Earthquake and Post-Earthquake Fire Testing of a Full-scale 5-story Building outfitted with Nonstructural Components on the World's Largest Outdoor Shake Table

Presentation to EERI Southern California San Diego Chapter

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UCSD WPI HOWARD UNIVERSITY SAN DIEGO STATE UNIVERSITY

EERI SD Meeting - 11/14/2012

What can this project contribute to society?

- System-wide test; landmark data set for earthquake engineering community
  - Publically available
  - Evaluating engineering models used in design practice
  - Evaluating suitability of current design codes & contributing to next-generation design codes
    - Improving construction & design practices
  - Ultimately reduce economic and human losses in future earthquakes

Overall Scope (bncs.ucsd.edu)

- Centerpiece of Project: Three-phased full-scale test program conducted on a 5-story building-NCS system
  - @Largest outdoor shake table in the world (nees.ucsd.edu)

Size	7.6m x 12.2m
Peak accel : bare table, 400T payload	4.2 g, 1.2 g
Peak velocity	1.8 m/s
Stroke	±0.75m
Max vertical payload	20 MN
Force capacity of actuators	6.8 MN

Project Support

- $5M+, multi-organizational 3 year project
  - National Science Foundation (NSF) Network for Earthquake Engineering Research (NEESR) Core Research funding (2009; UCSD/SDSU/HU: $1.27M)
  - Structural Skeleton (design/construction/demo) – Englekirk Advisory Board ($1.5M est)
  - Charles Pankow Foundation (precast cladding) - $250k
  - California Seismic Safety Commission (hospital aspect) - $360k
  - Industry consortium - materials, equipment, installation + (approx) $200k (cash)
  - Fire (payload/WPI) supported through CSSC ($50k), Hilti ($50k), ARUP

Core Team

Name	Affiliation	Name	Affiliation
Tara Hutchinson (PI)	UC San Diego	Gonzalez, Amanda	San Diego State University

Mahmoud Faghihi	Englekirk & Sabol Consulting Structural Engineers, inc.

Partners

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

Federal, state, non-profit

Design contributions

Industry Partners

REGAL INDUSTRIES, INC.
AB&I
WATTS
DELCO SALES
PACIFIC STAIR CORPORATION
USG
STATE FARM INSURANCE
B.A.C.
WESTERN FIRE PROTECTION
IBM
HILTI
MASON INDUSTRIES
SQUARE D by Schneider Electric
sto
CEMCO Steel Framing and Metal Lath
AGI
RUSKIN
MMFX TECHNOLOGIES CORP
SURE-BOARD
MORLEY BUILDERS
megaFlex
HRC
BauGrid
Armstrong
WEIR MINERALS
Schindler
CLARK PACIFIC Precast. Building for Life.
LAWRENCE DOORS
DASMA
PRE-CAST CONCRETE PRODUCTS

Medical Field

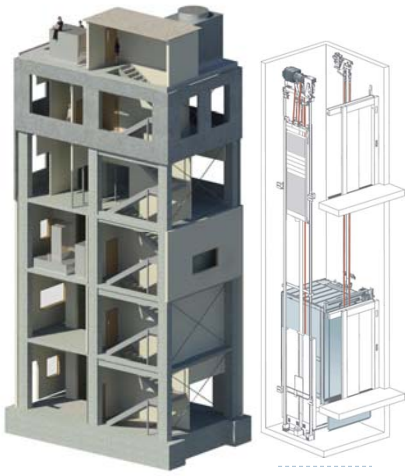
Hill-Rom
Responder
STANLEY Healthcare Solutions
HELMER
BIAMP SYSTEMS
stryker
TANNOY
Rauland
MODULAR SERVICES COMPANY
besam

Structural System

- Special reinforced concrete moment resisting frame
- 2 bay x 1 bay; 1-MF bay long (shaking) direction
- 14' story heights; 5 floors; 70' + 5' foundation + 13' tower = 88' (tallest so far on UCSD table)
- Elevator shaft and stairway openings at floor diaphragms
- 34' x 20' c/c footprint
- ~ 1 sec longitudinal period (fundamental mode)
- ~2.5 sec longitudinal period (base isolated)

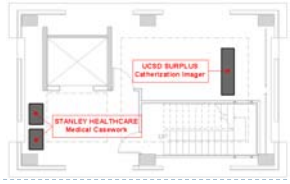
NCSs in the Building: Overview

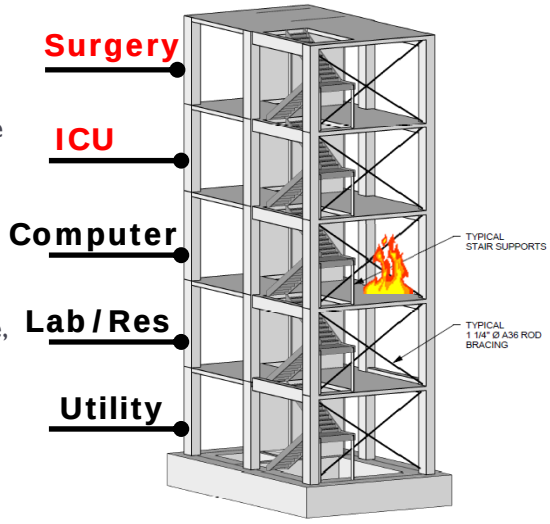
- Egress systems:
  - Operable Elevator
  - Stairs
- Facades:
  - Concrete cladding
  - Balloon framing
- Hospital equipment
- Roof mounted equipment
- Sprinkler and riser systems
- Ceilings
- Interior partition walls
- HVAC components and subassemblies
- Furnishings
- Anchorage
- Lighting
- IBM servers
- Penthouse



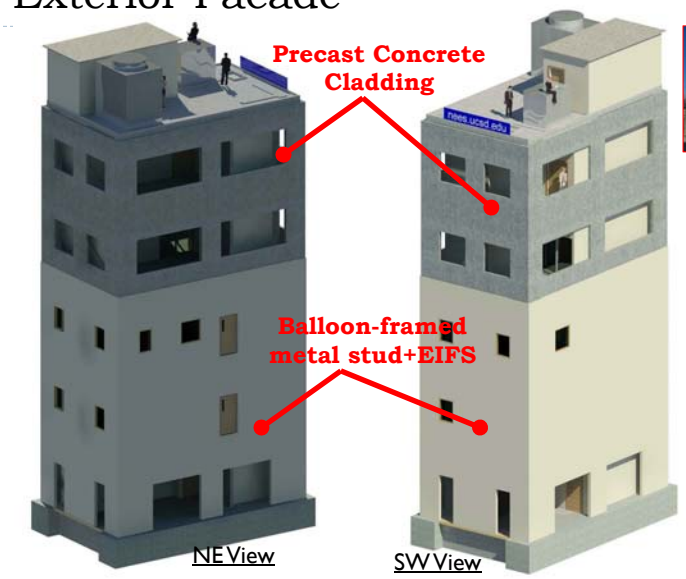
NCSs in the Building: Occupancy

- Each floor has a different type of occupancy
  - Two floors of hospital use
  - Ceiling, partitions, sprinklers all floors
  - MP concentrated @ L3
  - Electrical all floors
  - Roof-mounted penthouse, chiller, AHU

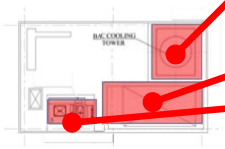


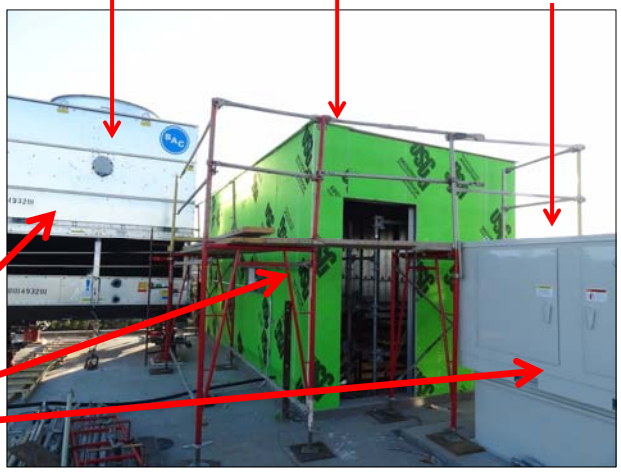


Exterior Facade



Roof Mounted Equipment NCSs





Level 5: Surgery Suite

Level 4: Intensive Care Unit (ICU)

