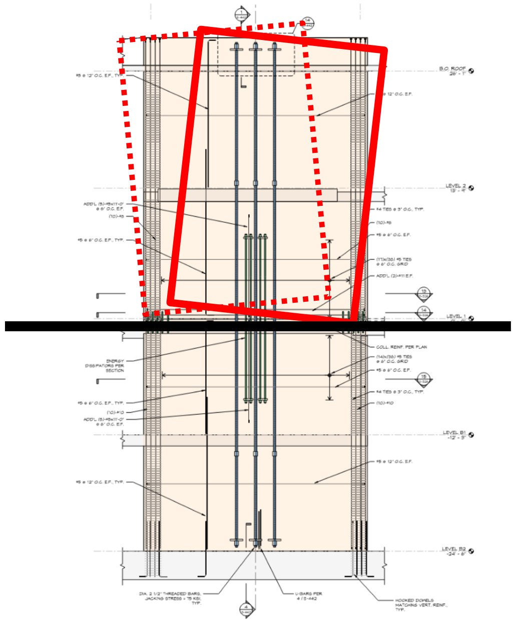
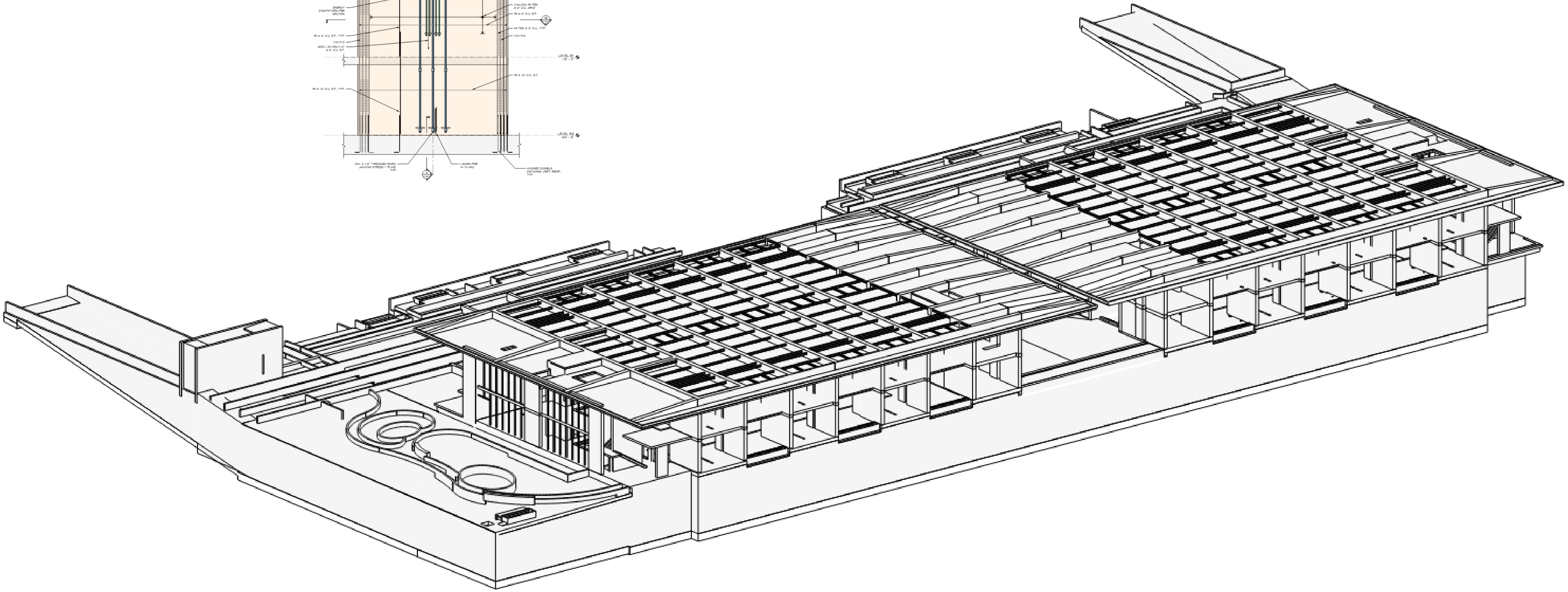
Design in the Shared Space
Practice and Research

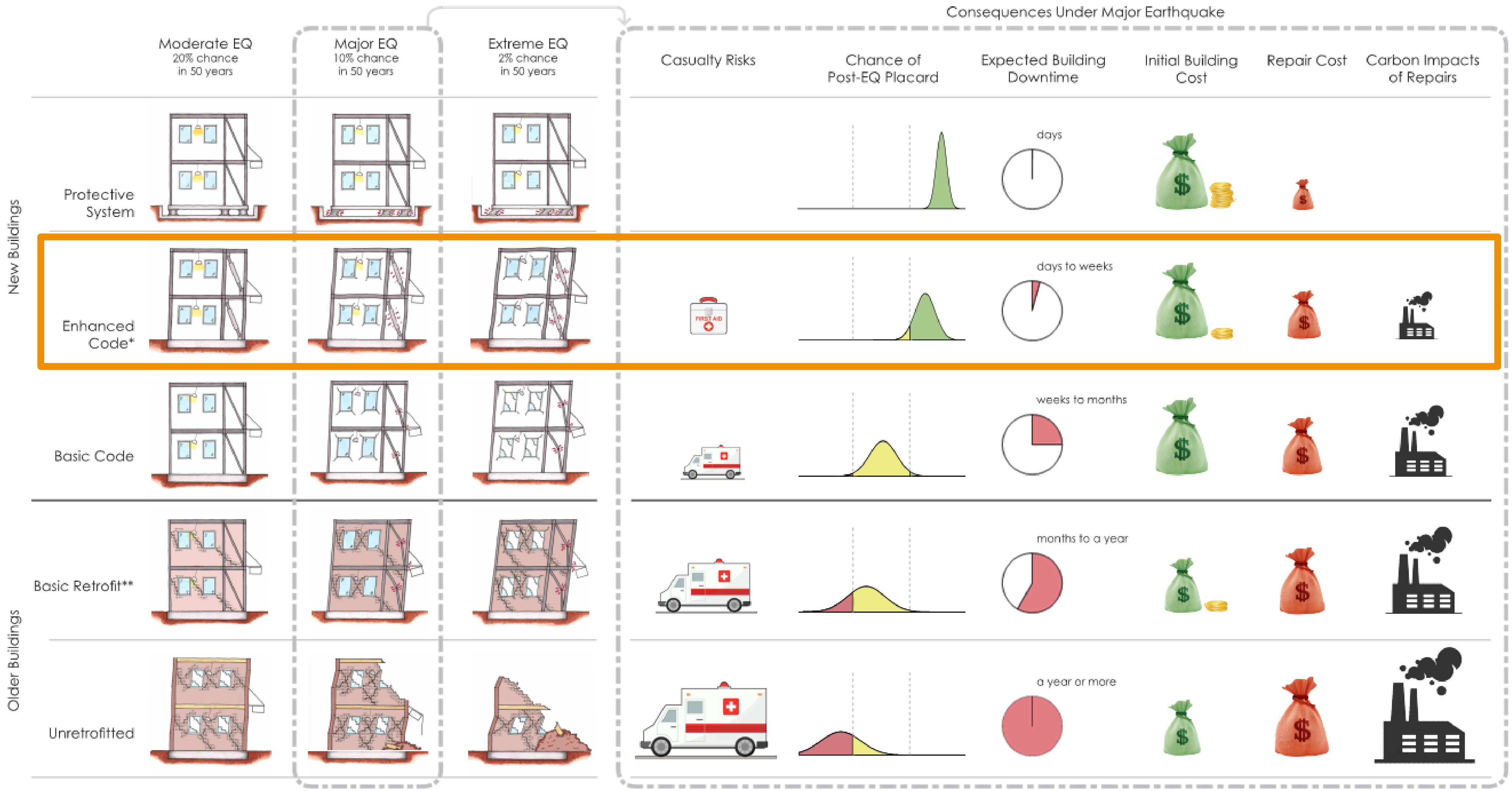
The Salk Institute – Jacobs Science and Technology Center


B.O. ROOF
26' - 1"
@ 12" O.C. E.F.
LEVEL 2
13' - 9"
#4 TIES @ 3" O.C., TYP.
(10)-#8
#5 @ 6" O.C. E.F.
(17)x(38) #5 TIES
@ 6" O.C. GRID
ADD'L (2)-#11 E.F.
LEVEL 1
COLL. REINF. PER PLAN
(14)x(38) #5 TIES
@ 6" O.C. GRID
#5 @ 6" O.C. E.F.
#4 TIES @ 3" O.C., TYP.
(10)-#10
LEVEL B1
-12' - 9"
#5 @ 12" O.C. E.F.
LEVEL B2
-24' - 6"
HOOKED DOWELS
MATCHING VERT. REINF.,
TYP.



