ACIES

Asociación Colombiana de Ingeniería Estructural

Presentación Técnica

"Innovation in the Seismic Design of Steel Structures"

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ACIES Seminar - Innovation in the Design and Evaluation of Steel Structures

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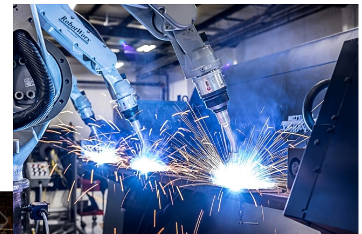
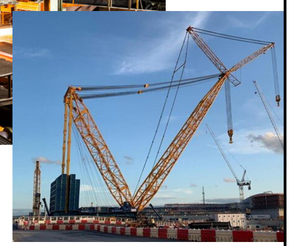
1. Introduction

- Steel structures go back over 140 years
- Much progress has been made, driven by various factors
  - Fastening Technology Improvements – Rivets, bolts, welds, robots
  - Material improvements – strength, ductility, consistency
  - Equipment advancements – cranes, computerized control of fabrication equipment





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Introduction (cont.)

- Increased knowledge of structural performance – analysis tools, testing/research, performance to extreme demands (Earthquake, e.g.)
- All these advances have allowed Engineers to continually innovate

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2. Where Steel Structure Innovation Can Occur

A. Architectural Design/Configuration
B. System Selection/Development
C. Use of High-Performance Products
D. Structural Analysis Techniques/Modeling
E. Connections

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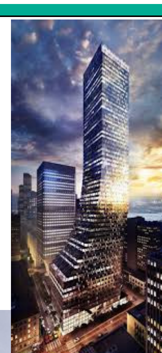
A. Architectural Design/Configuration

- Architectural forms grow ever more complex
- Structural challenges can be met due to advances in modeling, analysis and construction technology





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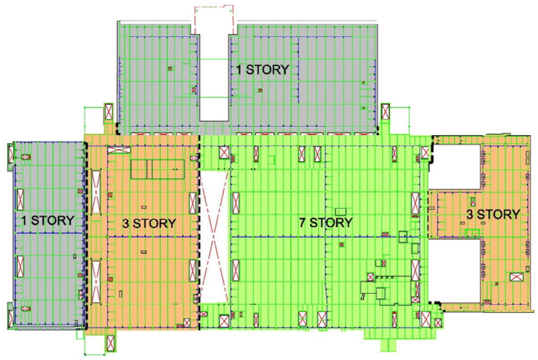
Use Seismic Joints to Create Multiple Regular Structures



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B. System Selection/Development

- U.S. codes define 82 structural systems of various materials
  - So, a LOT to choose from, but most major structures come for only a handful of the 82
- New systems are based on a combination of research, validation and economic factors
  - Innovative ideas usually spur initiation of process

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Steel Plate Shear Walls (SPSW) – 2010

- Concept developed in Canada
  - NBCC Code provisions developed
- SPSW like plate girder design approach (tension field theory)
  - Thin plate welded between steel frame beams and columns
  - Can generate tremendous strength and stiffness as compared to braced frames
  - UC Berkeley and U of Buffalo research as well

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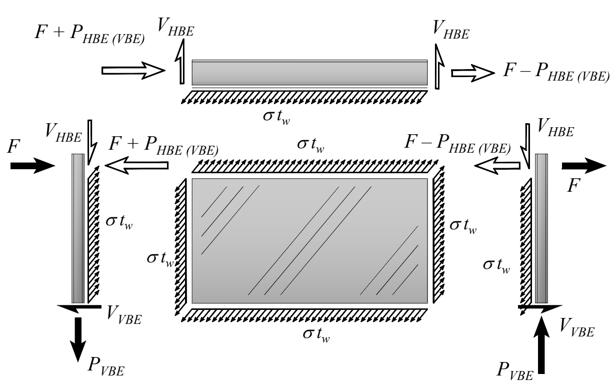
Design of Steel Plate Shear Walls



