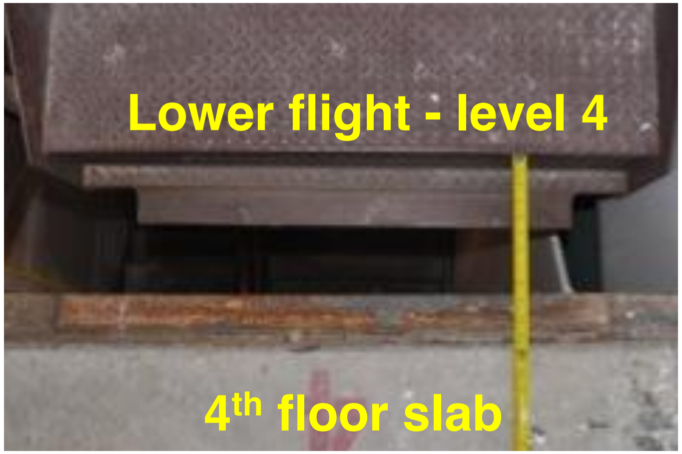
Balloon framing clip detachment

Toppled equipment

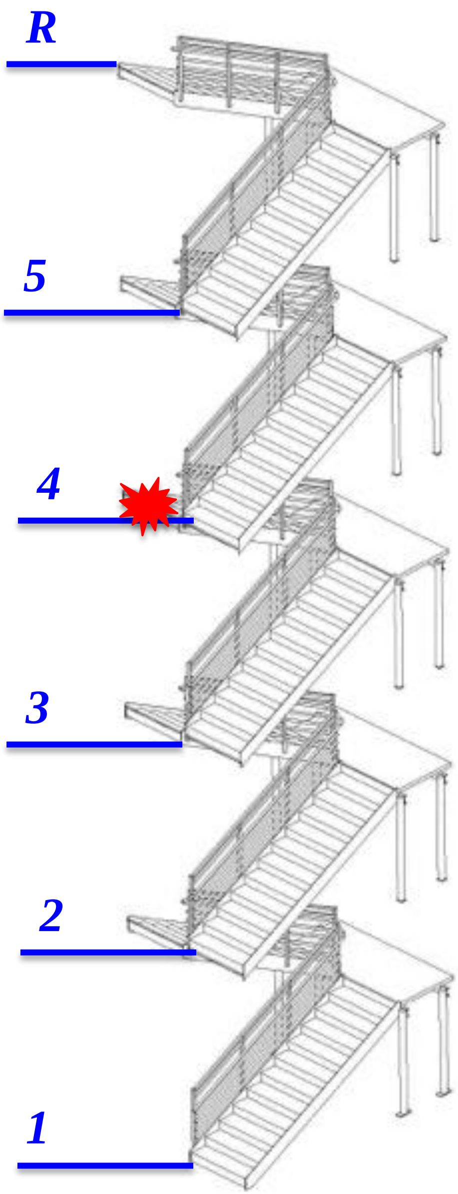
Egress: Stairs

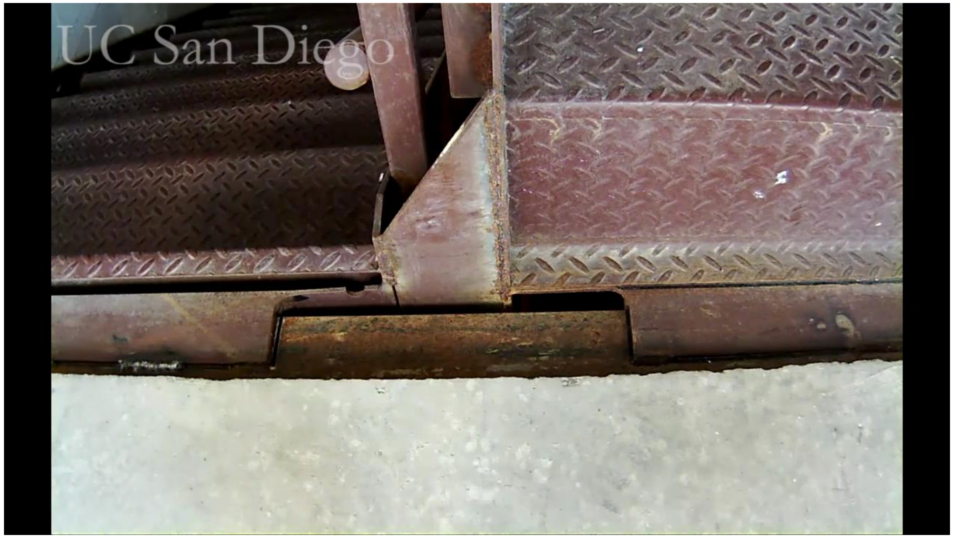


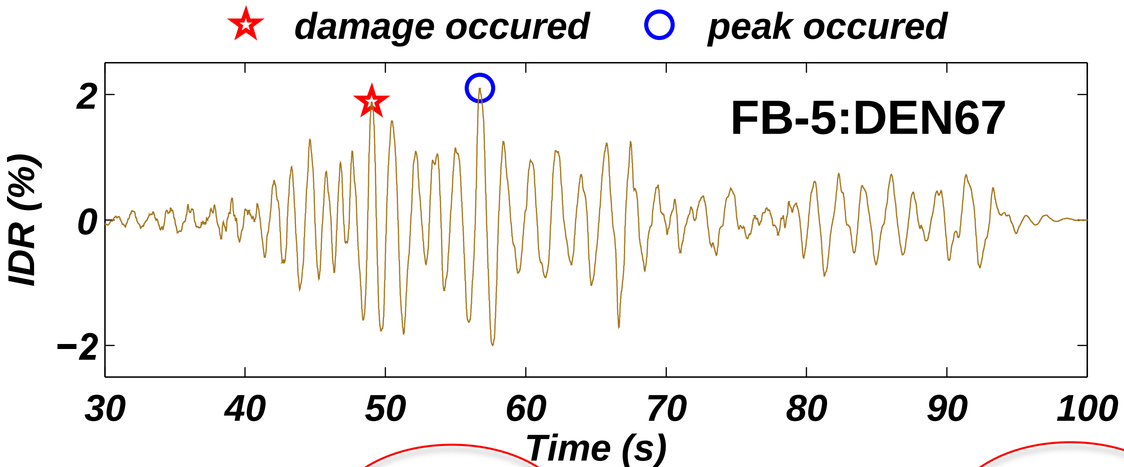




Upper Flight–Slab Connection Plate Fracture