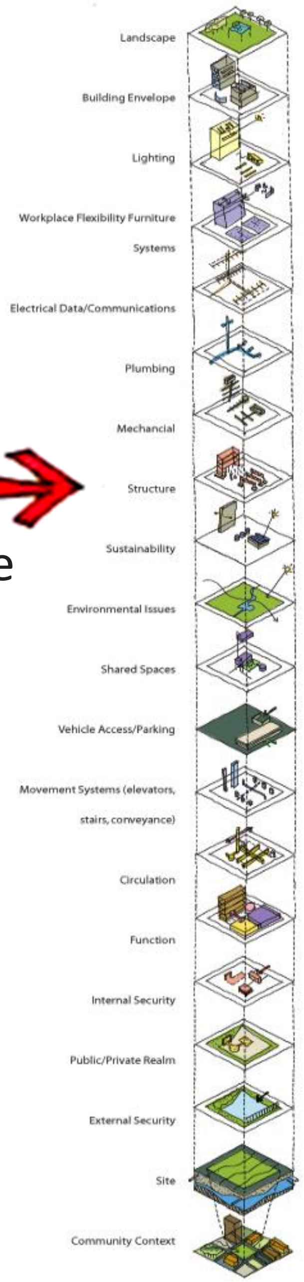
OPTIONS FOR EARTHQUAKE RESISTANT DESIGN

Design Decisions Have Measurable Consequences



Structure

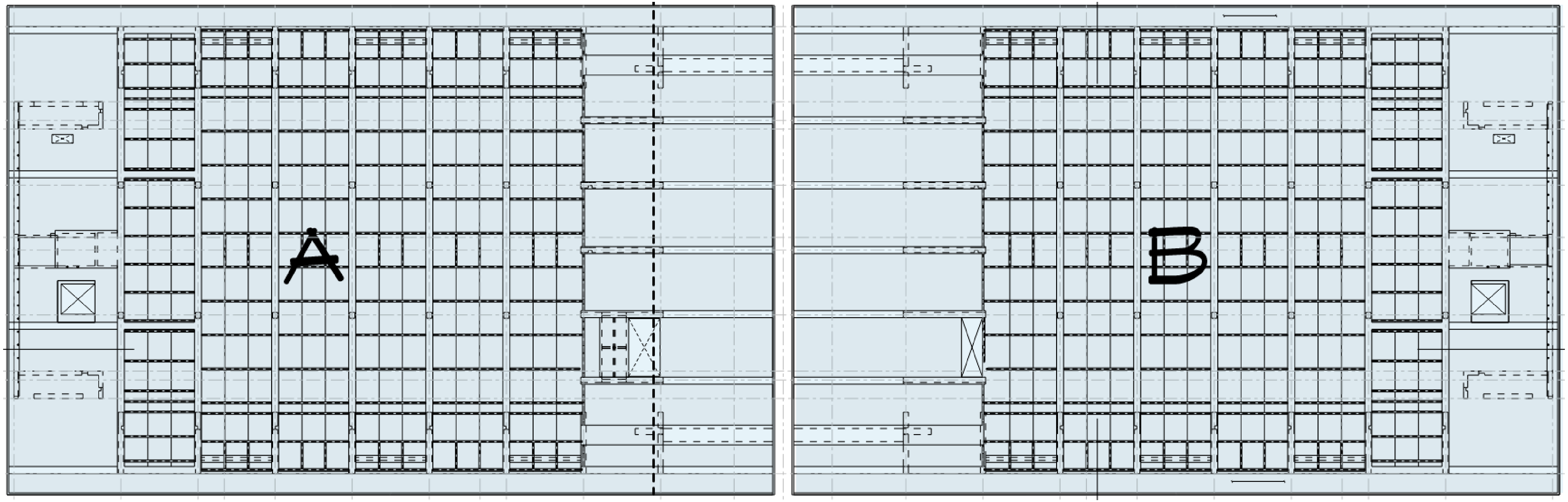
25% of building value

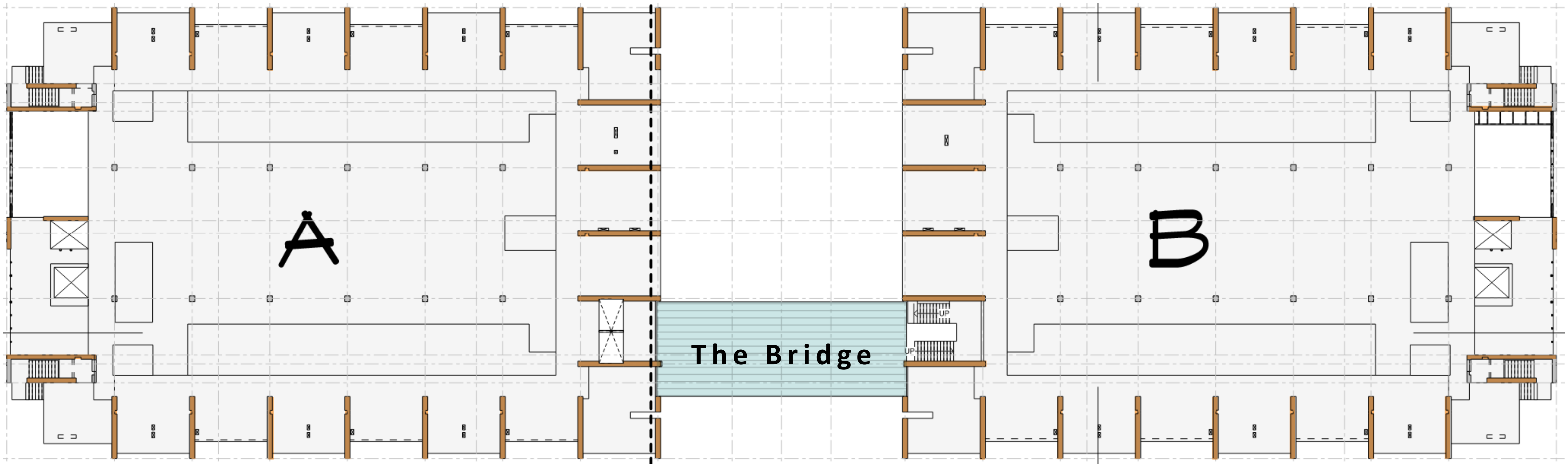


75% of building value

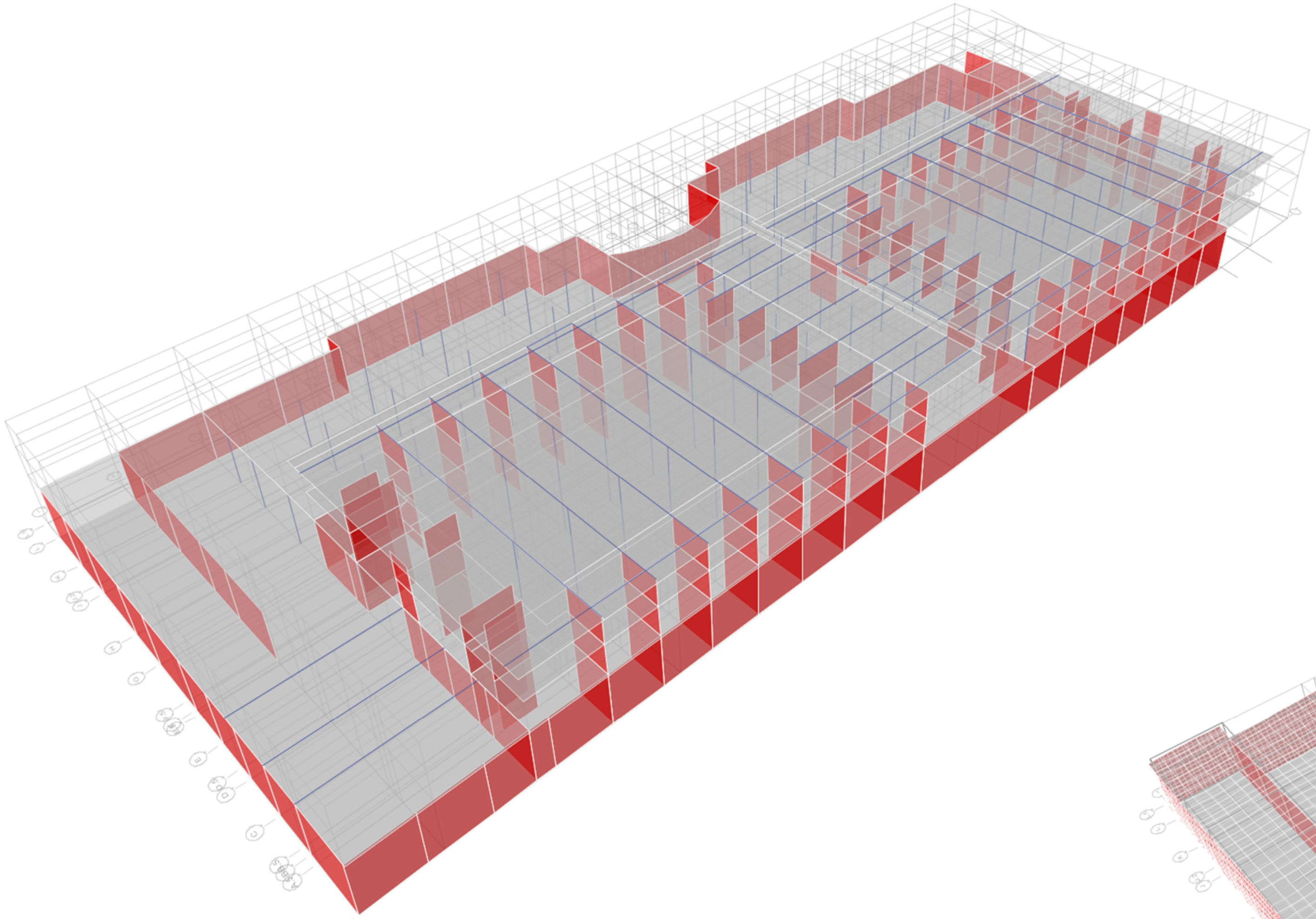
Image courtesy of BNIM

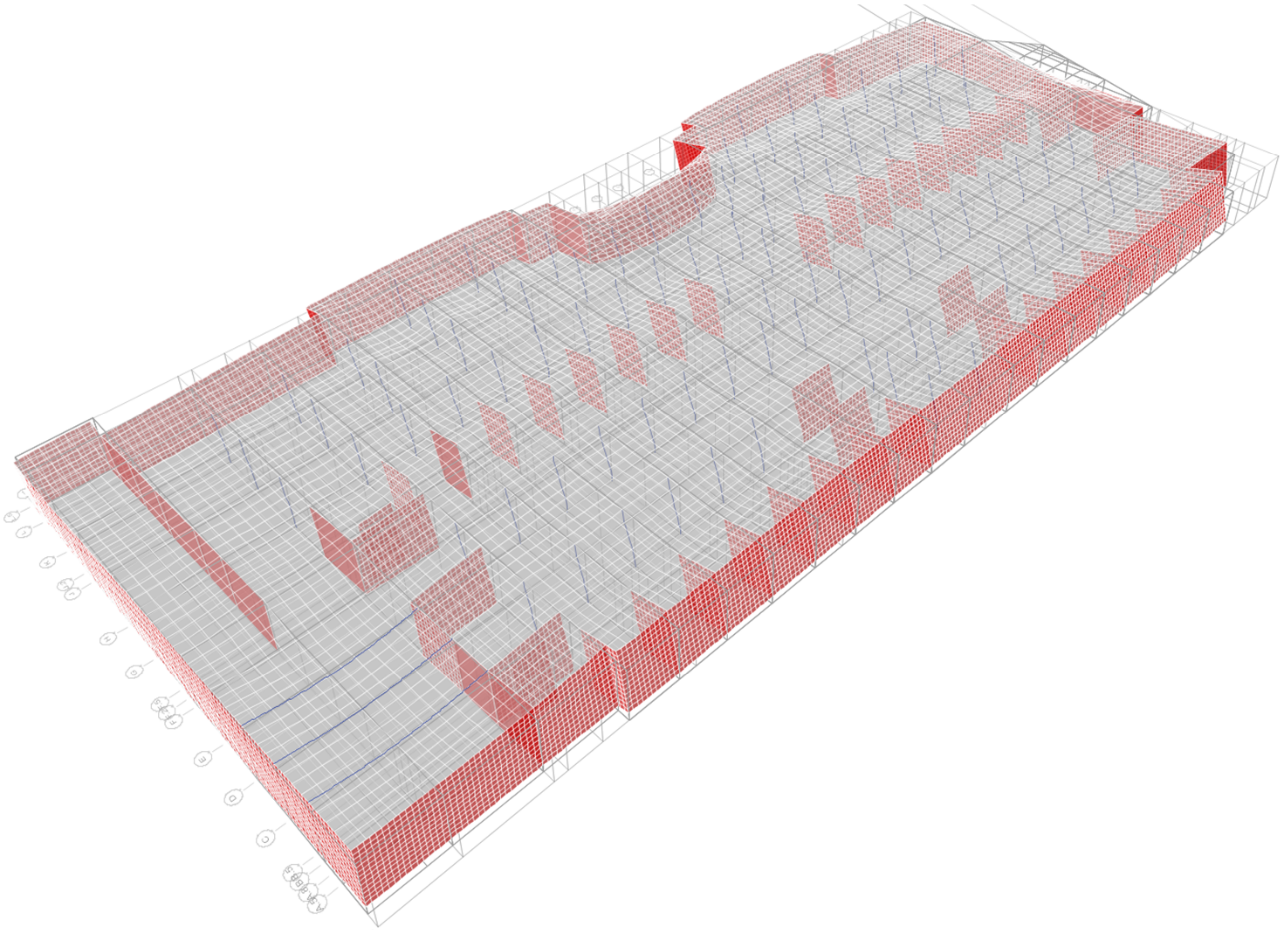
Two Halves



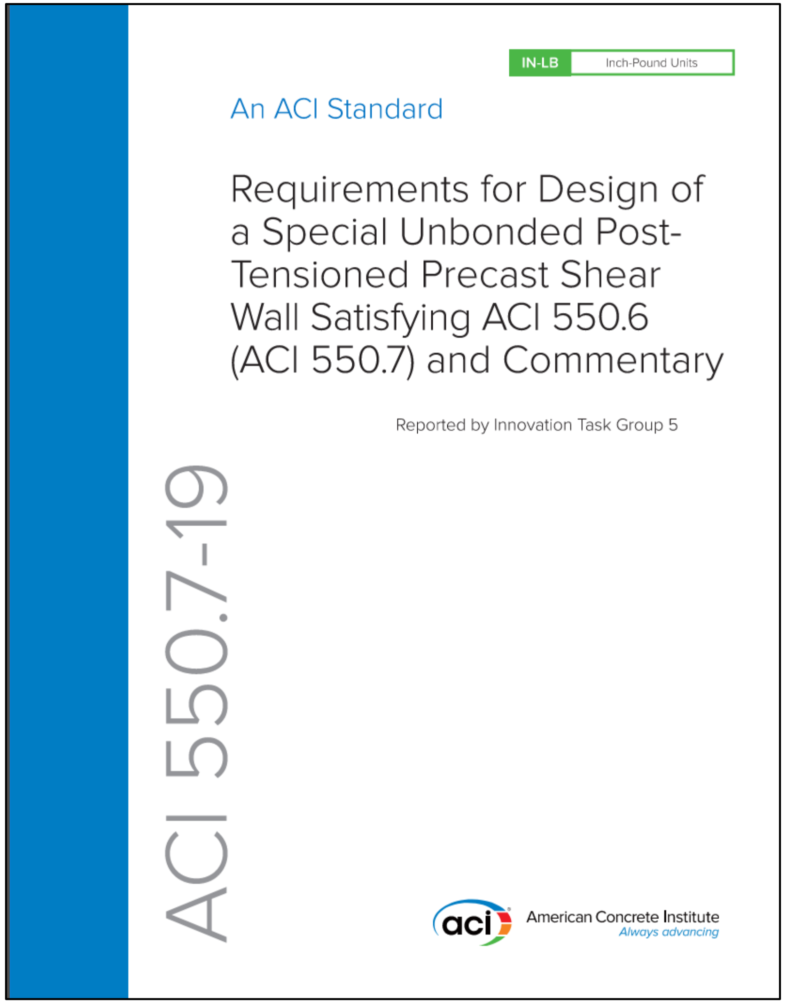

A
B
The Bridge
UP
UP

The Base





Design Basis



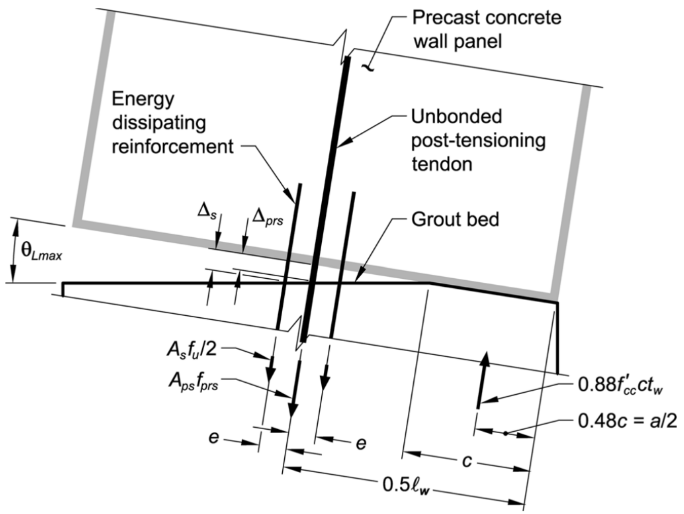


Fig. R6.2—Conditions as probable flexural strength for base of wall of Fig. R1.1(a).