Level 3: Server Room & Burn Rooms

Level 2: Residential & Laboratory Space

500-800lb strapped & unstrapped refrigerator units

Level 1: Utility Floor

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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

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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

Phase 3: Controlled live fire, pressurization & smoke tests

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

Seismic Test Phase Instrumentation

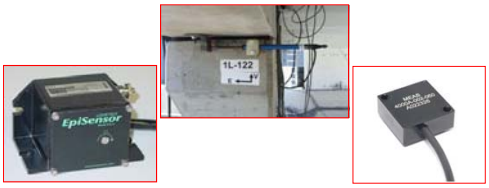
- **Acceleration:**
  Accelerometers
  (find Displacement)
- **Relative Displacement:**
  String Potentiometers+
  Linear Potentiometers
- **Force:**
  Load Cells
- **Strain:**
  Strain Gauges

+GPS system (6 receivers)

+Video Cameras (87)

420 channels NEES@UCSD + 90 channels NEES@UCLA= 510 channels

Structure + major NCSs



Seismic Test Phase Camera Summary

Camera Type	Number of Cameras	Purpose
IP	56	Capture visual data within the structure with input from industry partners – emphasis on NCS's
Coax	16	Capture visual data within the structure – emphasis on NCS's
HD Camcorder	8	Capture overall views and external visual data
GoPro	7	Capture visual data within the structure – emphasis on structural components

Total Number of Cameras: 87

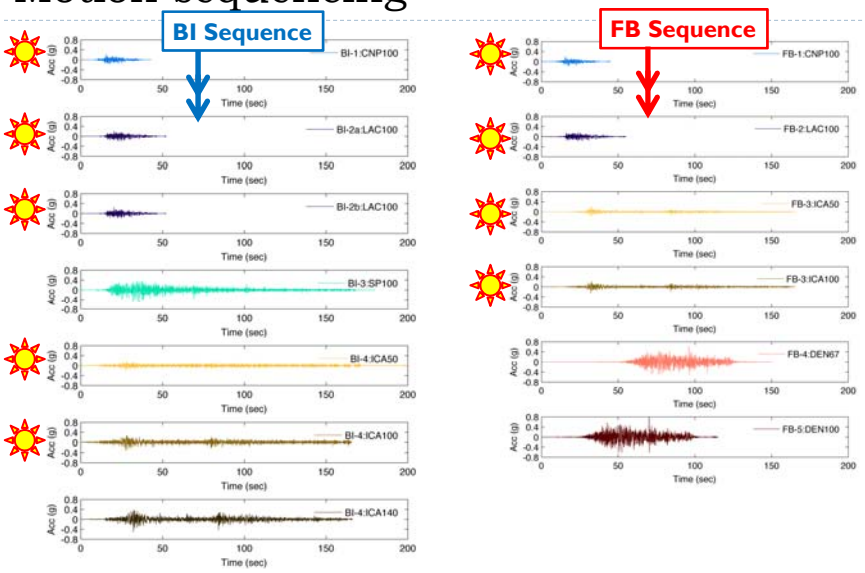
Motion selection, sequencing & scaling goals

- Overlap between portion of BI & FB motions
- < 0.5% Peak 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

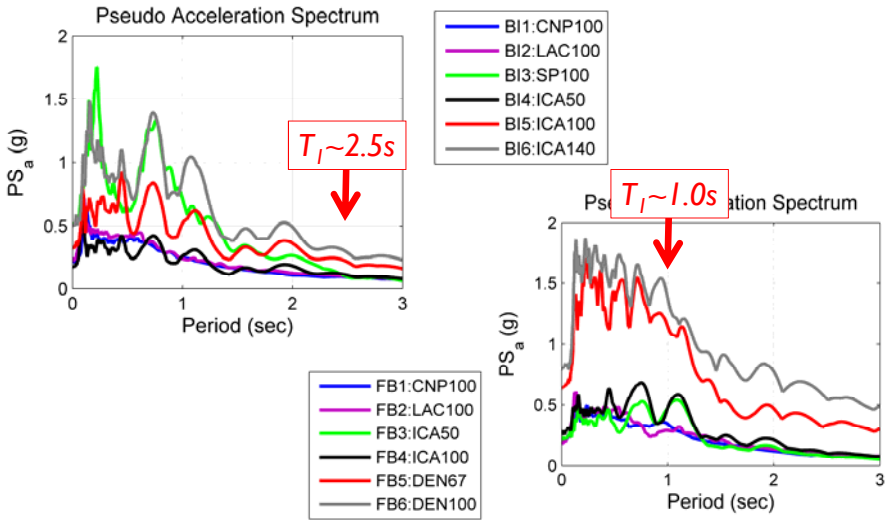
Motion selection (target seed) & scaling

Motion No.	Date	Earthquake (seed) record	Short name	Target
1	16-Apr-12	Canoga Park, Northridge, 1994	BI-1: CNP100	~Service level
2	16-Apr-12	LA City Terrace, Northridge, 1994	BI-2: LAC100	~Service level
3	17-Apr-12	LA City Terrace, Northridge, 1994	BI-3: LAC100	~Service level
4	17-Apr-12	San Pedro, Maule, Chile 2010	BI-4: SP100	Duration
5	26-Apr-12	ICA, Pisco, Peru, 2007	BI-5: ICA50	Duration, mult runs
6	27-Apr-12	ICA, Pisco, Peru, 2007	BI-6: ICA100	
7	27-Apr-12	ICA, Pisco, Peru, 2007	BI-7: ICA140	
8	7-May-12	Canoga Park, Northridge, 1994	FB-1: CNP100	~Service level
9	9-May-12	LA City Terrace, Northridge, 1994	FB-2: LAC100	~Service level
10	9-May-12	ICA, Pisco, Peru, 2007	FB-3: ICA50	Sequencing
11	11-May-12	ICA, Pisco, Peru, 2007	FB-4: ICA100	~ 1-1.5% IDR
12	15-May-12	Pump Station #9, Denali, Alaska, 2002	FB-5: Den67	~ DE
13	15-May-12	Pump Station #9, Denali, Alaska, 2002	FB-6: Den100	~ 50%>DE

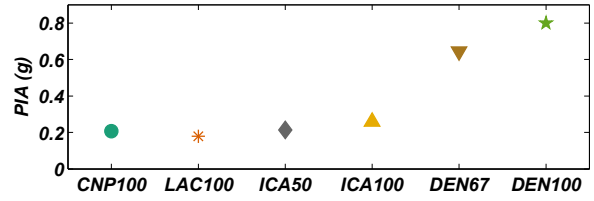
Motion sequencing

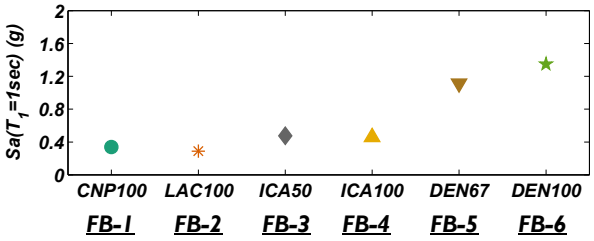


Motions – BI & FB Test Phase



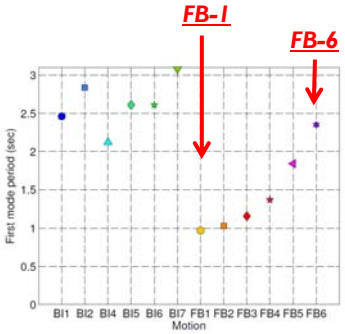
PIA and Sa(T_1) of FB input motions





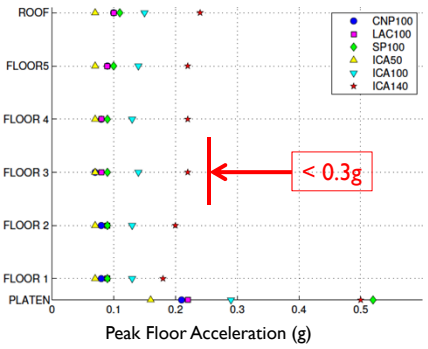
Achieved Motions:

- PIAs range from 0.2-0.8g
- Sa(T1) range from around 0.3 to 1.3g (T1 = 1sec)

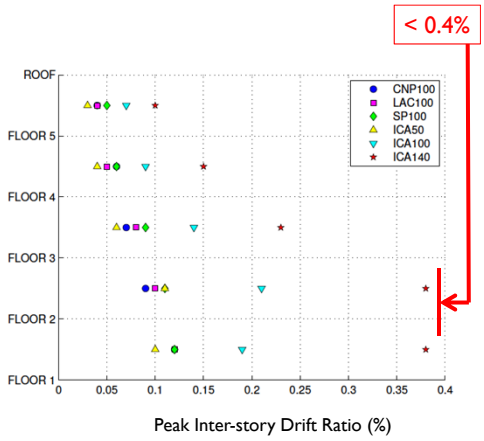


Structural System Response

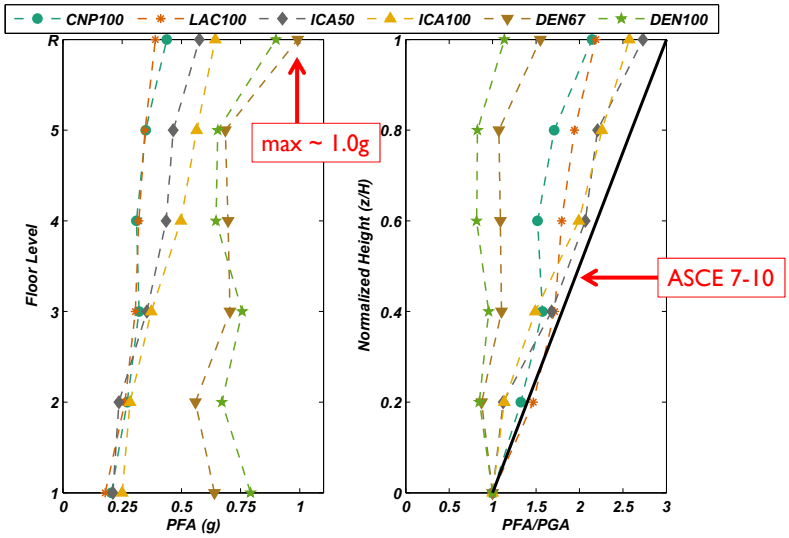
Phase 1: Base isolated building-NCS system



BI-7: ICA140 – Test Video

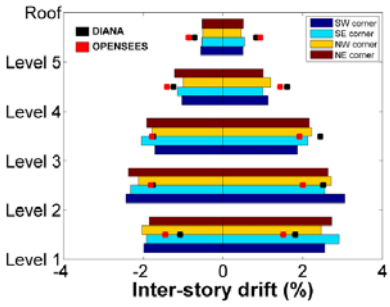


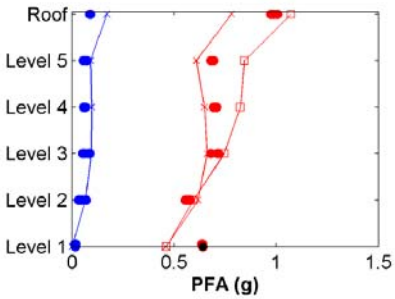
Phase 2: Fixed base building-NCS system



Phase 2: Fixed base building-NCS system

~ 'Design' EQ: Denali (Alaska) seed motion (aka Den67)





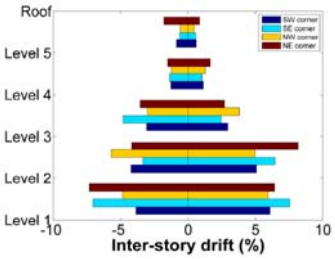
Peak IDR ~ 3.0%, peak floor accelerations ~ 1.0g

FB-6: Den100 – Joint Video

Final State of Building-NCS System

- FB Phase (Den100 ~ 50%>Den67)
  - Final motion resulted in two level soft story mechanism
    - Fractured longitudinal rebar in frame beams
    - Punching shear mechanism in slab
    - Isolated within levels 1-2 & 2-3
    - **Highly unique performance data set - building exposed to extreme damage state**

FB-6: Den100 – Test Video



Impact on Nonstructural Components & Systems:

Spaziergang

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Egress Subsystems: Seismic Test Observations

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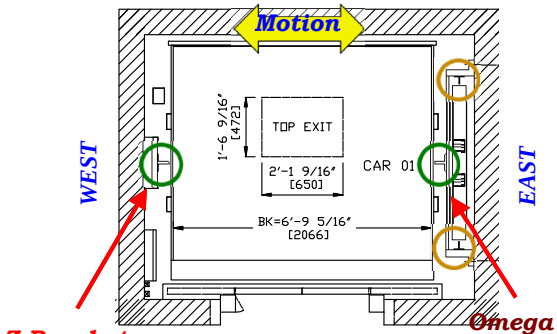
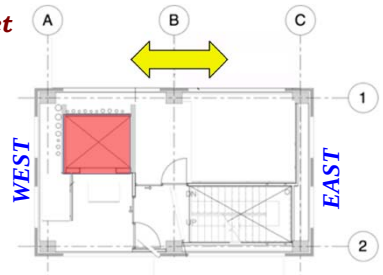
Elevator: Design Details



Cabin:
- 6'-9 3/8" x 5'-6 7/8" x 7'-9"
- Capacity: 3500lbs
- Weight: 2200lbs
- 40% payload (approx.1400 lbs) added to the cab

Counterweight:
- 8'-10 3/4" x 4-1 5/8"
- Weight: 3600lbs

Door System:
- 3'-6" x 7'-0"
- Weight: 252lbs per floor



Brackets & Rails:
- Omega bracket @ 7' o.c. w/ 2 cwt guide rails and 1 cab rail on east shaft wall
- Z bracket @ 7' o.c. w/ one 1 cab guide rails on west face
- Cwt rails: 8 lb/ft;
- Cabin rails: 12 lb/ft

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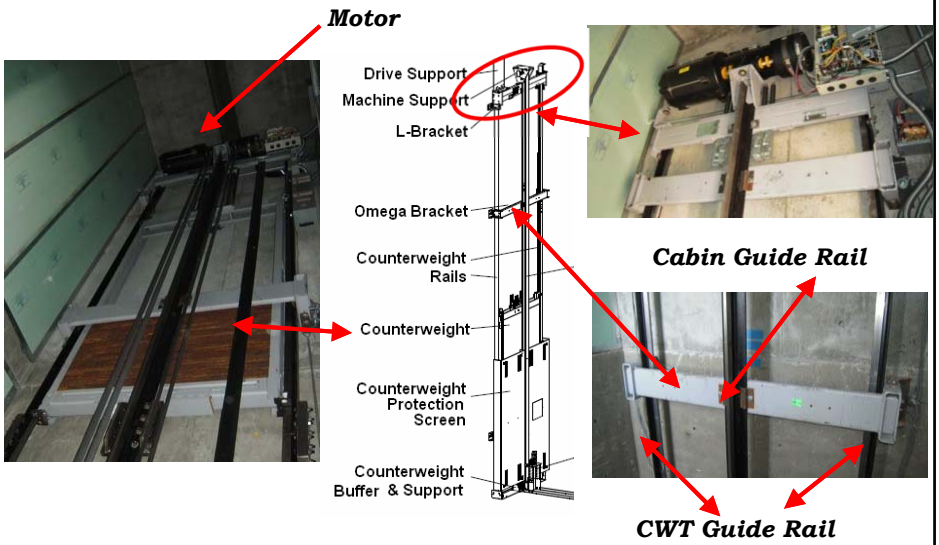
Elevator: Installation & Counterweight