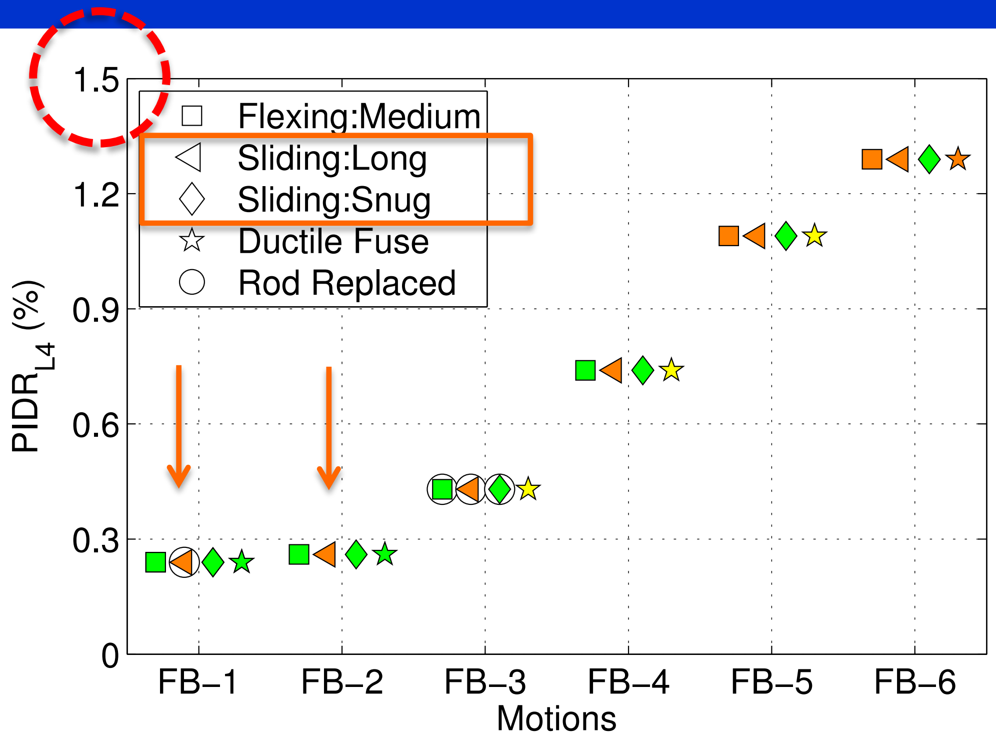




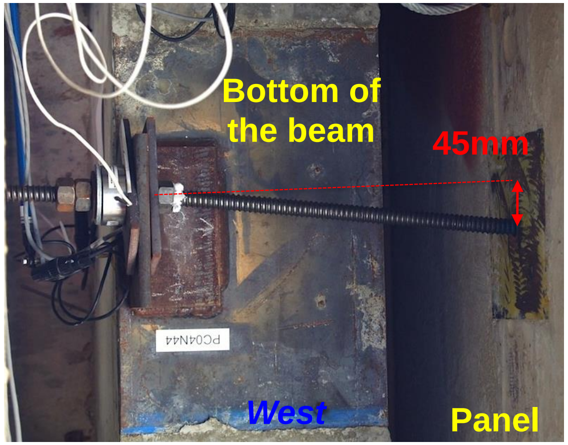


IDRmax (%): 2.10 **IDR@damage (%): 1.88**

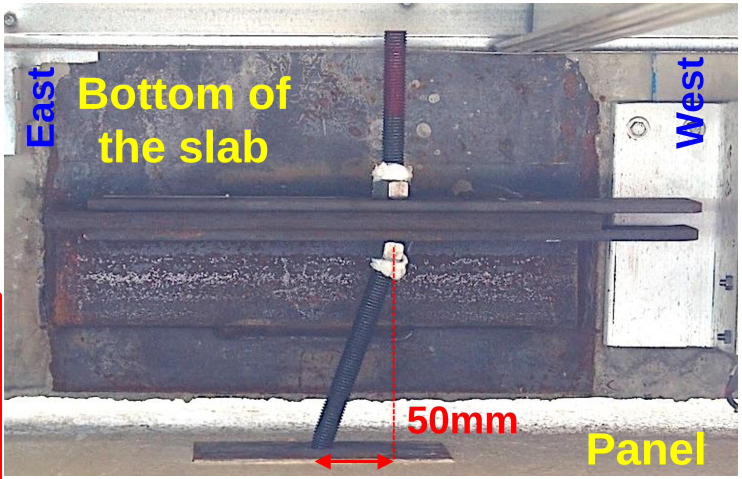
Drift-Compatible Façade Connections



Damage Level:
Green=None | Yellow=Minor | Orange=Moderate | Red=Severe