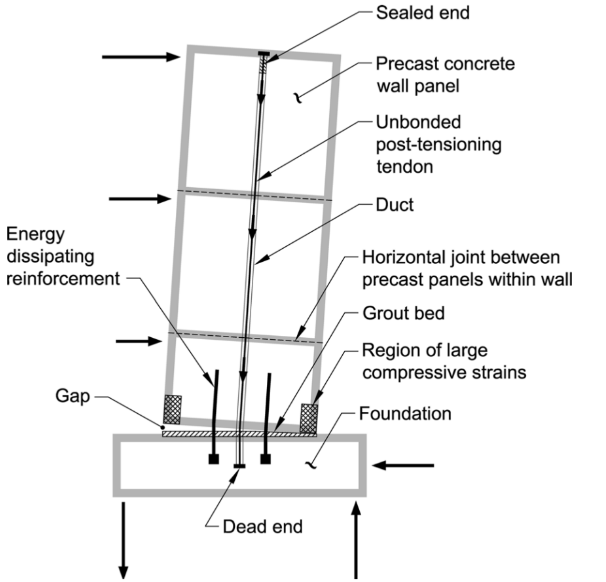


Fig. R1.1(a)—Main features of uncoupled unbonded post-tensioned precast shear wall.

Seismic Performance of Precast Reinforced and Prestressed Concrete Walls

Tony Holden[1]; Jose Restrepo[2]; and John B. Mander[3]

Abstract: Two geometrically identical half-scale precast concrete cantilever wall units were constructed and tested under quasi-static reversed cyclic lateral loading. One unit was a code compliant conventionally reinforced specimen, designed to emulate the behavior of a ductile cast-in-place concrete wall. The other unit was part of a precast partially prestressed system that incorporated post-tensioned unbonded carbon fiber tendons and steel fiber reinforced concrete. Hysteretic energy dissipation devices were provided in the latter unit in the form of low yield strength tapered longitudinal reinforcement, acting as a fuse connection between the wall panel and the foundation beam. The conventional precast reinforced wall performed very well in terms of the ductility capacity and energy absorption capability, reaching 2.5% drift before significant strength degradation occurred. The precast partially prestressed wall unit achieved drift levels well in excess of 3% with no visible damage to the wall panel prior to failure. Test results and performance comparisons between the precast partially prestressed wall system and the precast conventionally reinforced unit are presented.

DOI: 10.1061/(ASCE)0733-9445(2003)129:3(286)

CE Database keywords: Seismic stability; Walls; Concrete, reinforced; Concrete, precast.

Introduction

The earthquake-structural engineers' role has historically focused on ensuring life safety while recognizing the limitations that economics places on design. To design a structure elastically using conventional design methods and philosophies has generally been considered impractical. Engineers, in general, have designed structures for reduced lateral forces and accepted damage in potential plastic hinge zones, which are specifically detailed for ductility. No other economic parameters, such as the cost of damage to equipment and stored goods and the cost associated with loss of operation following a moderate or strong earthquake, are currently accounted for in the design process.

One of the main disadvantages of conventional cast-in-place construction, or precast concrete construction designed to behave as "if monolithic," is that regions in the lateral force resisting system are likely to be sacrificed in moderate and strong earthquakes. Significant damage involving large residual lateral displacements and wide residual cracks is expected to occur with such systems; hence, the cost and consequences of damage after an earthquake can be significant to the building occupant. Uncoupling the energy dissipation mechanism from the structure is an ideal solution that was first conceived and implemented through seismic isolation. This solution, however, has generally been restricted in the United States and New Zealand to nationally significant structures.

The excellent seismic performance of buildings constructed incorporating structural walls is well documented (Wood et al. 1987; Wyllie 1989; Fintel 1995). For example, during the 1988 Armenia earthquake poorly designed and constructed buildings that incorporated precast concrete walls as the main lateral force resisting system performed substantially better than buildings built with other structural systems (Wyllie 1989). Buildings where lateral force resistance was provided by structural walls also showed excellent performance during the 1985 Chilean earthquake (Wood et al. 1987).

Although structural walls are a common and cost-effective way of providing lateral force resistance to buildings in seismic areas of the world there has been a drive to make wall systems more economical. Historically, cast-in-place reinforced concrete has been the most commonly used method of construction for structural wall systems. More recently, there has been an increased use of precast concrete walls of either the tilt-slab or factory-built variety; their design being carried out to emulate the behavior of their cast-in-place counterparts.

Fig. 1 schematically compares the response of (a) a conventional reinforced concrete system; (b) a fully prestressed precast concrete system; and (c) a partially prestressed (hybrid) concrete system. For the last two prestressed wall systems the tendons, if left unbonded over a certain length, remain elastic during rocking. In this way the elastic restoring force will essentially prevent residual lateral displacements from occurring. Since the concrete is not bonded to the tendons, considerably less cracking is induced than in monolithic walls that rely solely on bonded reinforcement to provide the lateral force resistance. The behavior of such a system can be described as being bilinear elastic. In these systems cosmetic damage is restricted to the bottom corners of the wall about which it rocks. By armoring the ends of a prestressed concrete wall with steel plates and embedding a mating steel plate in the foundation, it is possible to avoid any damage,

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RESEARCH ARTICLE

WILEY

Shake-table test of a two-storey low-damage concrete wall building

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Funding information
International Joint Research Laboratory of Earthquake Engineering; New Zealand Ministry of Business, Innovation and Employment; New Zealand center of earthquake resilience (QuakeCoRE); Concrete NZ

Abstract

The increasing need to reduce damage and downtime in modern buildings has led to the development of a low-damage design philosophy, where the earthquake loads can be resisted with damage confined to easily replaceable components. Post-tensioned (PT) concrete walls have emerged as a popular low-damage structural system that have been implemented in a range of buildings. In order to provide essential evidence to support the development of low-damage concrete structures, a system-level shake-table test was conducted on a two-storey low-damage concrete wall building implementing state-of-art design concepts. The test building included PT rocking walls that provide the primary lateral-load resistance in both directions, a frame that utilized slotted beam connections, and a range of alternative energy dissipation devices that were installed at wall base or/and beam-column joints. The building was subjected to 39 tests with a range of intensity ground motions, incorporating both unidirectional and bidirectional ground motions on the structure with different combinations of wall strength and energy dissipating devices. The building performed exceptionally well during the intense series of tests, confirming the suitability of both the design methods and the connection detailing implemented. The building achieved an immediate occupancy performance objective even when subjected to maximum considered earthquake hazard shaking. The building exhibited only minor damage at the conclusion of testing, with distributed cracking in the floors and cosmetic spalling in the wall toes that did not compromise structural capacity or integrity and could be easily repaired with minimal disruption. The test has provided a rich dataset that is available for further analysis of the building response and validation of design methods and numerical models.

KEYWORDS
displacement-based design, energy dissipating device, low-damage design, post-tensioned wall, precast concrete, PRESSS, repairability, rocking wall, seismic design, self-centering, shake-table test, slotted beam, system level, wall-to-floor

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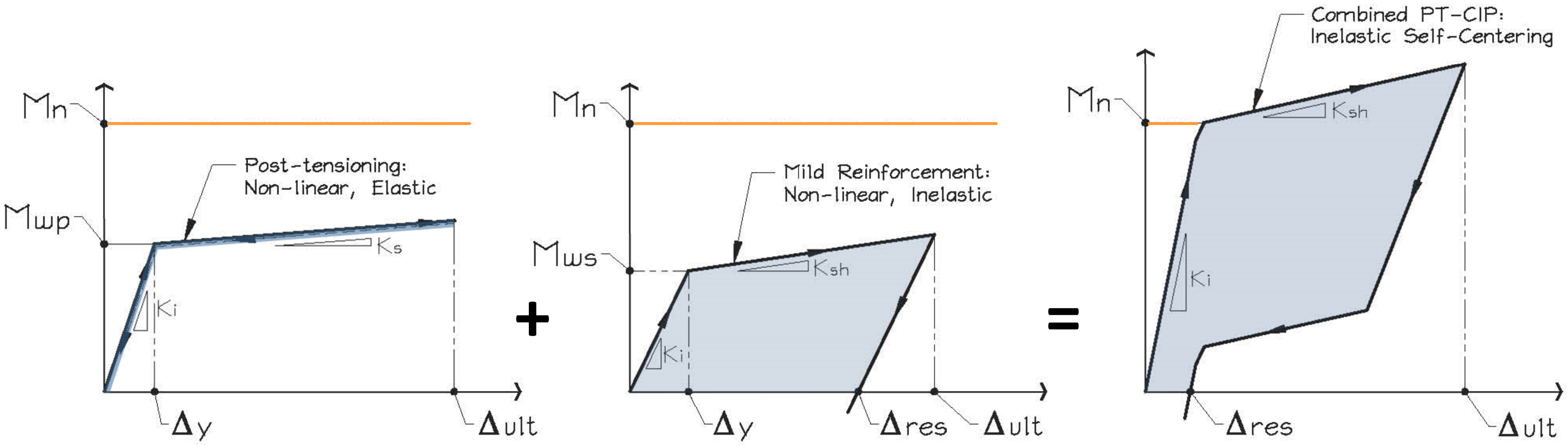
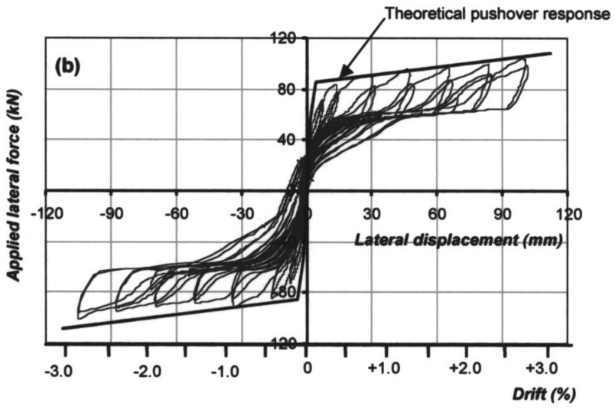
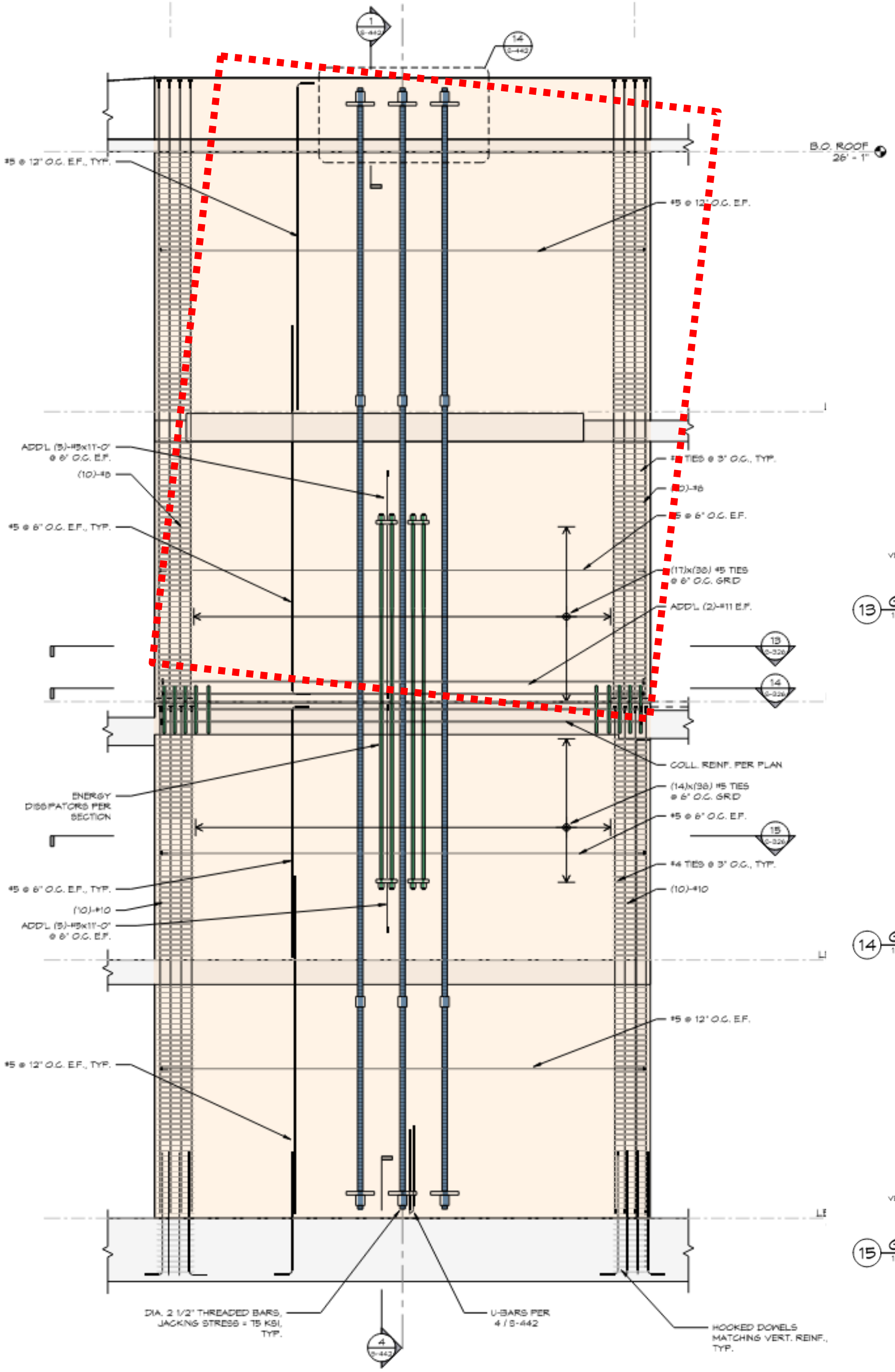