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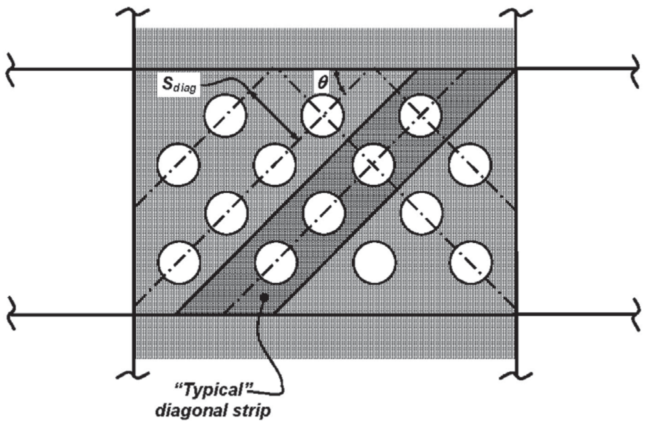
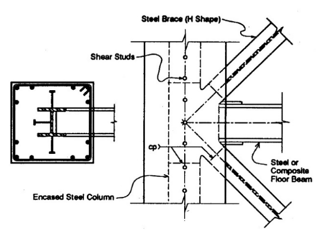
Perforated Shear Walls to Fine Tune Design

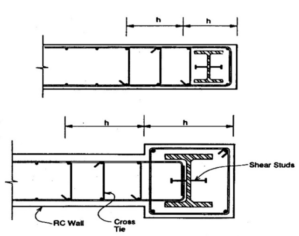


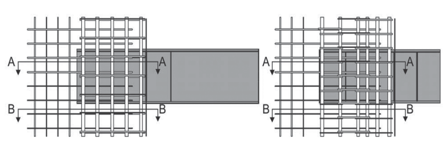
Source: AISC Seismic Commentary

Composite Systems – "Best of Both Worlds"

- Steel and Reinforced Concrete Composite Construction
  - Utilizes Concrete for Compression and Strength and Steel For Tension and Shear Strength and Ductility
  - Identifies Numerous System Options, for both frames and walls (12 total)
  - Detailed Requirements for Member and Connection Design between Steel and R/C Elements

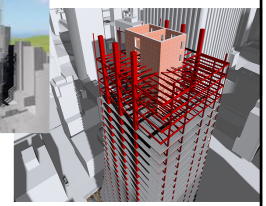






Composite Sandwich Wall – "Speedcore"

- Originally developed for modular nuclear reactor designs
- Found to simplify high-rise office or mixed-use buildings as all steel system
  - Eliminates conflicts between steel frame and concrete core
  - Allows for more efficient erection
  - Saved almost one year of construction on Rainier Square Tower!

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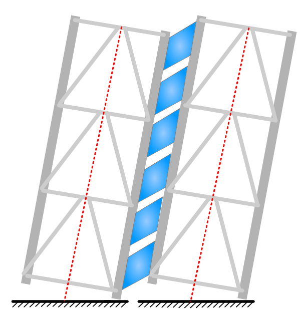
What About the Future? Where Do We Go From Here?

- What will 2040 look like???
  - Continued innovation and emphasis on "high performing systems"
    - Self-Centering
    - Rocking
    - Partially Restrained Connections



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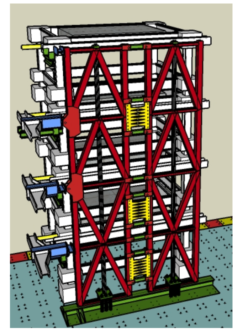
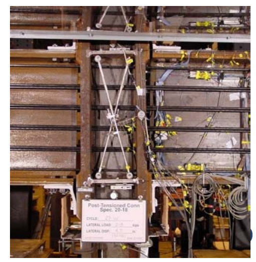
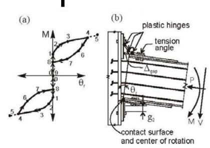
Self-Centering Systems

- Multiple research efforts
  - Lehigh and Stanford/U of Illinois, e.g.
  - Both moment frames and braced frames
- Many existing systems have some limited capacity to self-center, but it is not considered in design
  - Gravity frames with column continuity (AISC splice requirement)
  - But, may not always be present
- Should residual displacements start to enter our criteria for higher performing systems?