Flexing Connection



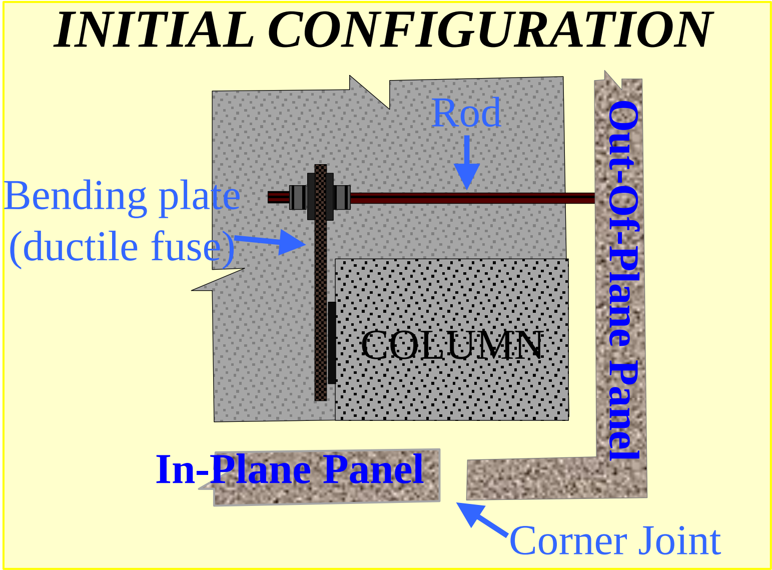
Sliding Connection

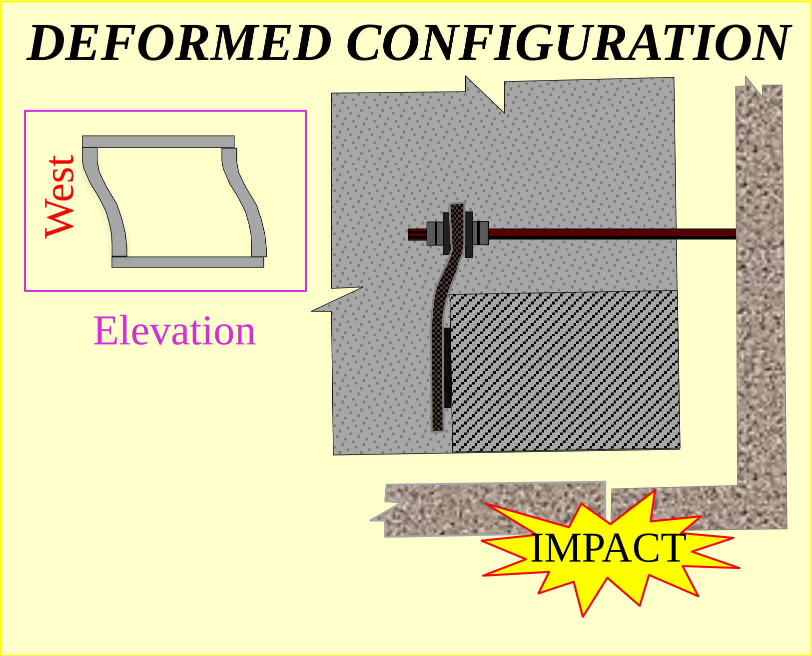
1) Intended performance of flexing connections
2) Unexpected yielding of sliding connections at low drift amplitudes

Colliding Corner – Ductile Fuse (new idea)