Elevator: Damage Progression

Test Sequence		Brackets	Rails	Door System	Functionality
Fixed-Base Tests	CNP100	Non-Visible	Non-Visible	Non-Visible	Fully Functional
	LAC100	Non-Visible	Non-Visible	Non-Visible	Fully Functional
	ICA50	Non-Visible	Non-Visible	Non-Visible	Fully Functional
	ICA100	Non-Visible	Non-Visible	Non-Visible	Fully Functional
	DEN67	N/A	N/A	Moderate	Functional
	DEN100	Minor	Minor	Severe	Non-Functional

FB4:DEN67

- Elevator Door Gap (Minor)

FB5:DEN100

- Door Jamb at levels 2 and 3 (Severe)
- Door Jamb at level 1 (Moderate)
- Guide rail elastic bending at levels 2 and 3 due to structural permanent drift (Minor)

Elevator: Door Damage at Level 3

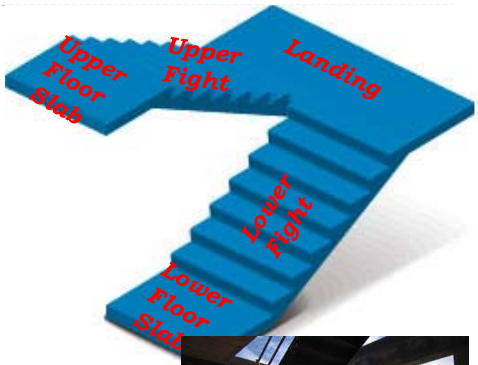
Door Jamb
After FB4-DEN67
(functional)

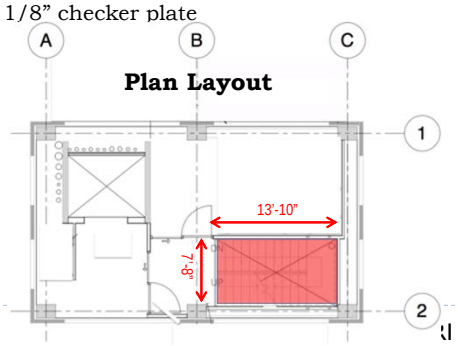
Door Jamb
After FB5-DEN100
(non-functional)

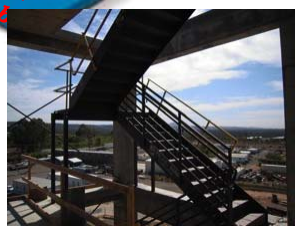
Stair Components and Terminology

Lower and Upper Flights
- 14 Gage checker plate for riser and tread
- 1/4"x10" A36 steel plate for stringer

Landing
- (4) HSS 3x3x1/4 for landing posts
- (2) C8x11.5 for the landing joist
- 1/8" checker plate



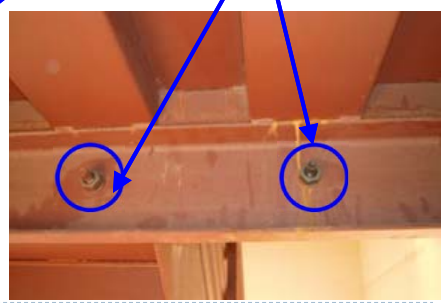




Flight to Landing Connections

Lower flight – landing connection
- (2) 5/8x1-1/2 A325 TC bolts per stair flight

Upper flight – landing connection
- (2) 5/8x1-1/2 A325 TC bolts per stair flight



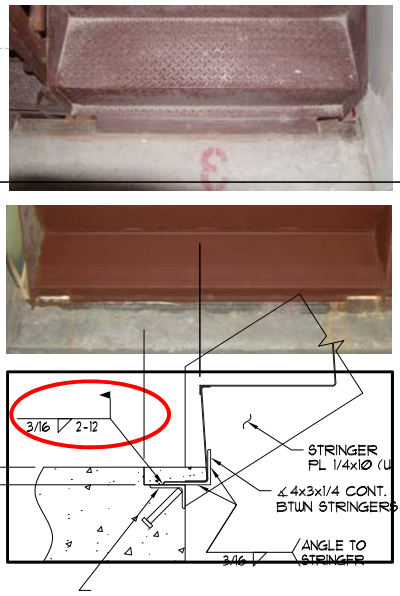
Lower Flight to Slab Embed Connections

Lower flight – floor connection

- 4”x3”x1/4” angle
- 3/16” fillet weld 2” long @ 12” welded to embed (effective weld length 6” connection angle assumed 3’ wide to embed)
- 3/16” fillet weld 2” long @ 12” welded to tread (effective weld length 6” connection angle assumed 3’ wide to embed)
- Electrode: E70 (70 ksi)

Weld Design Strength (LRFD)

- Weld design strength: φRn
- φ = 0.75 (from AISC Table J2.5)
- Load angle not considered
- Weld design strength = 0.75(0.60)(70)(cos(45)(3/16”)(6”)) = 20.0 (kips)



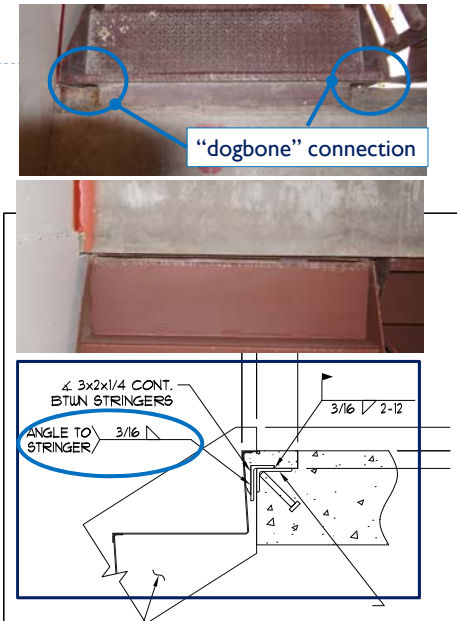
Upper Flight to Slab Embed Connections

Upper flight – floor connection

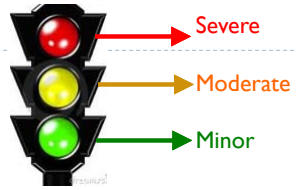
- 3”x2”x1/4” angle connection
- 3/16” vertical fillet weld to stringers (3” on both side, 6” in total)
- 3/16” fillet weld 2” long @ 12” to embeds (same as lower connection)
- Electrode: E70 (70 ksi)

Weld Design Strength (LRFD)

- Weld design strength: φRn
- φ = 0.75 (from AISC Table J2.5)
- Load angle not considered
- Weld design strength = 0.75(0.60)(70)(cos(45)(3/16”)(6”)) = 20.0 (kips)



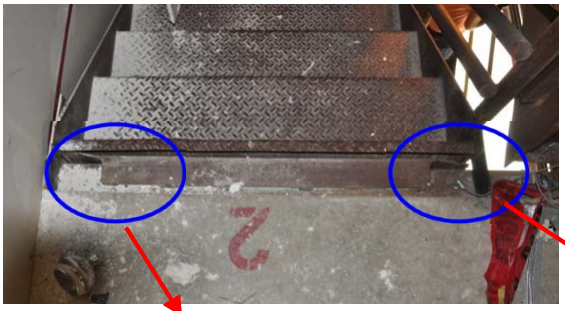
Handrail Fracture (minor)