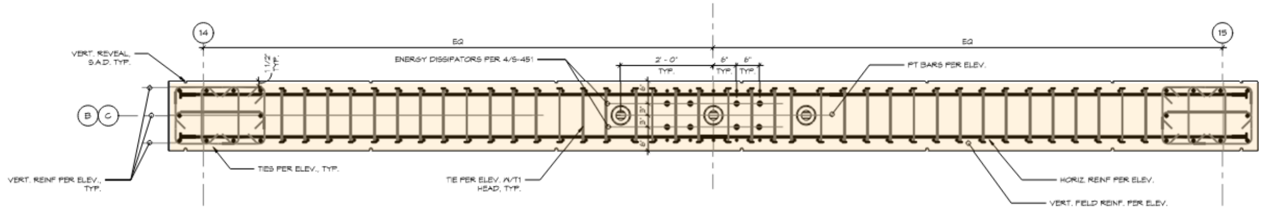
Mn
Mwp
Post-tensioning:
Non-linear, Elastic
Ks
Ki
Δy
Δult
+
Mn
Mws
Mild Reinforcement:
Non-linear, Inelastic
Ksh
Ki
Δy
Δres
Δult
=
Combined PT-CIP:
Inelastic Self-Centering
Mn
Ksh
Ki
Δres
Δult



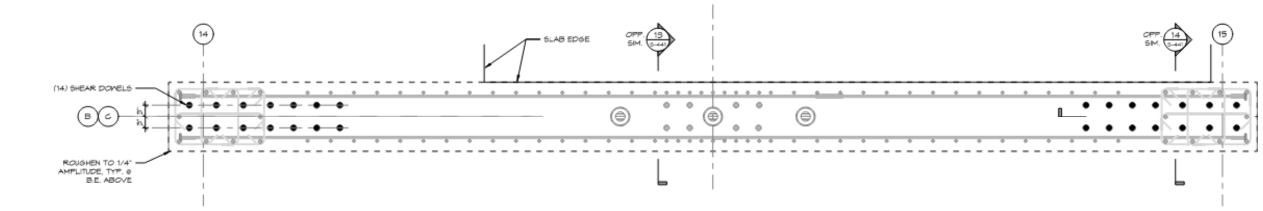
Theoretical pushover response
(b)
Applied lateral force (kN)
120
80
40
-120
-90
-60
-30
0
30
60
90
120
Lateral displacement (mm)
-3.0
-2.0
-1.0
+1.0
+2.0
+3.0
Drift (%)

The Walls

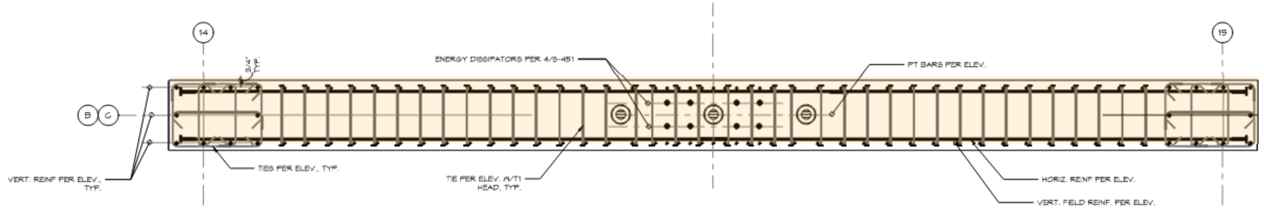




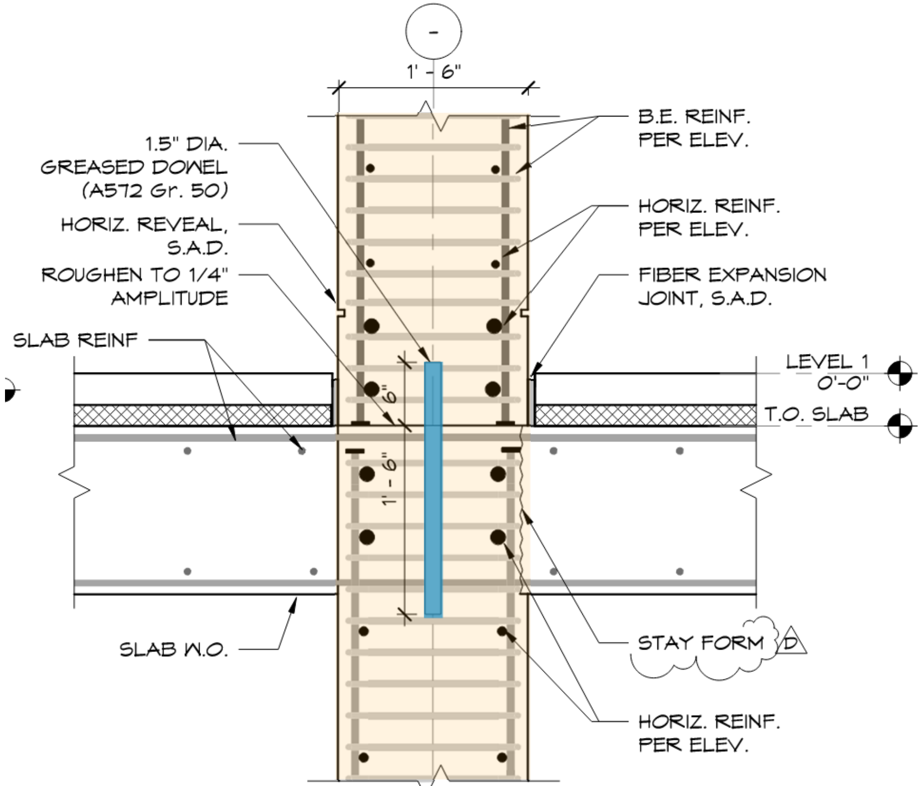
13 GRID B/14 & C/14 - LEVEL 1-ROOF
1" = 1'-0"



14 GRID B/14 & C/14 - INTERFACE
1" = 1'-0"

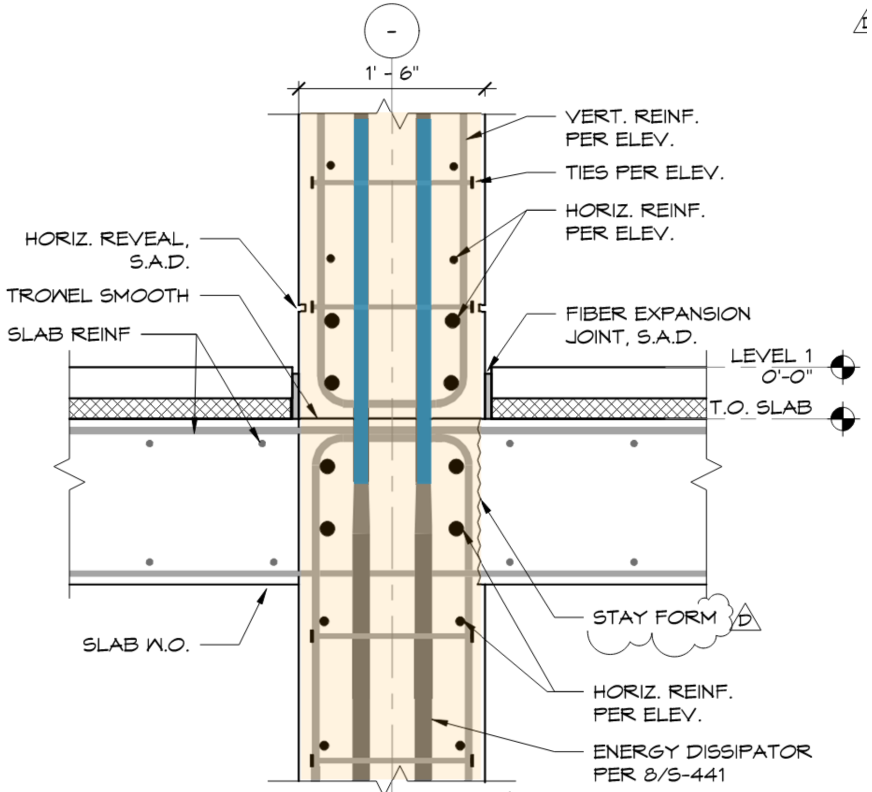


15 GRID B/14 & C/14 - LEVEL B2-1
1" = 1'-0"



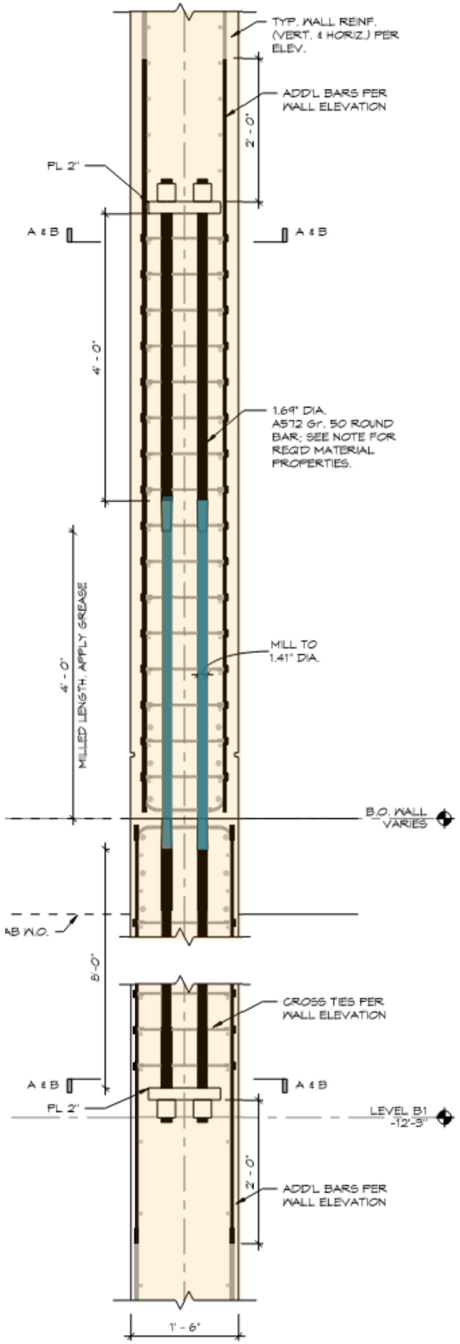
10 SHEAR WALL INTERFACE

1" = 1'-0"