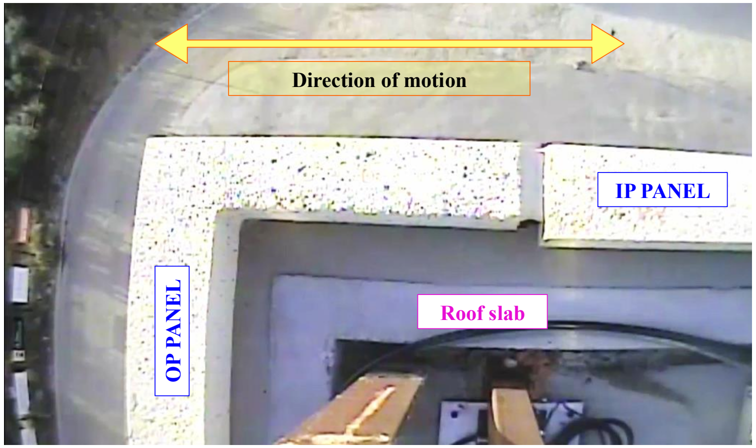
New corner system design to allow for smaller corner joints:

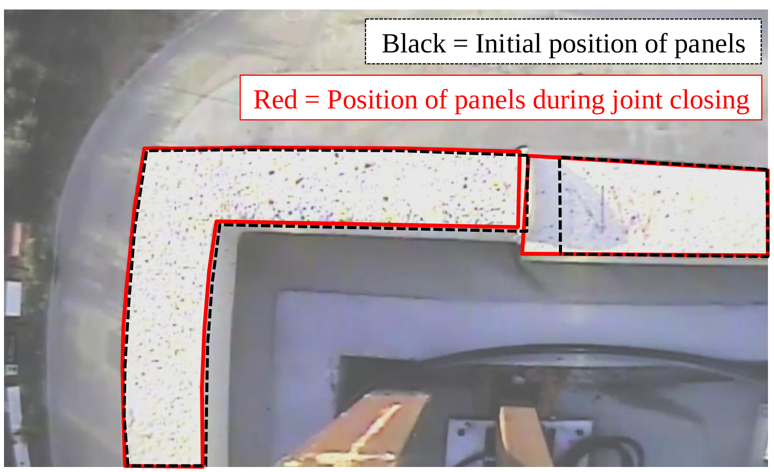
- Elastic Drifts→ Gap closure
- Inelastic drifts→ Impact but overload prevented by ductile fuse