Intermediate landing

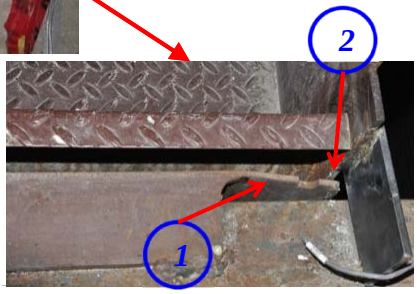
Floor level

Upper Flight-Floor Connection Plate



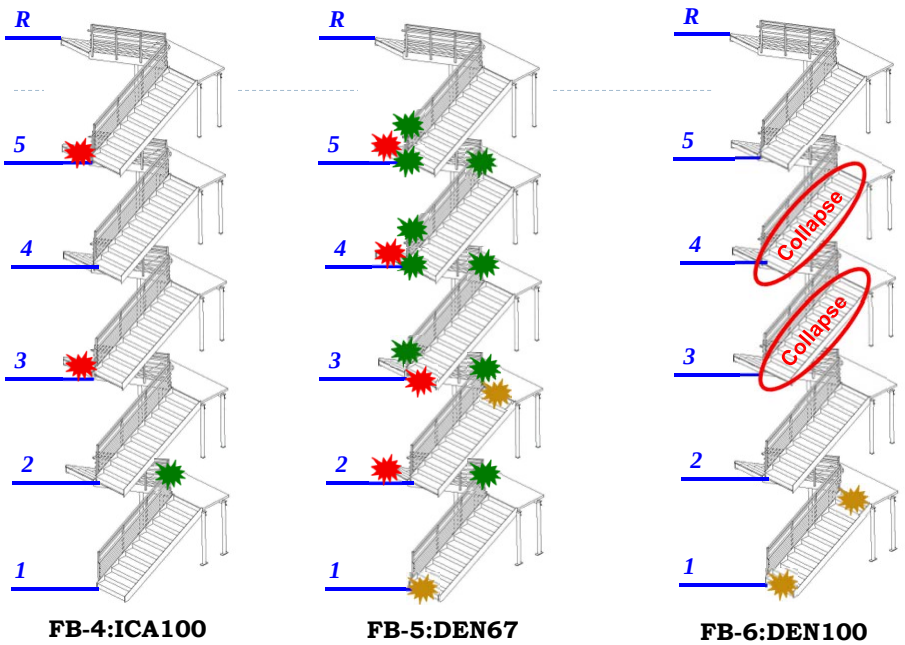
Damaged due to:

1. Plastic yielding of connection plate (minor/moderate)
2. Flight-connection plate weld failure (moderate/severe)



Lower Flight-Floor Weld Fracture & Full Detachment (severe)

Test Video: Den100



FB-4:ICA100 FB-5:DEN67 FB-6:DEN100

ASCE 7-10 Chapter 13 Relative Seismic Displacement for NCSs (in general)

13.3.2.1 Displacements within Structures

For two connection points on the same Structure A or the same structural system, one at a height h_x and the other at a height h_y, D_p shall be determined as

$$D_p = \Delta_{xA} - \Delta_{yA} \qquad (13.3\text{-}6)$$

Alternatively, D_p is permitted to be determined using modal procedures described in Section 12.9, using the difference in story deflections calculated for each mode and then combined using appropriate modal combination procedures. D_p is not required to be taken as greater than

$$D_p = \frac{(h_x - h_y)\Delta_{aA}}{h_{sx}} \qquad (13.3\text{-}7)$$

ASCE 7-10 Chapter 13 Relative Seismic Displacement for NCSs in general

h_x = height of Level x to which upper connection point is attached

h_y = height of Level y to which lower connection point is attached

Δ_{aA} = allowable story drift for Structure A as defined in Table 12.12-1

Δ_{aB} = allowable story drift for Structure B as defined in Table 12.12-1

h_{sx} = story height used in the definition of the allowable drift Δ_a in Table12.12-1. Note that Δ_a/h_{sx} = the drift index.

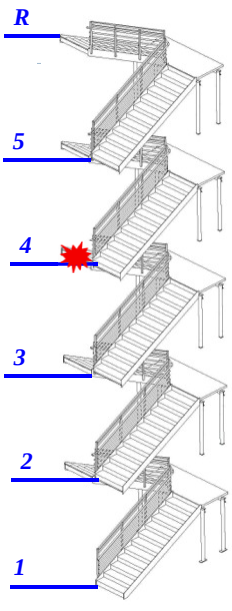
ASCE 7-10 Chapter 12 Table 12.12-1

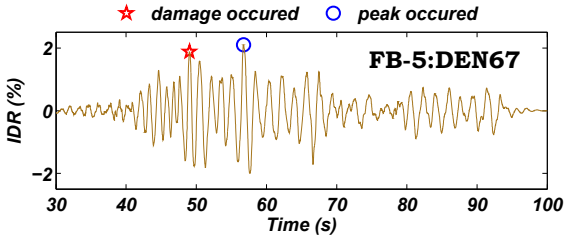
Table 12.12-1 Allowable Story Drift, Δ_a[a,b]

Structure	Risk Category I or II	III	IV
Structures, other than masonry shear wall structures, 4 stories or less above the base as defined in Section 11.2, with interior walls, partitions, ceilings, and exterior wall systems that have been designed to accommodate the story drifts.	$0.025h_{sx}$[c]	$0.020h_{sx}$	$0.015h_{sx}$
Masonry cantilever shear wall structures[d]	$0.010h_{sx}$	$0.010h_{sx}$	$0.010h_{sx}$
Other masonry shear wall structures	$0.007h_{sx}$	$0.007h_{sx}$	$0.007h_{sx}$
All other structures	$0.020h_{sx}$	$0.015h_{sx}$	$0.010h_{sx}$

[a] h_{sx} is the story height below Level x.
[b] For seismic force-resisting systems comprised solely of moment frames in Seismic Design Categories D, E, and F, the allowable story drift shall comply with the requirements of Section 12.12.1.1.
[c] There shall be no drift limit for single-story structures with interior walls, partitions, ceilings, and exterior wall systems that have been designed to accommodate the story drifts. The structure separation requirement of Section 12.12.3 is not waived.
[d] Structures in which the basic structural system consists of masonry shear walls designed as vertical elements cantilevered from their base or foundation support which are so constructed that moment transfer between shear walls (coupling) is negligible.

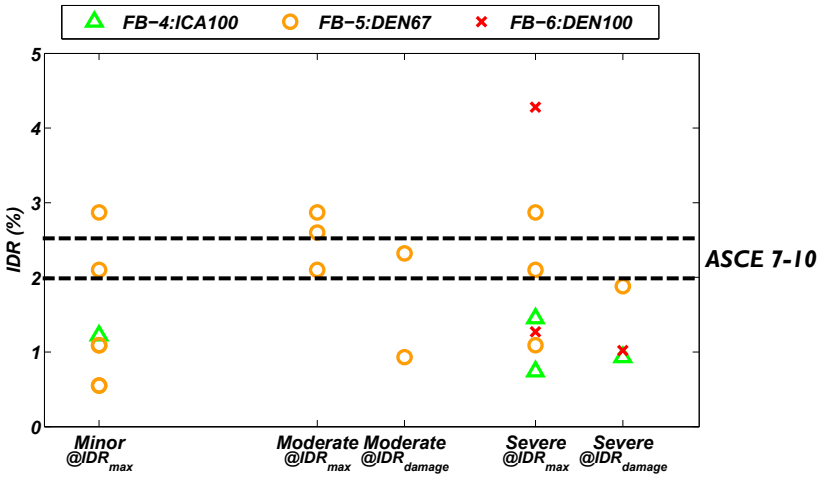
Upper Flight–Slab Connection Plate Fracture (Level 3-4)