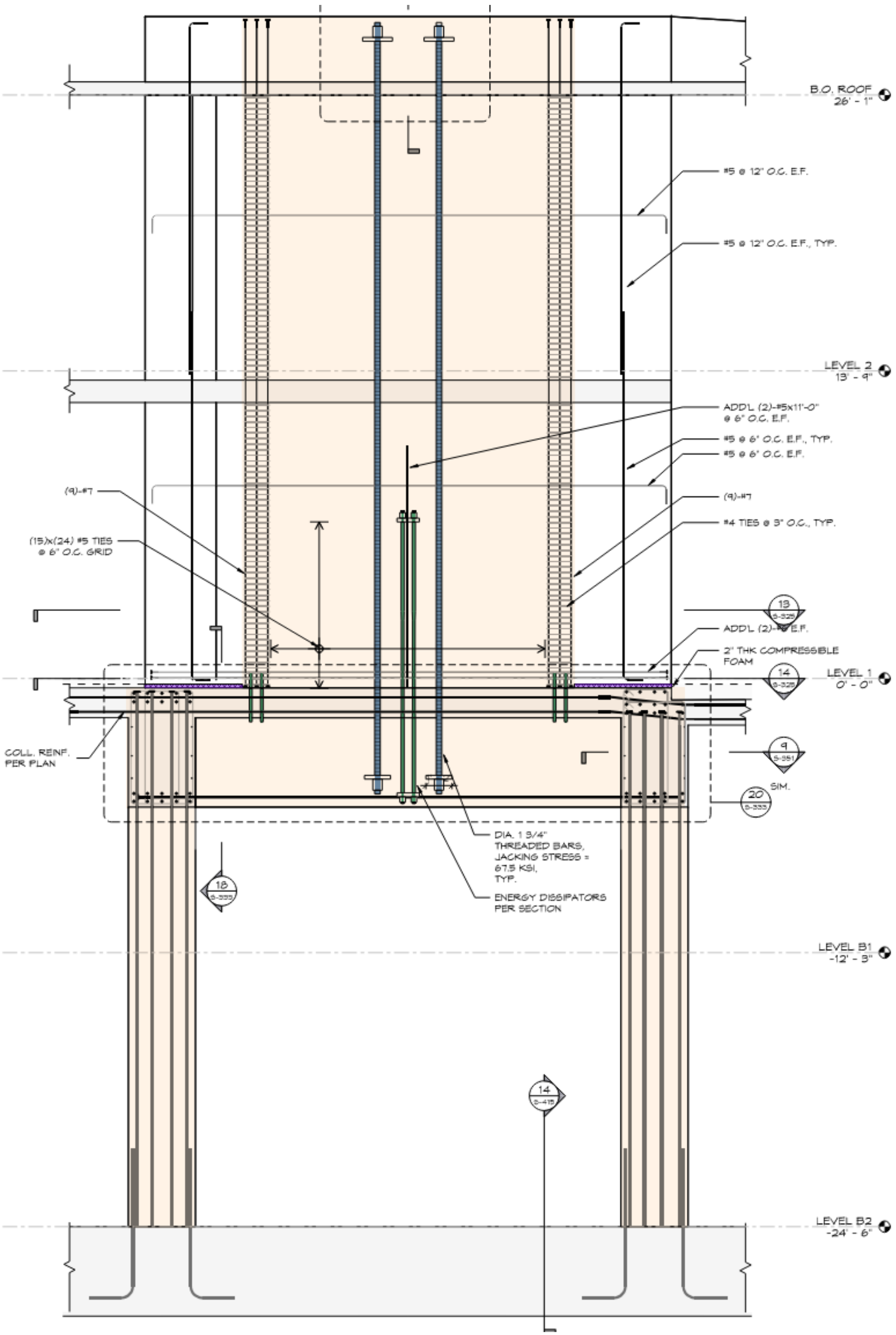


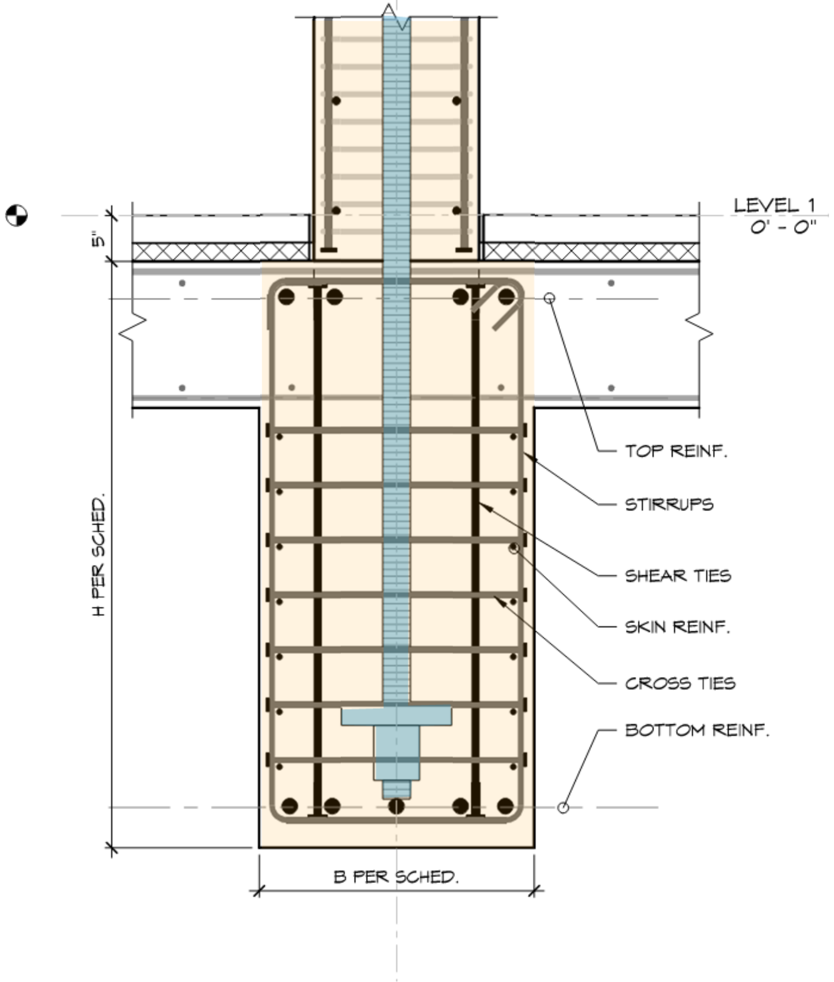
9 SHEAR WALL INTERFACE

1" = 1'-0"

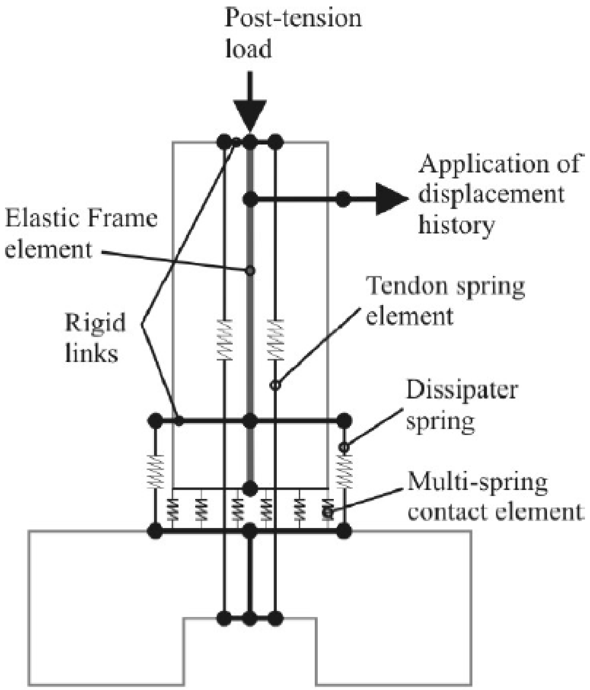


NOTE:
MATERIAL PROPERTIES:
-A572 Gr. 50
-YIELD STRENGTH: Fy = 60-65 ksi
-TENSILE STRENGTH: Fu = 80 ksi

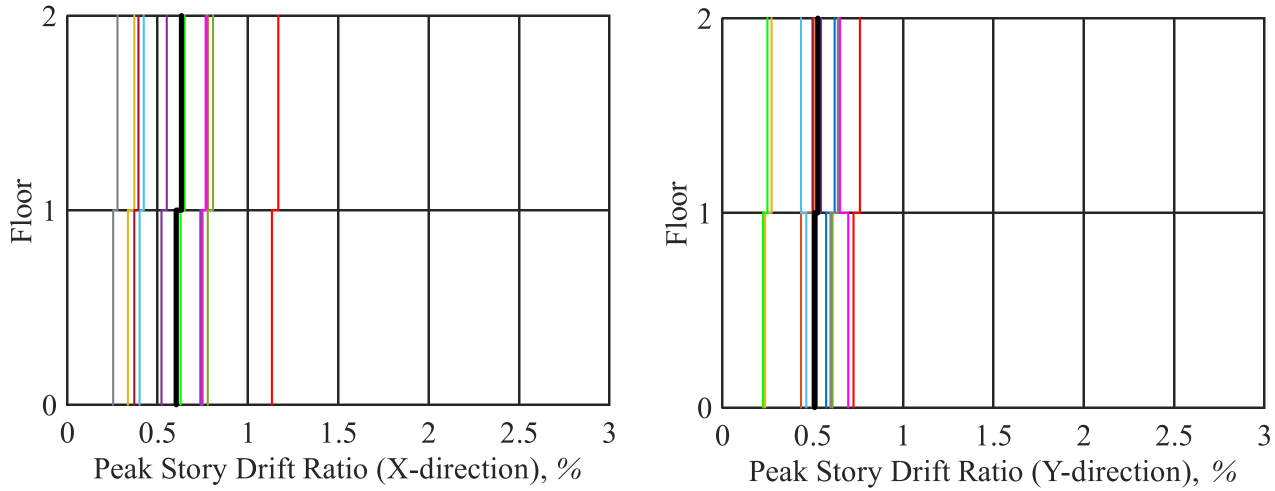

B.O. ROOF
26' - 1"
#5 @ 12" O.C. E.F.
#5 @ 12" O.C. E.F., TYP.
LEVEL 2
13' - 9"
ADD'L (2)-#5x11'-0"
@ 6" O.C. E.F.
#5 @ 6" O.C. E.F., TYP.
#5 @ 6" O.C. E.F.
(9)-#7
(9)-#7
(15)x(24) #5 TIES
@ 6" O.C. GRID
#4 TIES @ 3" O.C., TYP.
ADD'L (2)-#5 E.F.
2" THK COMPRESSIBLE
FOAM
LEVEL 1
0' - 0"
COLL. REINF.
PER PLAN
SIM.
DIA. 1 3/4"
THREADED BARS,
JACKING STRESS =
67.5 KSI,
TYP.
ENERGY DISSIPATORS
PER SECTION
LEVEL B1
-12' - 3"
LEVEL B2
-24' - 6"

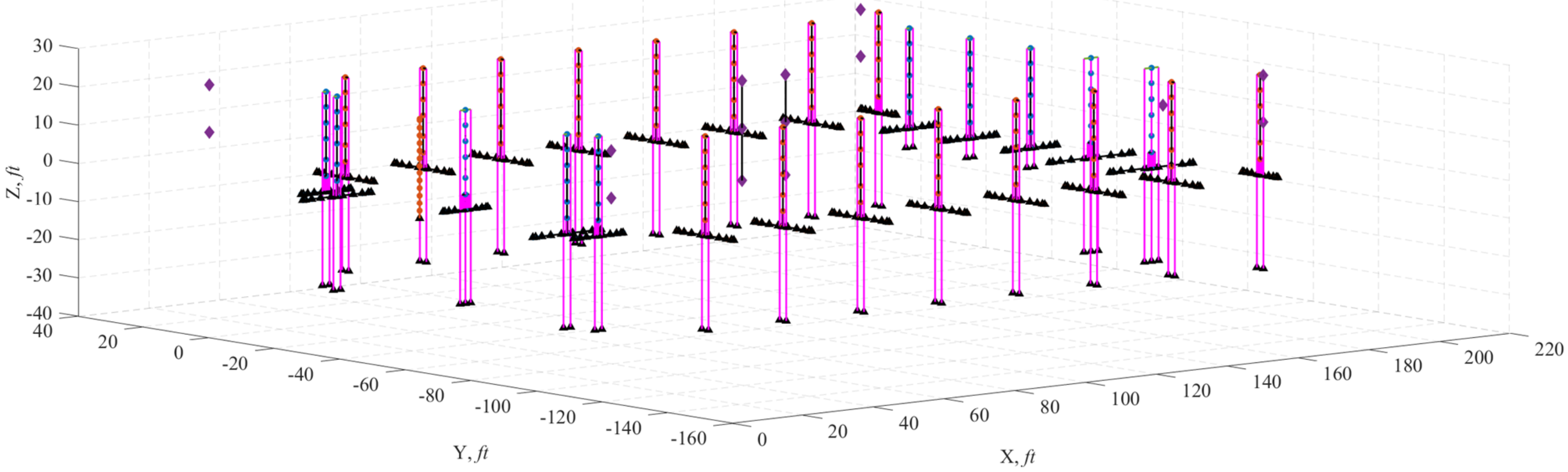

LEVEL 1
0' - 0"
5"
H PER SCHED.
TOP REINF.
STIRRUPS
SHEAR TIES
SKIN REINF.
CROSS TIES
BOTTOM REINF.
B PER SCHED.