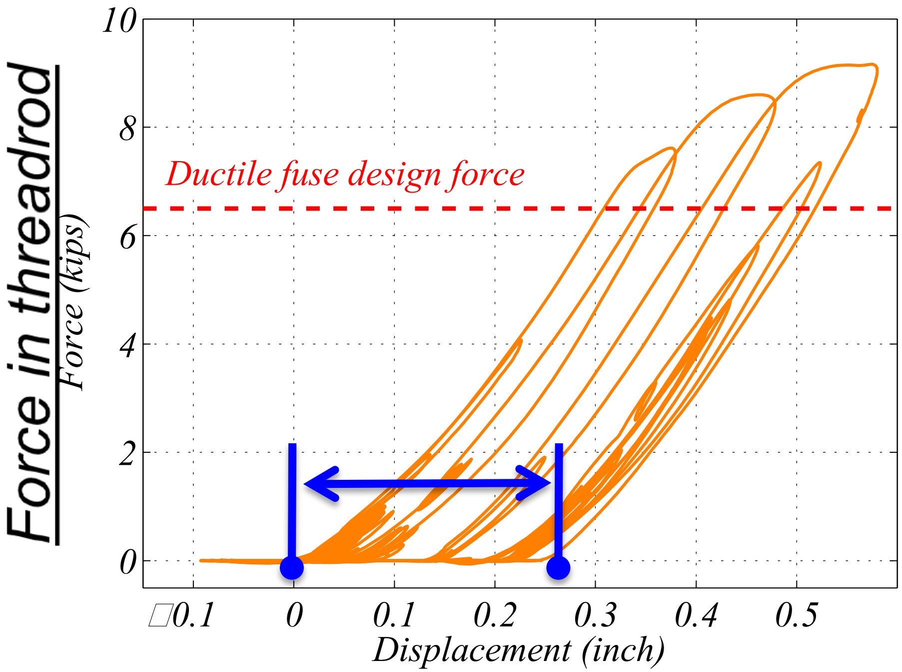




Ductile, Colliding Corners

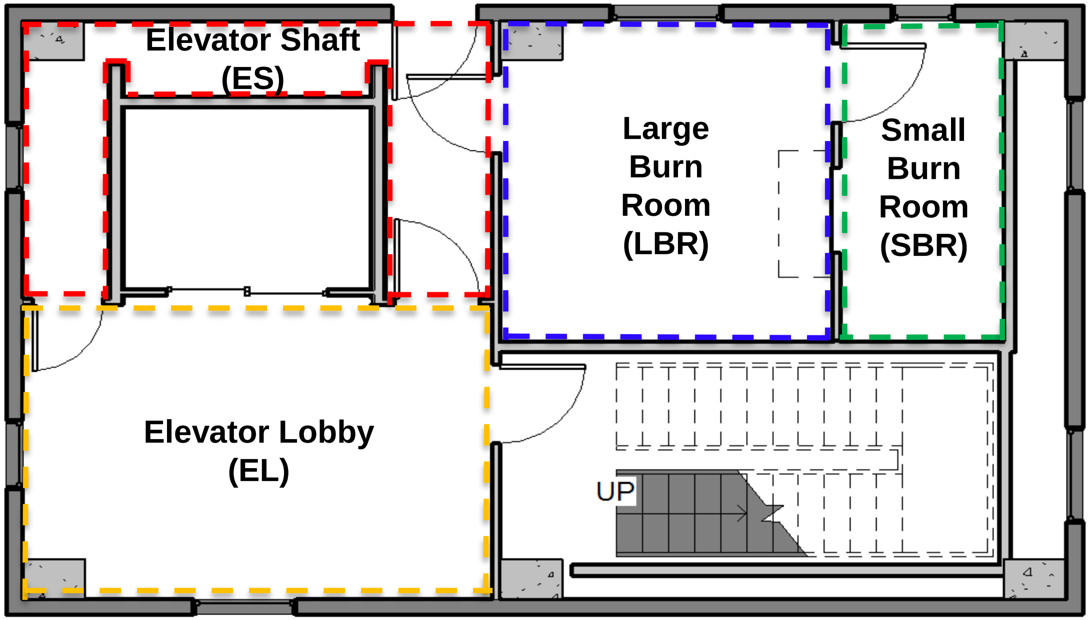






<u>*Connection Displacement (relative)*</u>

Live Fire Tests



Date	Sequence
May 23, 2012	1. LBR-1
	2. SBR
May 24, 2012	3. LBR-2
	4. ES
May 25, 2012	5. EL-1
	6. EL-2

- Series of 6 fires, heat release rate (HRR) varying from about 0.5 MW to about 1.5+ MW
- Goals: (a) obtain temperature data for simulations, (b) assess smoke spread, (c) assess potential for flame spread, and (d) assess potential for structural impact
- Burn time limited to about 15 minutes
- Heptane fuel - burned in pans (1 to 3, depending on desired fire size)

EL Fire Test 1/2: Representative Effects

Elevator controls melted

Intumescing of fire stop

With the damage to the gypsum wall system due to seismic motions, the fire was able to bring the system to failure much more quickly than any fire rating would suggest

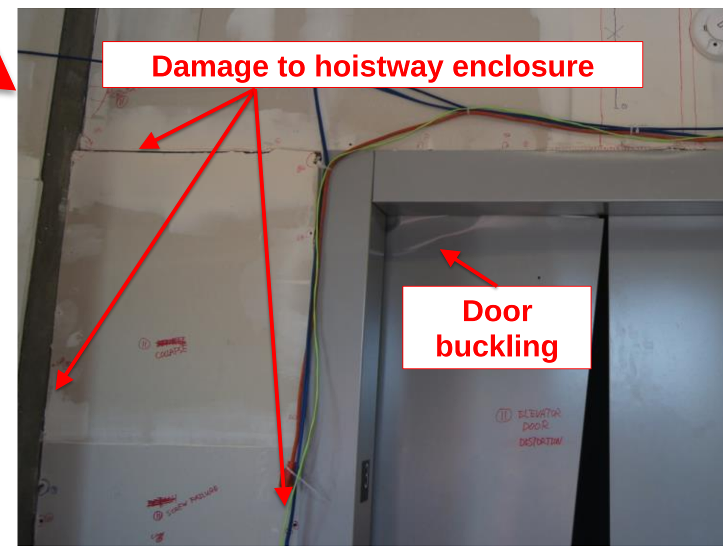
Spalling of concrete slab

Failure of wall system (after EL 2 test)

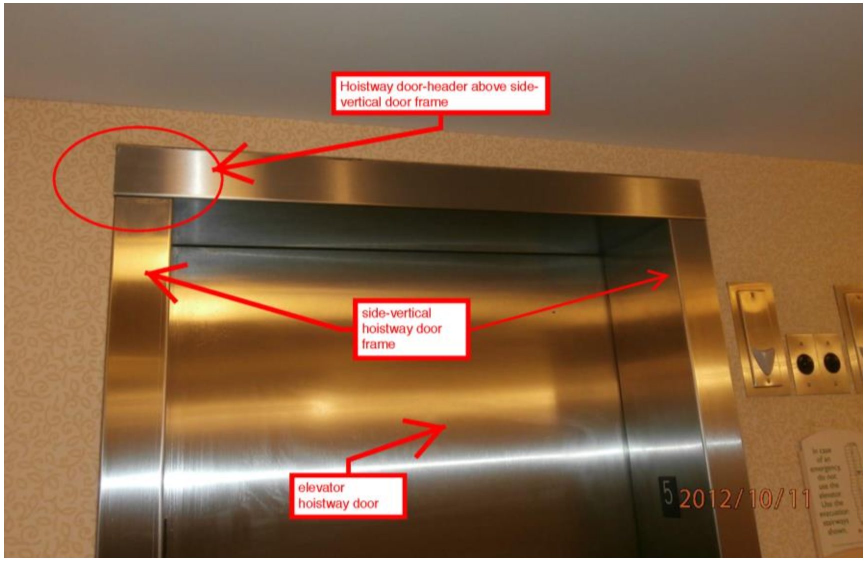
Egress: Elevator

Door Jamb
After FB5-DEN67
(functional)