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

Actual IDRs @ DSs



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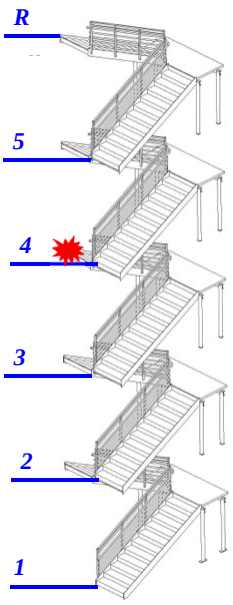
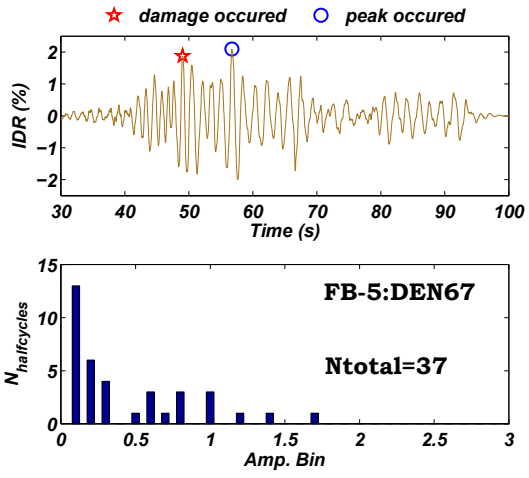
Upper Flight-Slab Connection Damage (Level 3-4): Cycle Counting





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

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Façade Subsystems: Seismic Test Observations

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Levels 1-3: Balloon Framing Construction

Metal "balloon framed" studs | **Gypsum sheathing** | **Styrofoam backing** | **Synthetic stucco**

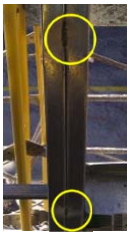
Levels 1-3: Stud and clip detailing

Stud top clip connections

Box header above opening

Vertical studs spacing @ 16”

Clip connection between vertical and horizontal studs



Welding of double studs

Interior Gypsum Damage - North Face (Level 1)

North Face (Level 1) – Clip Failures: shot pins

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South Face (Level 1) – Clip Failure: anchors

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Top South-West Corner

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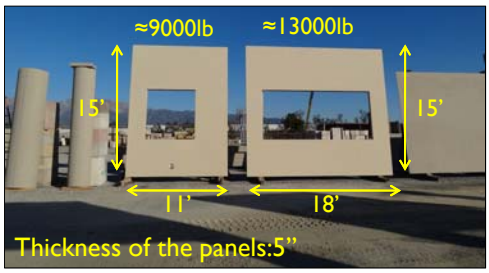
Levels 4-5: Precast Concrete Cladding (PCC)



- **16 PANELS:**
  - 8 smaller panels in the East and West sides (Out of Plane)
  - 8 larger panels in the North
  - and South sides (In Plane)
- **Panels supported by:**
  - Bearing connections at bottom
  - Push pull, sliding & flexing connections at top (MAJOR INTEREST FOR US)

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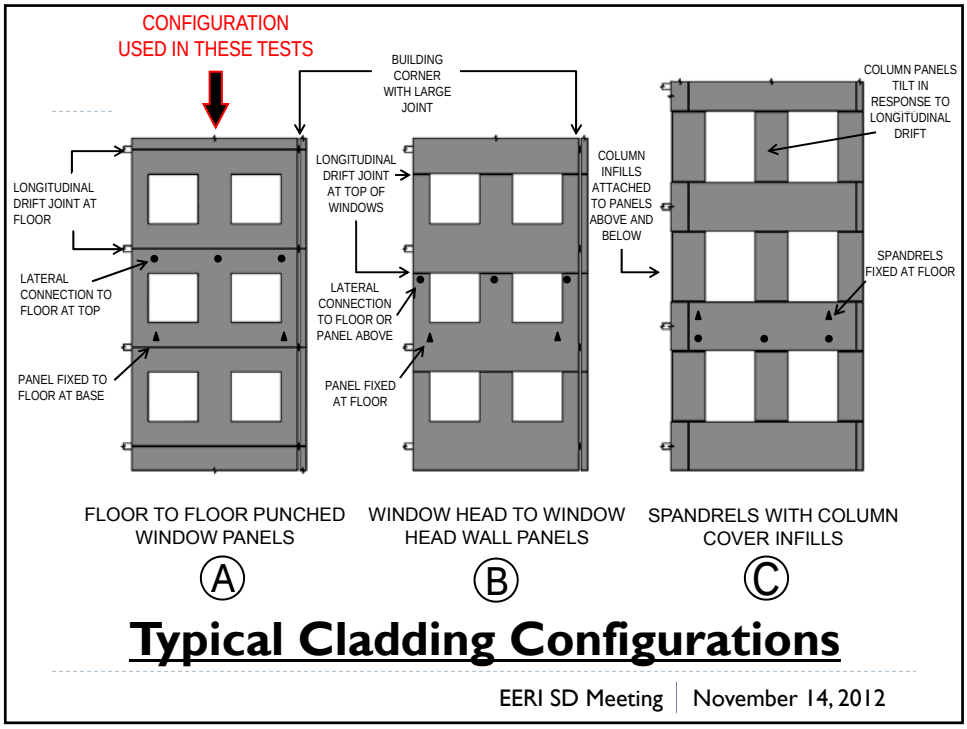

Typical Cladding Configurations

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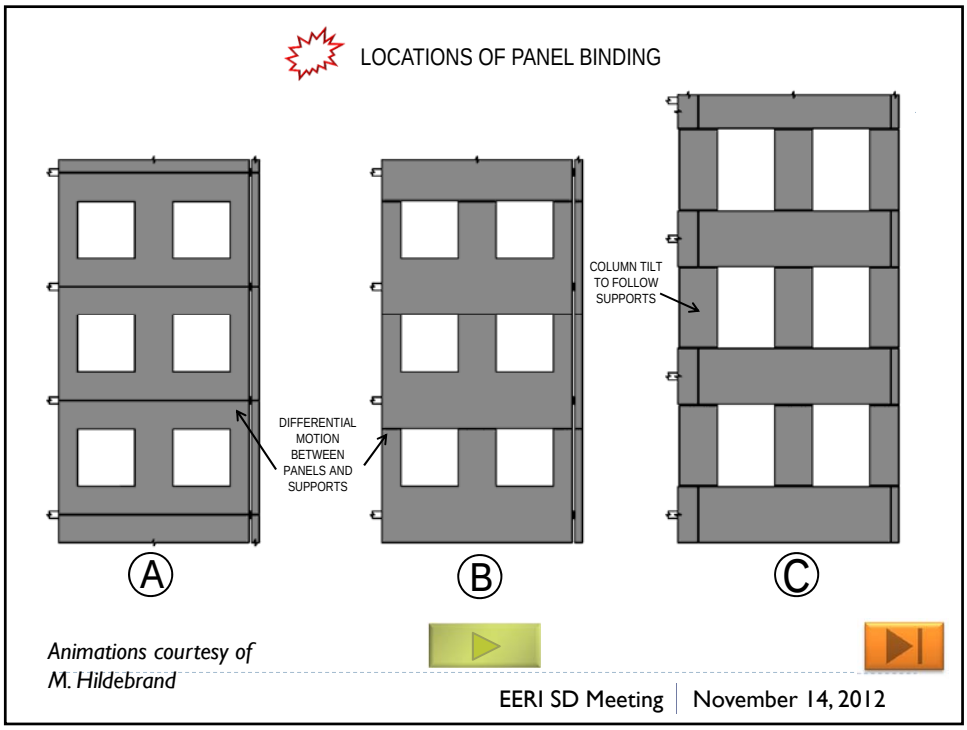