NLRHA w. OpenSees

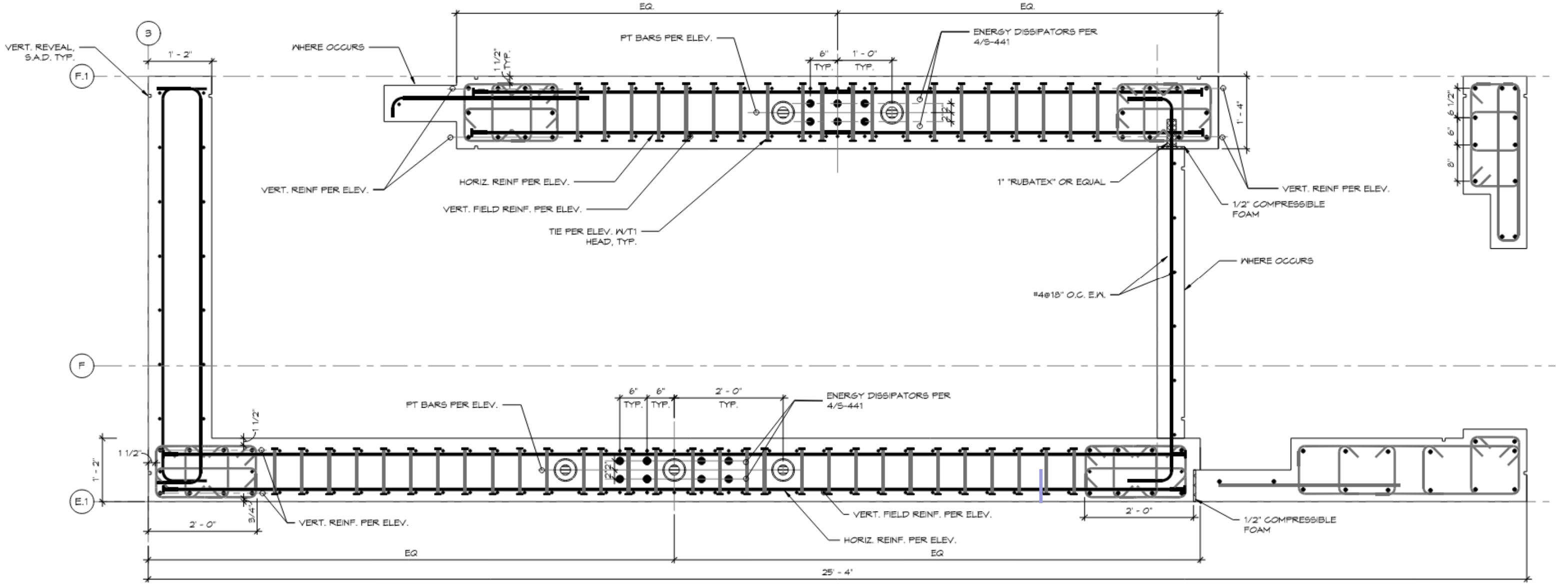


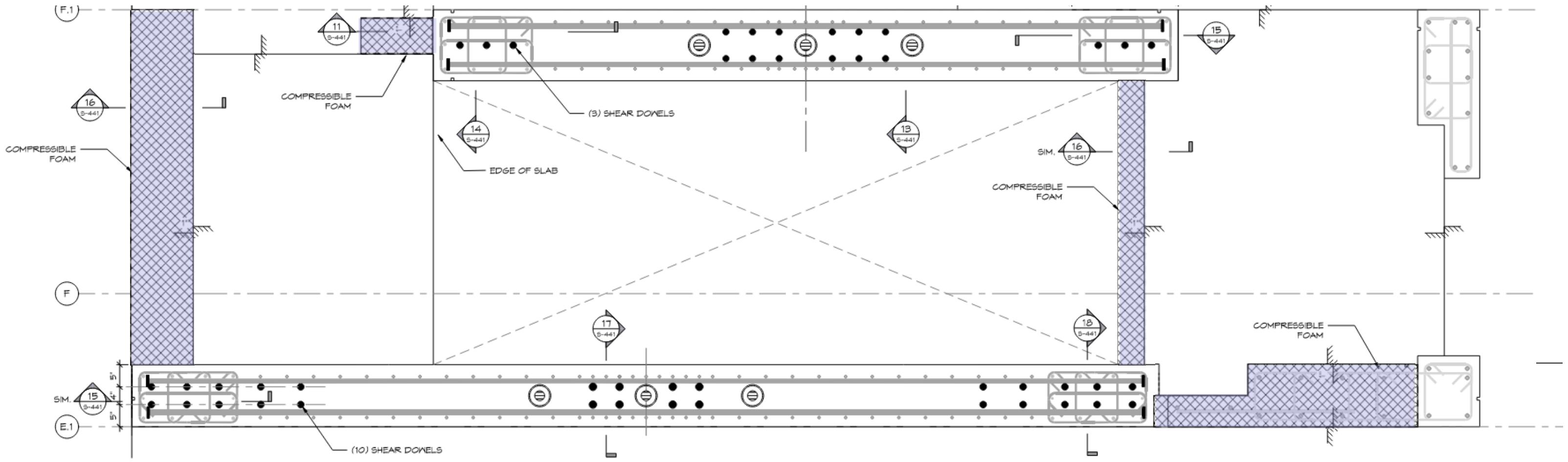
From: Marriott, D.J., 2009. The development of high-performance post-tensioned rocking systems for the seismic design of structures.