Door Jamb
After FB6-DEN100
(non-functional)

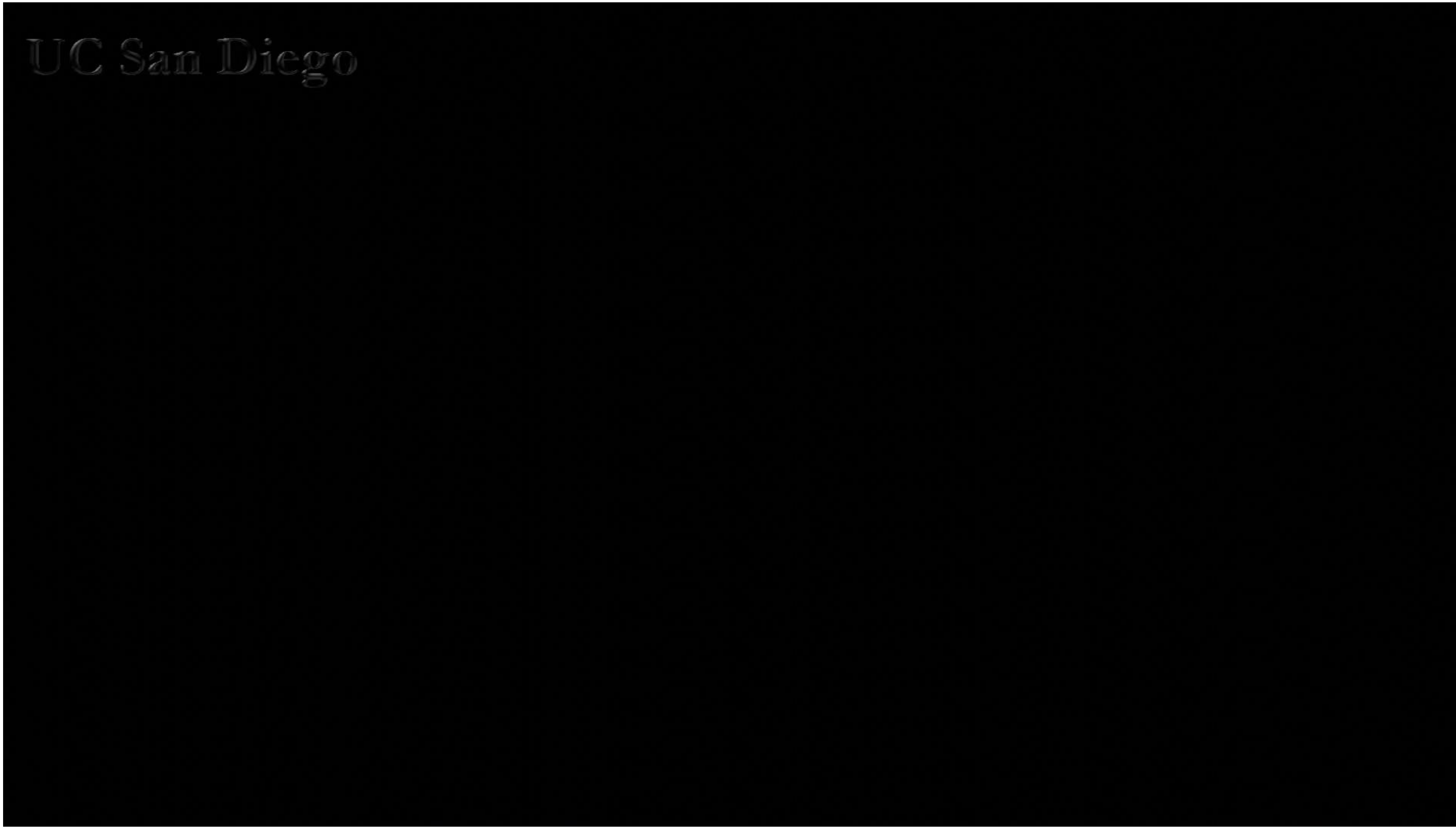


Elevator Improvements



Schindler Corp

Phase 2: Fixed base building-NCS System



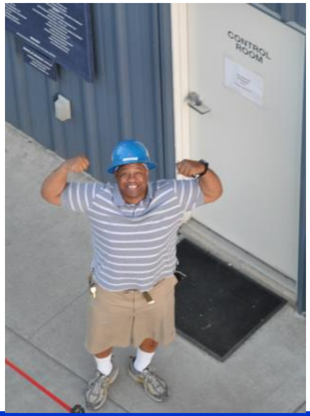
Videos: bncs.ucsd.edu

(there are many)