Animations courtesy of M. Hildebrand

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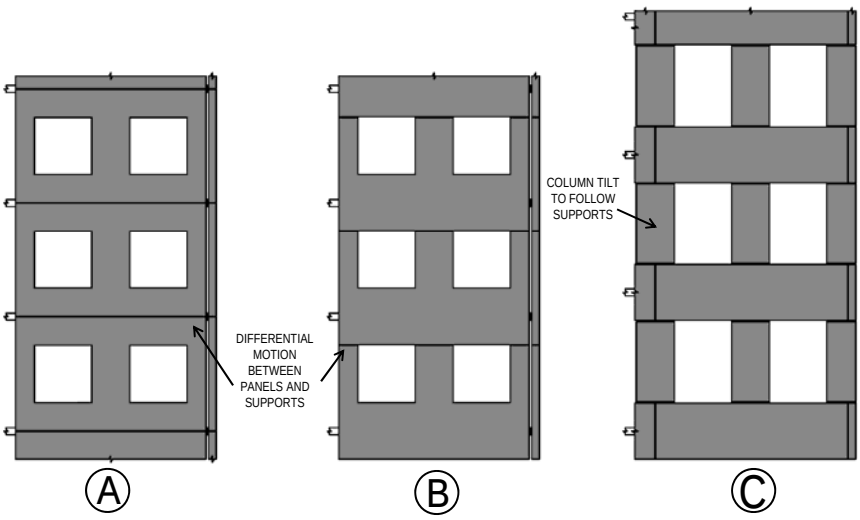
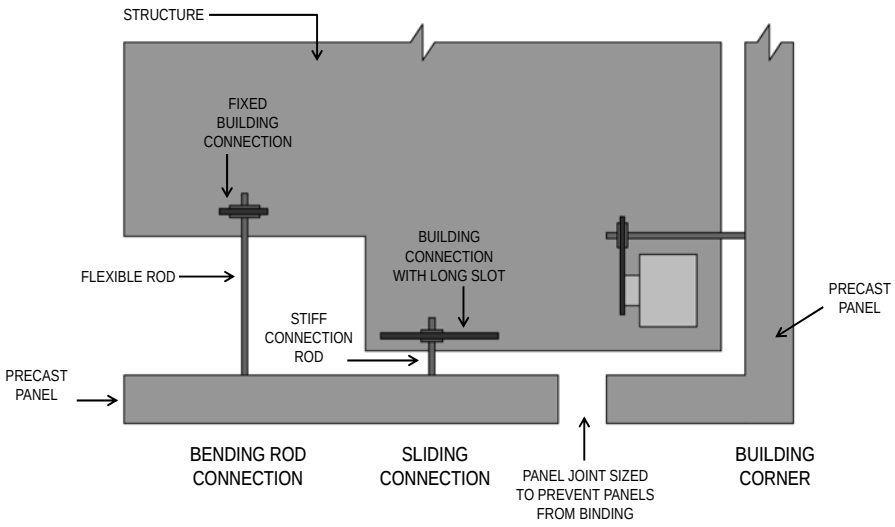
LOCATIONS OF PANEL BINDING



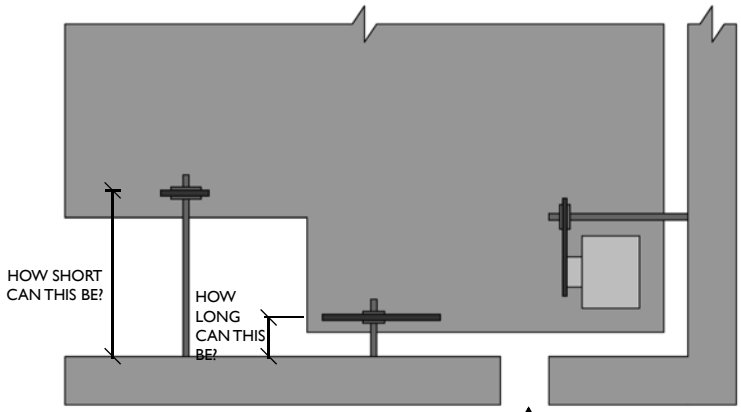
Press Esc

REFLECTED CEILING PLAN

PANEL CONFIGURATION Ⓐ



REFLECTED CEILING PLAN
PANEL CONFIGURATION Ⓐ



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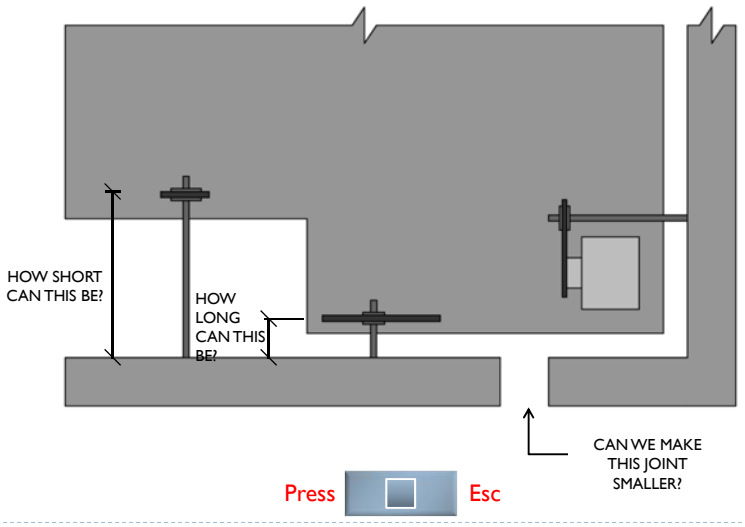
REFLECTED CEILING PLAN
PANEL CONFIGURATION Ⓐ



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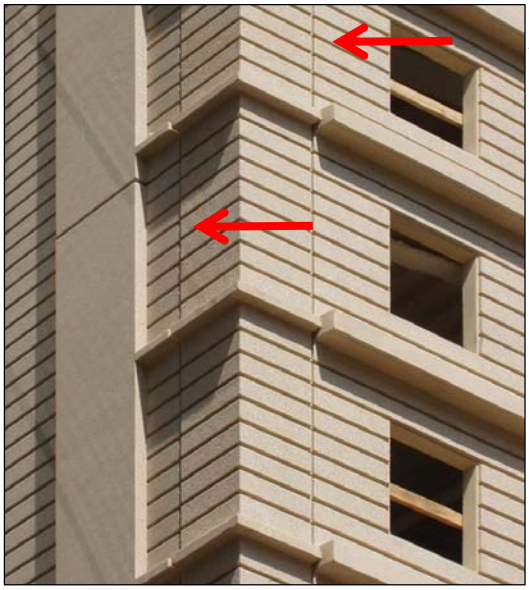
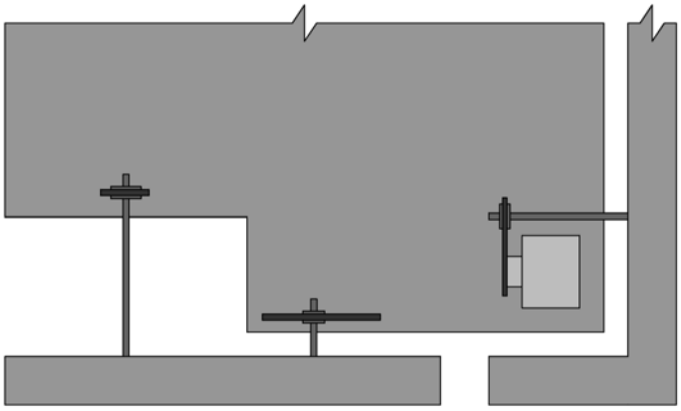


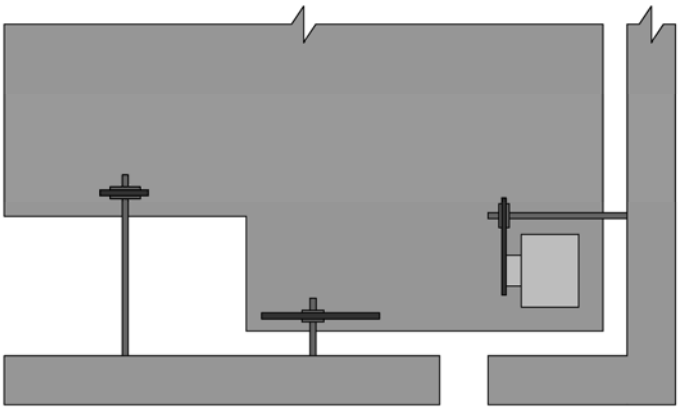
REFLECTED CEILING PLAN

PANEL CONFIGURATION Ⓐ

(PANEL CONTACT)



REFLECTED CEILING PLAN
PANEL CONFIGURATION Ⓐ
(PANEL CONTACT)