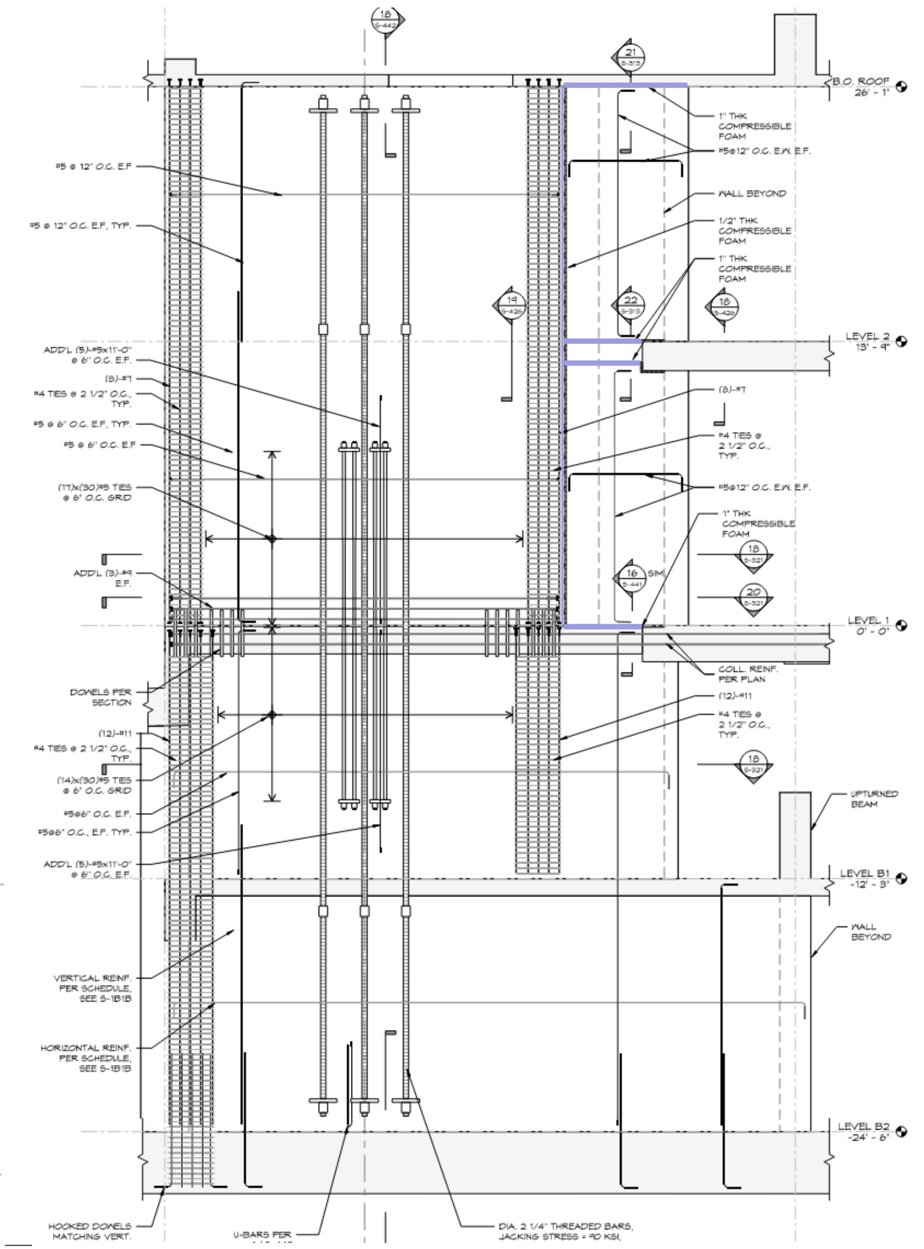




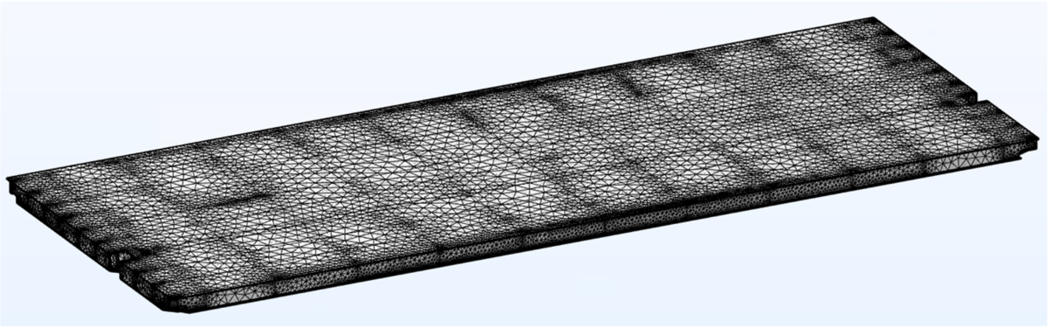
Structural Disengagement

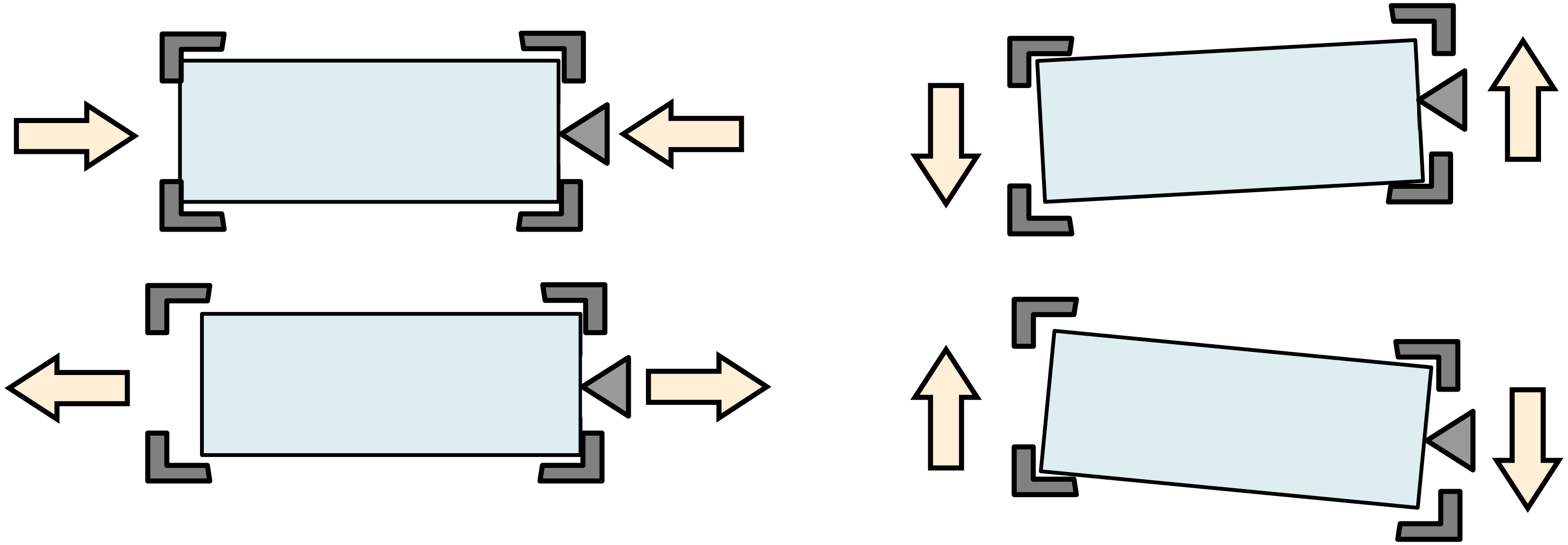




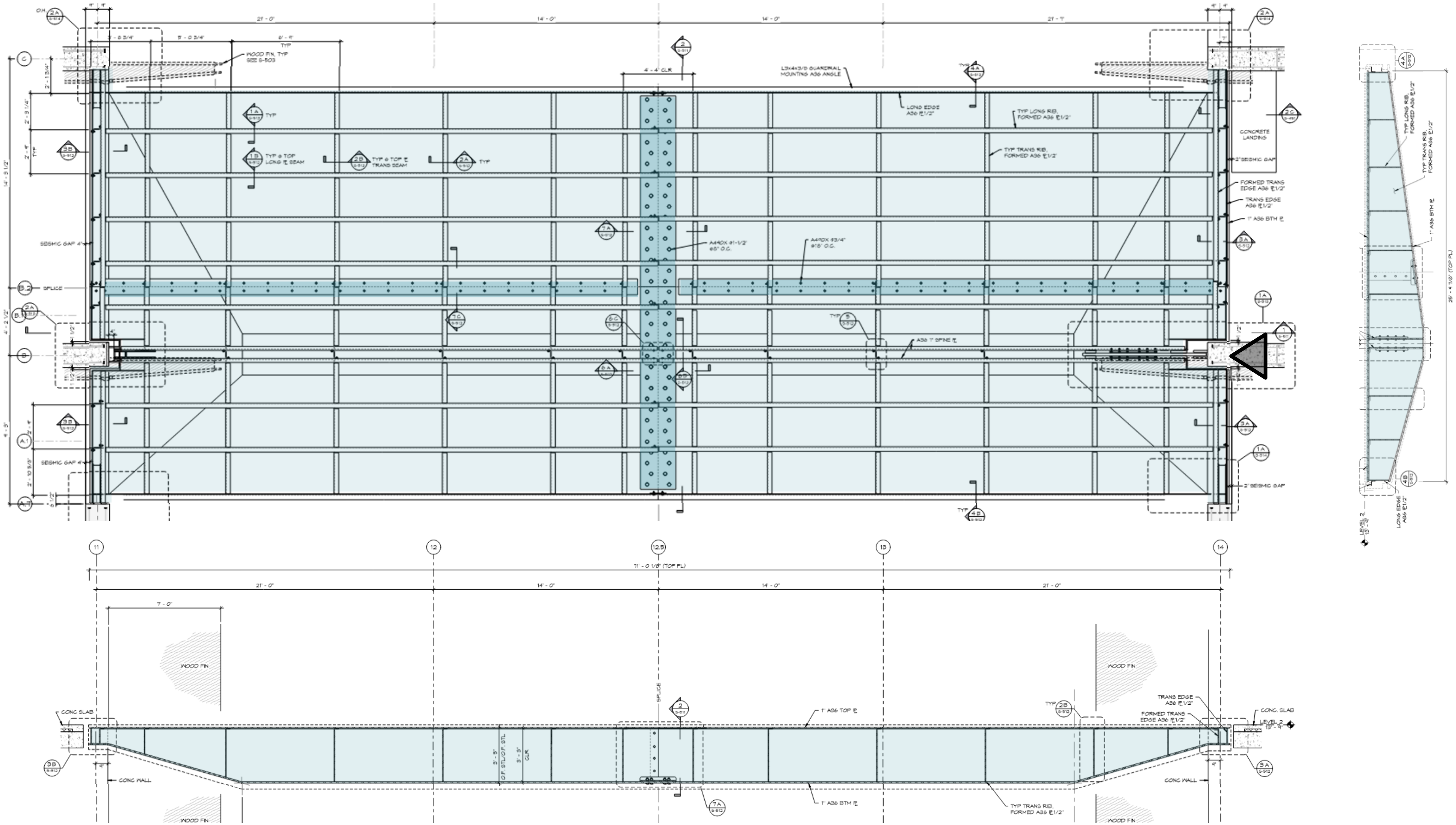


The Bridge



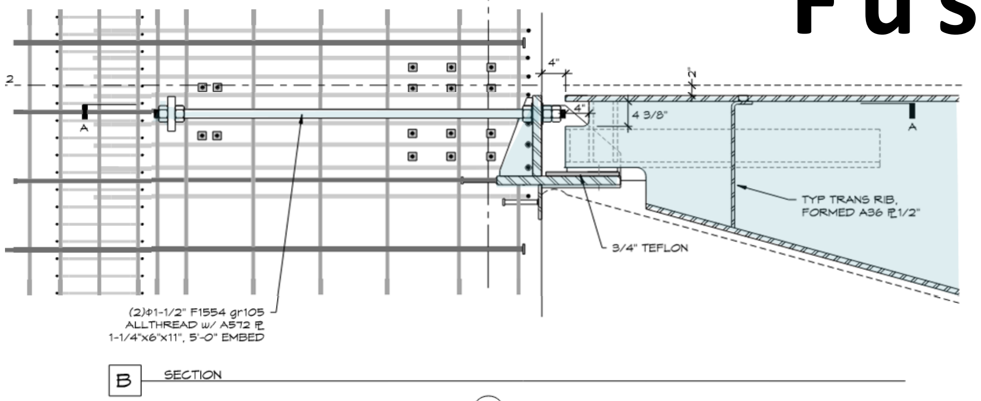


The Bridge

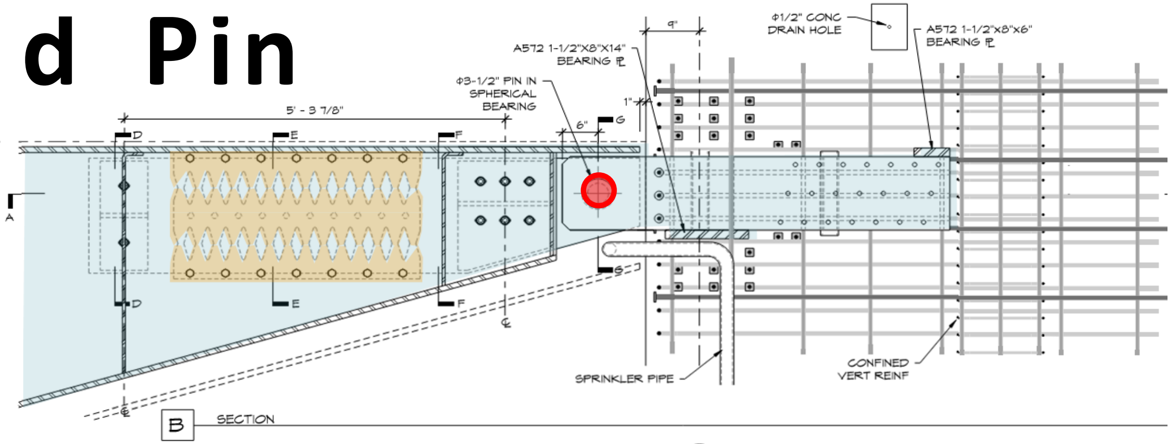


CONCRETE LANDING
SEISMIC GAP 4"
SPLICE
WOOD FIN
CONC SLAB
CONC WALL
1" A36 TOP PL
1" A36 BTM PL
TYP TRANS RIB, FORMED A36 PL1/2"

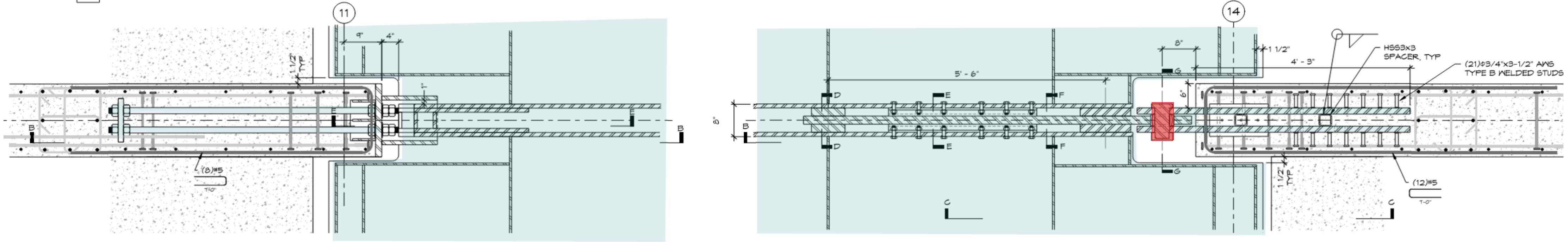
Fused Pin



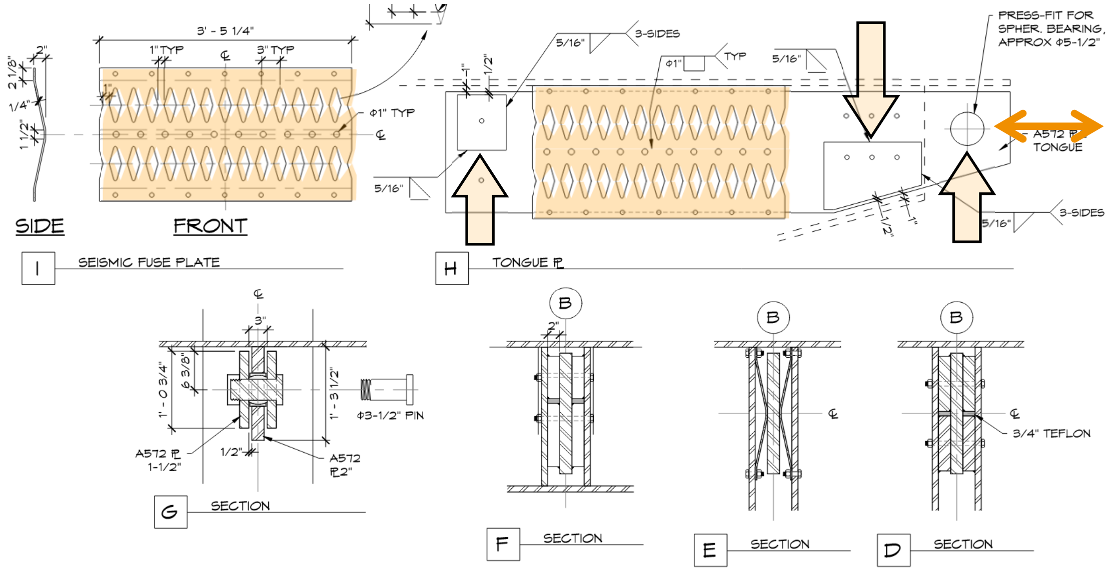
4"
4 3/8"
TYP TRANS RIB, FORMED A36 ℙ1/2"
3/4" TEFLON
(2)Φ1-1/2" F1554 gr105 ALLTHREAD w/ A572 ℙ 1-1/4"x6"x11", 5'-0" EMBED
B SECTION



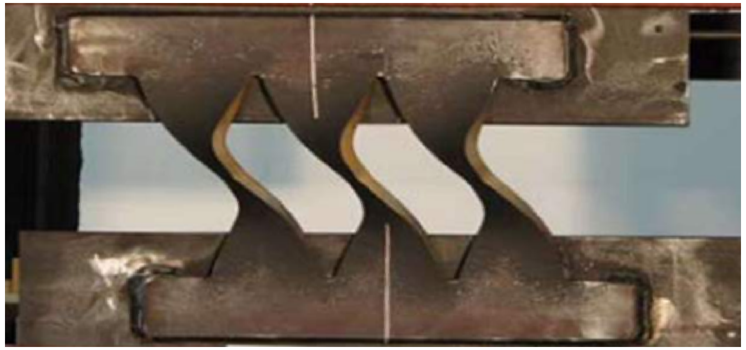
Φ1/2" CONC DRAIN HOLE
A572 1-1/2"x8"x6" BEARING ℙ
A572 1-1/2"X8"X14" BEARING ℙ
Φ3-1/2" PIN IN SPHERICAL BEARING
5' - 3 7/8"
9"
6"
SPRINKLER PIPE
CONFINED VERT REINF
B SECTION



11
9"
4"
(8)#5
5' - 6"
14
8"
4' - 3"
1 1/2"
HSS3x3 SPACER, TYP
(21)Φ3/4"x3-1/2" AWS TYPE B WELDED STUDS
(12)#5

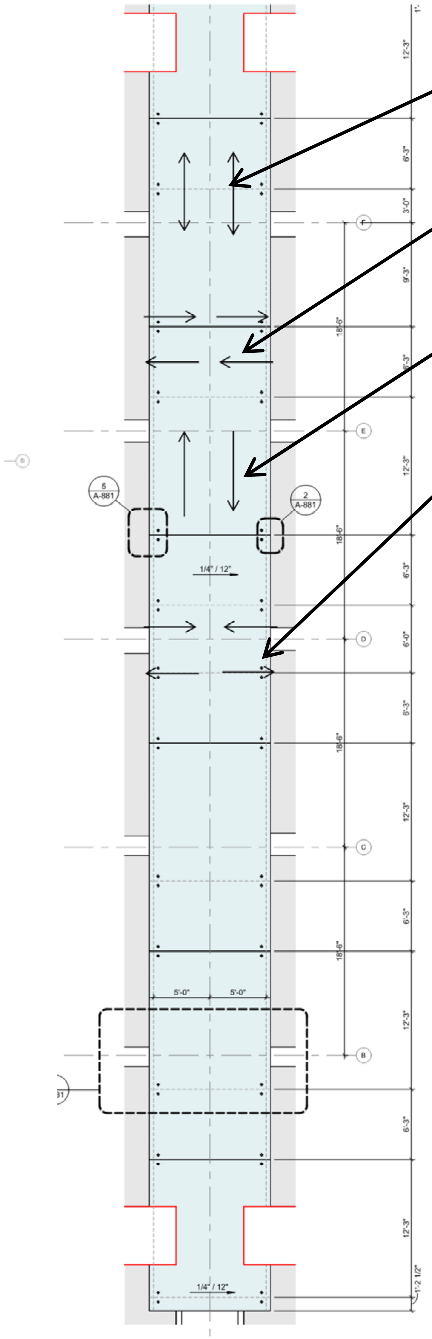


3' - 5 1/4"
1" TYP
3" TYP
Φ1" TYP
SIDE
FRONT
I SEISMIC FUSE PLATE
5/16"
3-SIDES
TYP
PRESS-FIT FOR SPHER. BEARING, APPROX Φ5-1/2"
A572 ℙ TONGUE
H TONGUE ℙ
Φ3-1/2" PIN
A572 ℙ 1-1/2"
A572 ℙ2"
G SECTION
F SECTION
E SECTION
3/4" TEFLON
D SECTION



Low-Damage Skylight

Lateral Displacements for Skylight & Operable Glass Window Wall:



Case 1:
E-W displacement, together

Case 2:
N-S displacement, together

Case 3:
E-W displacement, separating

Case 4:
N-S displacement, apart & together

Note:
Consider E-W and N-S cases concurrently.
I.e.,
-Cases 1+2
-Cases 1+4
-Cases 2+3
-Cases 3+4