PROJECT ACCOLADES

Project Accolades: Human Resources

- UCSD: Astroza, Ebrahimian, Wang (PhD 2015) & Pantoli, Chen (PhD 2016)
- WPI: Park (2014 PhD); Kim (MS 2013)
- SDSU: Espino & Aranda (MS 2012, 2014)
- Univ of Bologna: Selva & Bezzi (MS 2012, 2014)
- NEES-REU (8 UGs from SJSU, VPI, UCSD)
- NEES-RET: 6 SD teachers outfitted with mini-shake tables
- 3 Payload projects: WPI (fire), SIO (GPS) & Cal Poly SLO (mini-shakers)



Project Accolades: Technical Contributions

- **Award in Excellence for Research Projects (Western States Seismic Policy Council, 2014)**
- **5-part Technical Report Series (UCSD), 2-part Technical Report Series (WPI)**
- **Numerous technical papers (conference, journal)**
  - 2-part Earthquake Spectra (overarching, 2015)
  - “Data Paper” Earthquake Spectra
  - System ID: Astroza et al., Modeling: Ebrahaminian, Wang, Facades Pantoli et al., Egress Systems: Wang
- **Large volume of data (image, analog) publically available -> NEESHub**
- **ASCE 7-16 Code Changes**
  - Precast cladding connections
  - Stair (drift limits, importance factor)
  - Elevator detailing

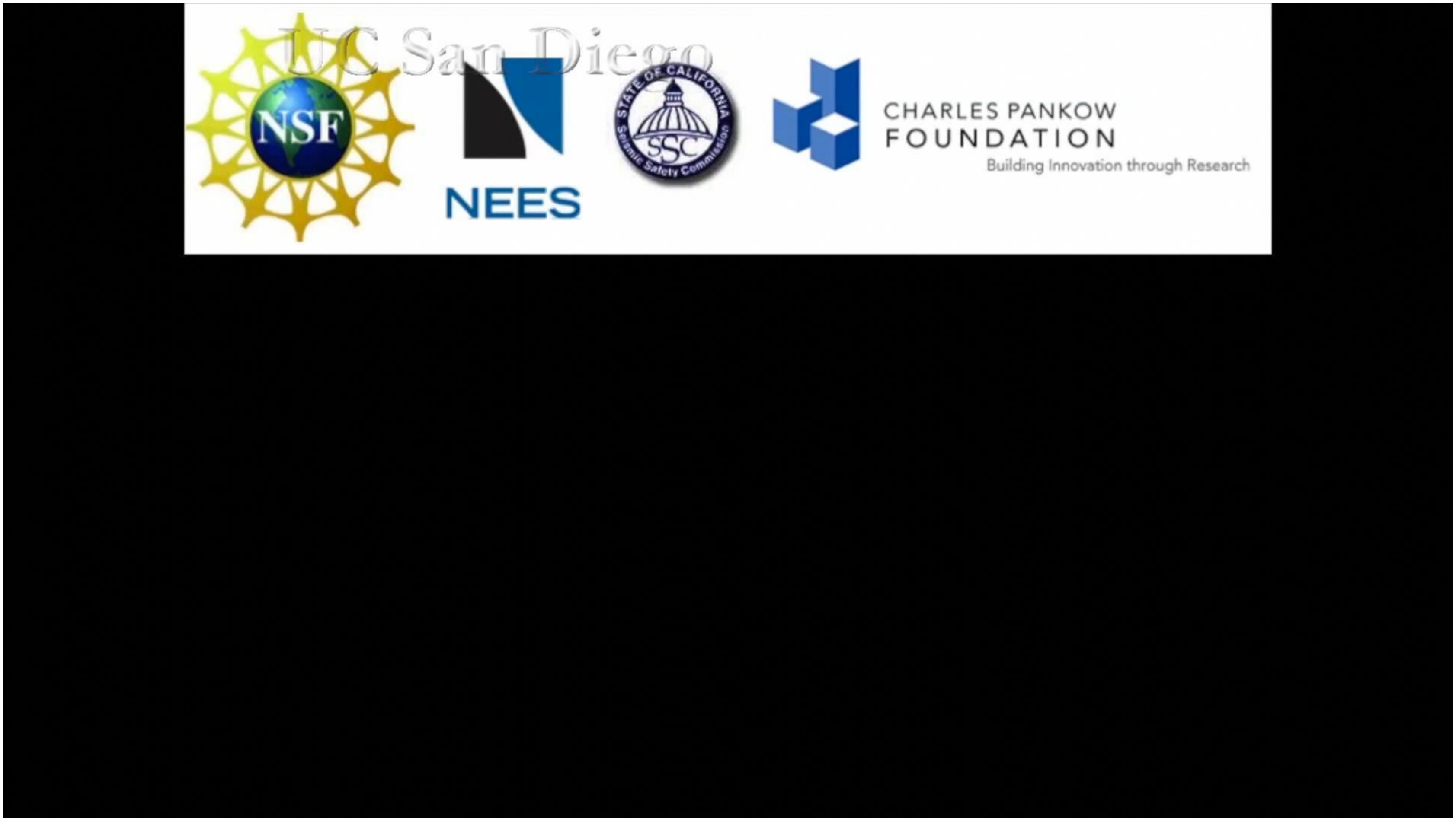
Project Accolades: Public Impact

- **Professional video publication (UCSD-TV)**

- **Educational video module series (4-part structural; 2-part nonstructural; geared towards undergraduate learning)**
- **Documented extensive media exposure**

Demolition – Don't forget it!