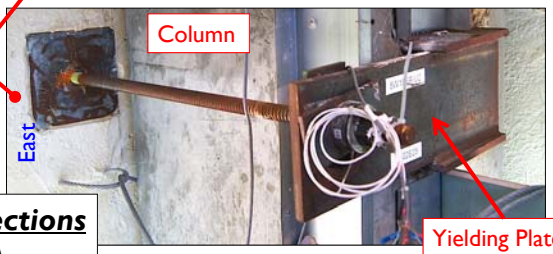


Press Esc

PCC: Connections-Overview

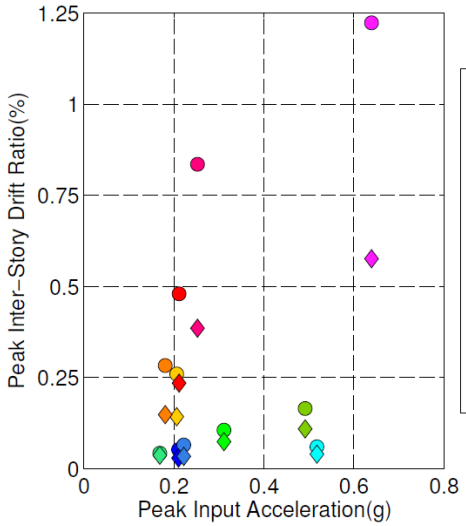
Sliding Connections

Flexing Connections



Push-pull Connections (new idea)

PIDR Demands Level 4 & 5



- < 0.20% BI Phase
- < 0.50% FB 'service level' events (CNP, LAC)
- DEN67 ('design event')
  - 0.6% = LVL 4-5
  - 1.2% = LVL 5-R
- DEN100 ~ 2%

Comparison of Façade Behavior

Medical Floors: Seismic Test Observations

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Summary of Observations – BI Testing

- Peak Floor Accel: ~0.25g (R), ~0.23g (L5), ~0.22g (L4)
- Max Interstory Drifts: ~0.2% (both L5 & L4)

- No damage to medical items
- Breakout doors gently closed
- Loose items gently rolled
- No tipping
- No contents fell to floor

Summary of Observations – FB Testing: Den67

- Peak Floor Accel: ~1.00g (R), ~0.65g (L5), ~0.70g (L4)
- Max Interstory Drifts: ~0.5% (L5), ~1.8% (L4)

- Contents fell to floor (rolling cabinet, wire rack)
- Tipped: L5 Bed (N-S), workstation on wheels, wire rack
- Bed pounded hole in partition wall
- Rolling rack pounded utility rack and instruments
- Breakout Door* jammed

Concluding Remarks (1/2)

- Egress subsystems:
  - Elevator system performed well and remained functional during all test motions except Den100 due to door failure at lower levels which was precipitated by supporting partition wall damage;
  - Significant damage to the stairs occurred at PIDR as low as about 1.0%; severe damage that would render the stairs unsafe for use occurred at PIDR > ~ 2.0%;
- Façade subsystems:
  - Levels 1-3: Lightweight balloon framing overlaid with gypsum & stucco. Damage in the form of stucco tearing, detachment at base, corners, and clip connections
  - Levels 4-5: PCC. Plastic yielding of long and medium rods occurred at low PIDR, however, the subsystem and its connections performed markedly well (and as intended) with no brittle fracture (loss of service) despite multiple EQ runs

Concluding Remarks (2/2)

- Medical Floors:
  - "Damage" primarily caused by:
    - Tipping (beds, wire rack, workstation on wheels)
    - Impact/Pounding (bed, rolling cabinet)
  - Performed well:
    - Items anchored and staged to standard recommendations for use
    - Items with design less than code level
- All subsystems demonstrated increased seismic resiliency when the building was base isolated – due to the low IDR and significant attenuation of floor accelerations

Hospitals for the Future: Broadcast Premiere

San Diego: UCSD-TV Oct 31

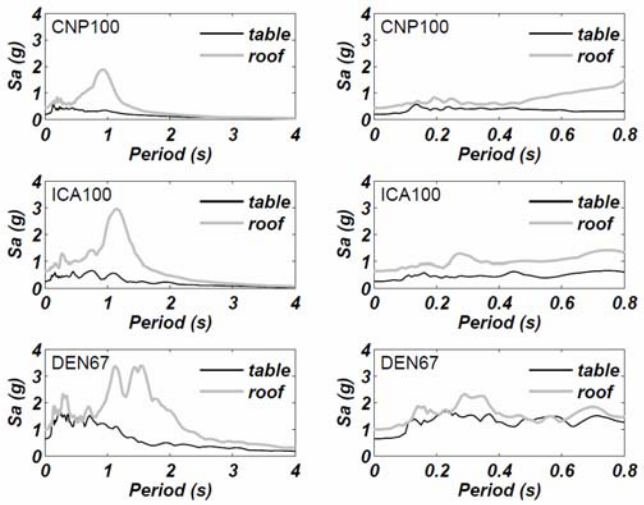
http://www.ucsd.tv/

Worldwide: UC-TV Oct 31

http://www.uctv.tv/

Thanks for your attention!

Input Acc. Spectra and Floor Acc. Spectra of FB Input Motions



FRS

- 5% damping elastic spectra

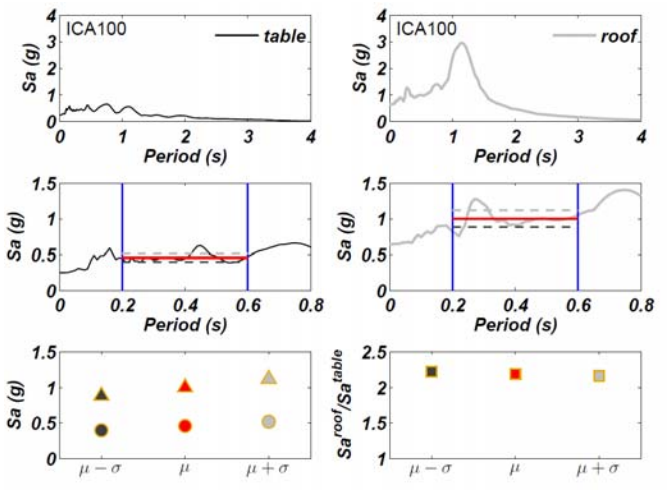
Three FB motions:

- FB-1:CNP100
- FB-4:ICA100
- FB-5:DEN67

X-axis window

- 0 ~ 4 second on the left
- 0 ~ 0.8 second on the right

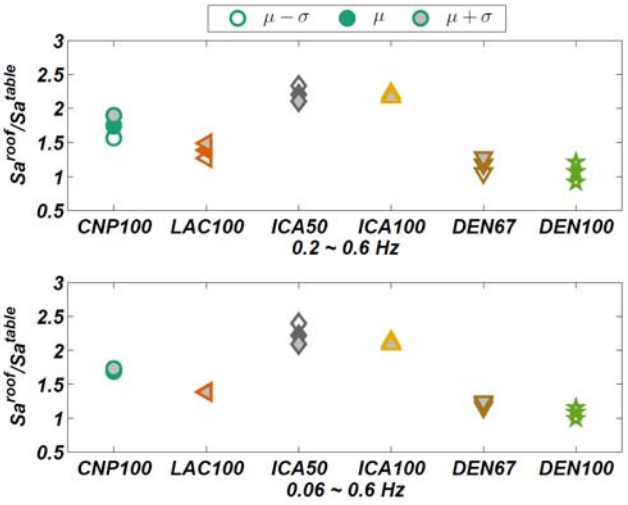
Spectral Acceleration Amplification Factors Processing



Procedure:

- Calculate Sa from both roof and input accelerations (0~4 seconds)
- Take Sa values from the range of interest and calculate the means and standard deviations
- Consider averaged Sa at three different statistic levels: μ-σ, μ, and μ+σ
- Obtain the unitless value of Sa^{roof}/Sa^{table}

Sa Ratios



Sa^{roof}/Sa^{table}

- All 6 fixed based test motions
- Two different range: 0.2 ~ 0.6 sec (top) and 0.06 ~ 0.6 sec (bottom)
- Range between 1.0 and 2.5
- Low variability against lower bound periods or statistic levels

Phase 2: Fixed-base building NCS system