Displacements (inches)				
Case	DBE Mean	DBE Max	MCE Mean	MCE Max
1	1.06	1.63	1.92	3.00
2	1.27	2.11	2.23	4.40
3*	1.51	2.31	2.72	4.25
4*	1.80	2.99	3.16	6.23

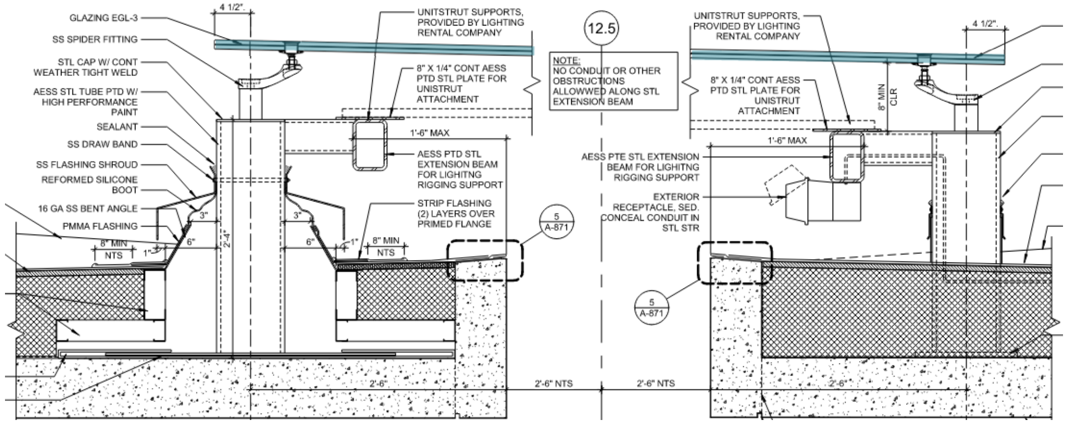
Recommended criteria:

*At **DBE Mean** displacements:*
-no structural damage to glazing systems
-no failure of seals or weathertightness

*At **MCE Mean** displacements*:
-no dislodging of glass
-no other life safety risks

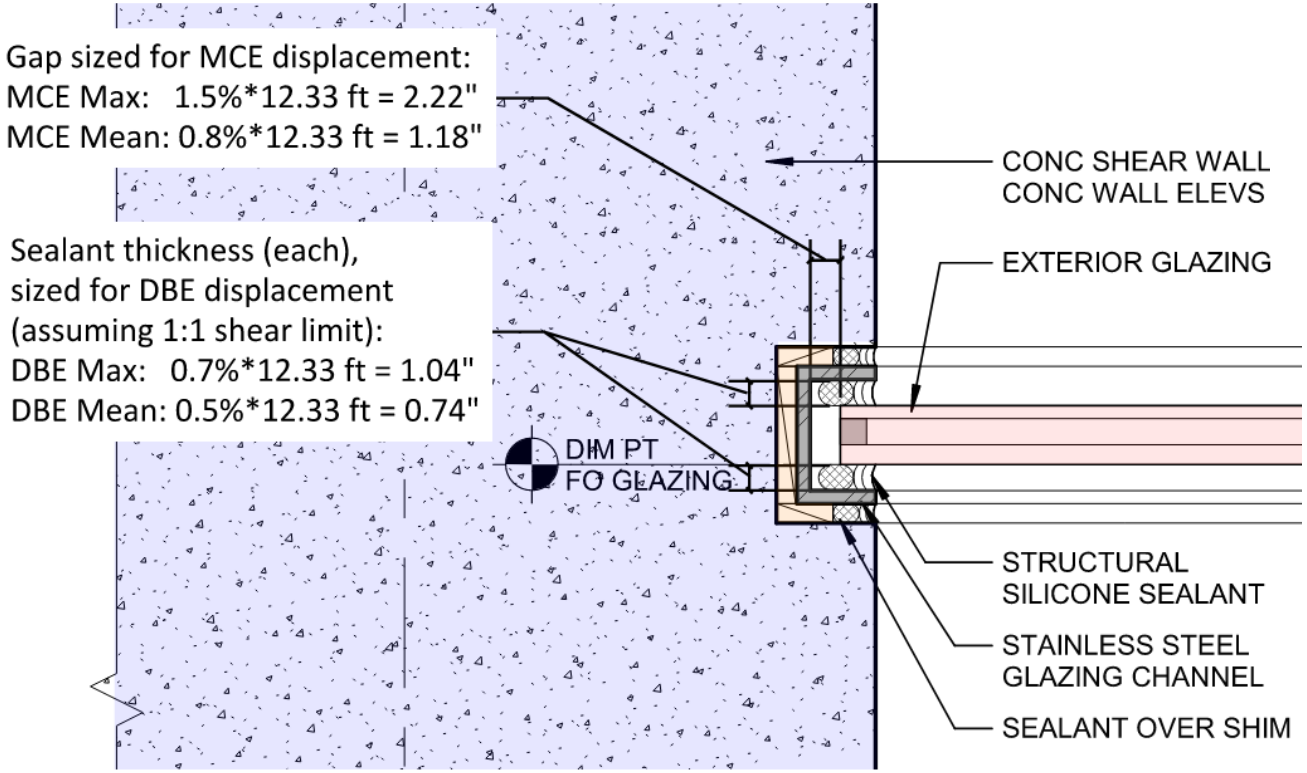
Notes:
*Case 3 & 4 displacements are derived from taking SRSS of the two buildings.

"DBE" = Design Basis Earthquake
"MCE" = Maximum Considered Earthquake

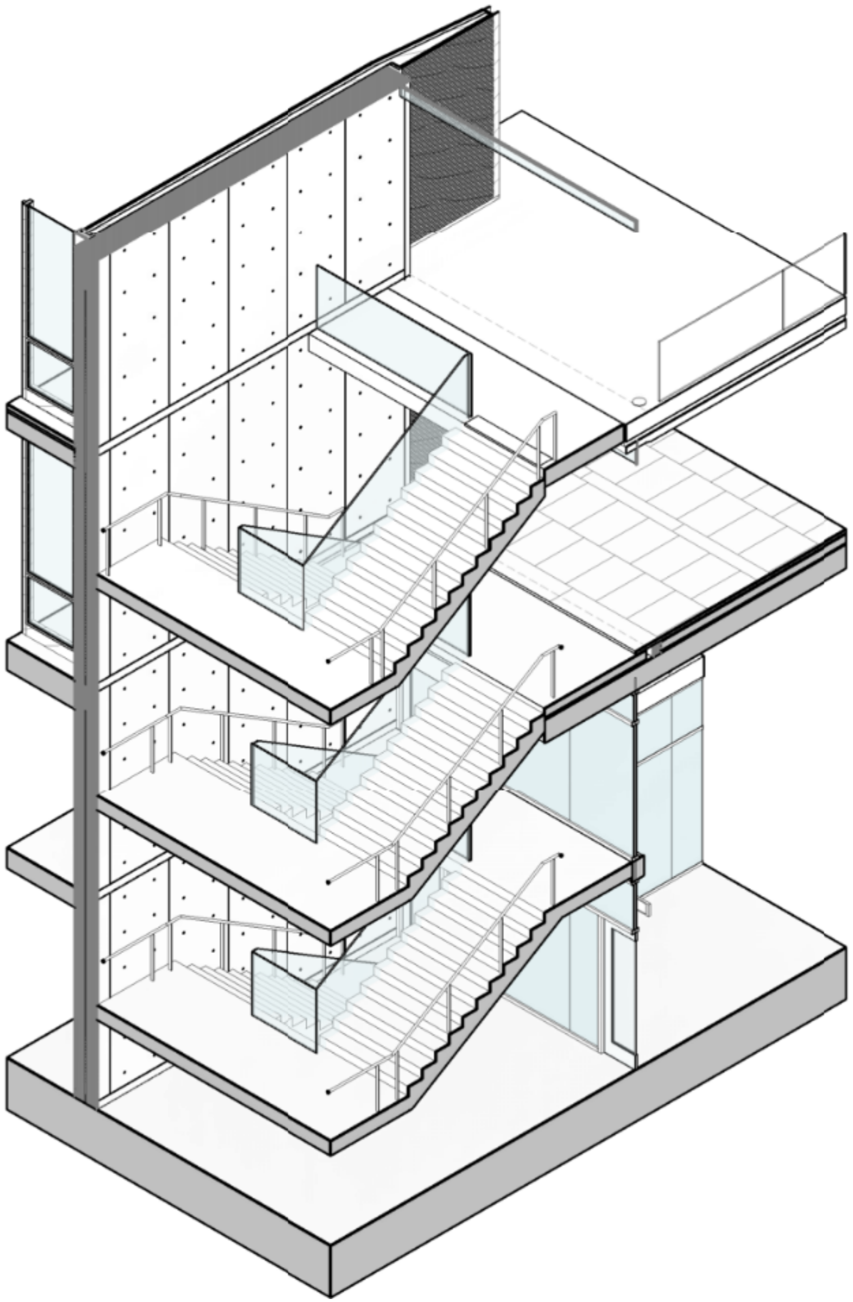


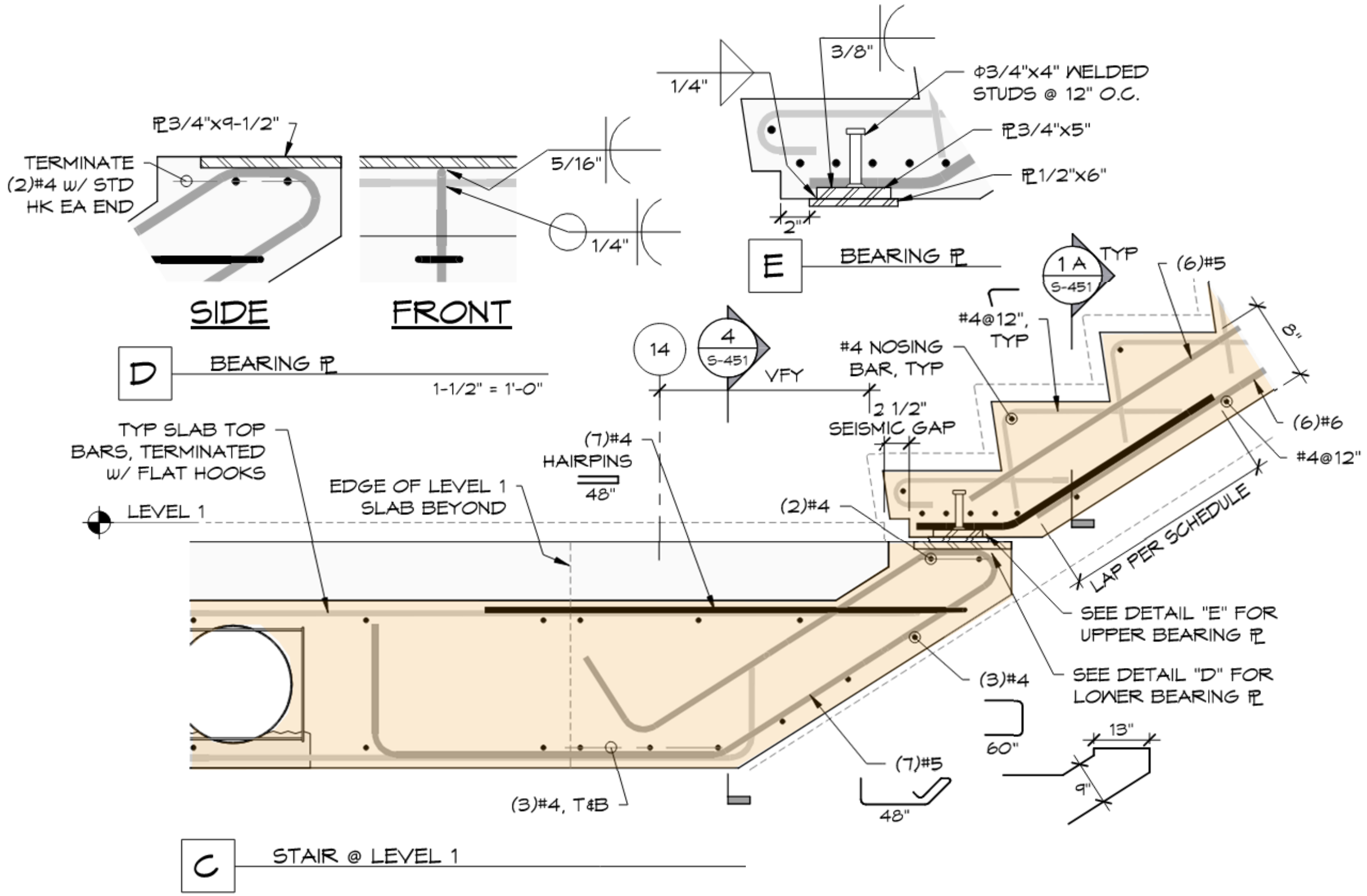
Free Side **Fixed Side**

Low-Damage Glazing



Low-Damage Stairs





Design in the Shared Space
Practice and Research

The Salk Institute