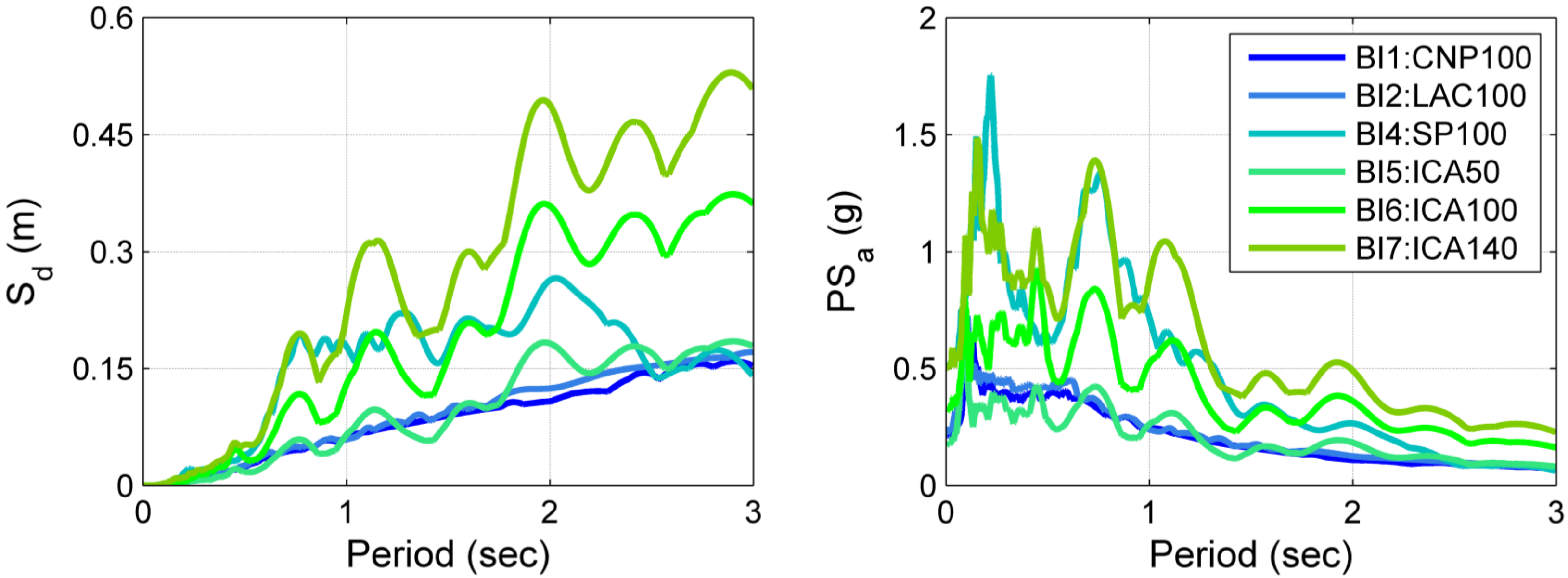
- $135k ++ lots of help from industry ($98k in just structural concrete; removal of ceiling, stairs, elevator by others)



The real stars of the show….


10205 POMERADO RD
CAUTION
Turner

Base	Station-scale (Earthquake)	Name	Type	Notes
Isolated (BI)	Canoga Park-100% (1994 Northridge earthquake)	BI-1: CNP100	SM	Serviceability level
	LA City Terrace-100% (1994 Northridge earthquake)	BI-2:LAC100	SM	Serviceability level
	LA City Terrace-100% (1994 Northridge earthquake)	BI-3:LAC100	SM	Serviceability level
	San Pedro-100% (2010 Maule-Chile earthquake)	BI-4:SP100	AM	Long duration
	ICA-50% (2007 Pisco-Peru earthquake)	BI-5:ICA50	AM	Long duration, multiple runs
	ICA-100% (2007 Pisco-Peru earthquake)	BI-6:ICA100	AM	Long duration, multiple runs
	ICA-140% (2007 Pisco-Peru earthquake)	BI-7:ICA140	AM	Long duration, multiple runs



Base	Station-scale (Earthquake)	Name	Type	Notes
Fixed (FB)	Canoga Park-100% (1994 Northridge earthquake)	FB-1:CNP100	SM	Low amplitude - expect service
	LA City Terrace-100% (1994 Northridge earthquake)	FB-2:LAC100	SM	Low amplitude - expect service
	ICA-50% (2007 Pisco-Peru earthquake)	FB-3:ICA50	AM	Long duration, multiple runs
	ICA-100% (2007 Pisco-Peru earthquake)	FB-4:ICA100	AM	Long duration, multiple runs
	Pump Station #9-67% (2002 Denali eq.)	FB-5:DEN67	SM	~Target design demand
	Pump Station #9-100% (2002 Denali eq.)	FB-6:DEN100	SM	~>50% larger than Design demands