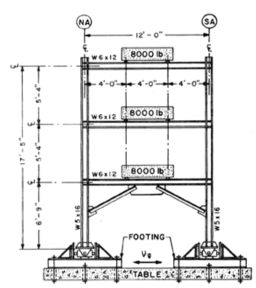






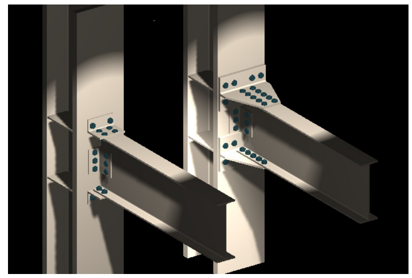
Rocking Systems

- Rocking systems
  - Early research (1970's) showed inherent stability due to gravity loads (tombstones, e.g.)
  - Need to be able to validate with local seismic hazard, such as near field, including uplift model
  - Impact effects seem to be minor
  - Can this be controlled? Demands on adjacent gravity systems could become very large



Partially Restrained Moment Frames

- All bolted, avoiding field welds (less inspection)
- Can get ductile mechanism, but have to work at it
- LOTS of failure modes to consider, so calcs are intensive
- Potential fit-up issues
- Limits in size, so likely need to use all columns in high seismic zones
- Some Proprietary Systems



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C. Use of High-Performance Products

- Present Building Codes Focus Primarily on Life Safety
- Limited Emphasis on Functionality or Repairability After Major EQ
  - Except Critical Post-EQ Facilities Such as Hospitals
- Some Owners Need Post-EQ Functionality or Limited Damage
  - Data Centers, Critical Manufacturing, etc.
  - Museums
- Recent Push for Post-EQ Resiliency
  - Concern Over Economic Recovery
  - Avoid post-Katrina New Orleans

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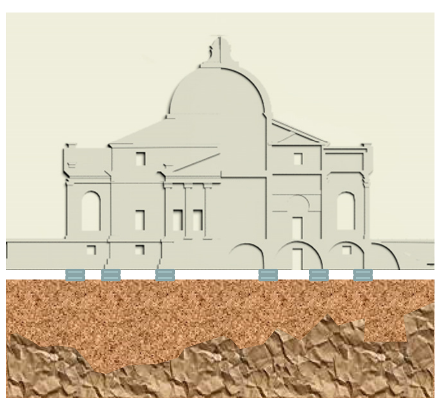
Response Modification Devices

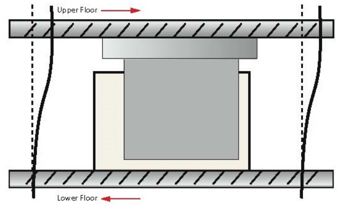
- Devices that provide seismic isolation and energy dissipation can significantly reduce the seismic demands on structures, reducing damage and need for repairs
- Design of seismic isolation and energy dissipation devices (dampers) are based on data from laboratory tests representing conditions anticipated during maximum EQ shaking
- Often implemented for structures intended for better than Life Safety performance

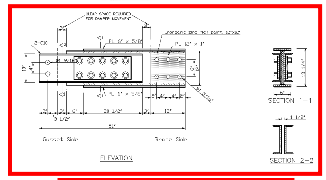
Seismic Isolation

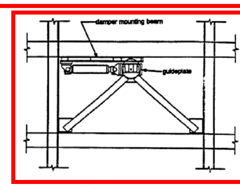


Viscous Damping

- Demonstrated high performance
- Reduced accelerations can protect valuable contents, but not as much as base isolation
- Protects structural elements from damage
- Increases construction costs by a few percent overall
- Starting to see much more widespread use, especially with moment frames







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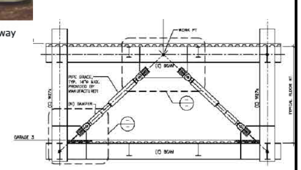
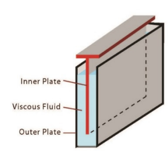
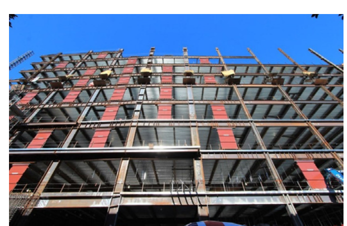
More on Dampers

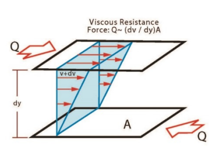
- Damping can reduce damage to the structure
- Can significantly reduce building drifts and steel tonnage in moment frames (up to 25% of seismic frame

Seismic fluid viscous dampers for large highway bridge, 1.5 million pounds output force.









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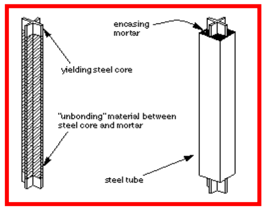
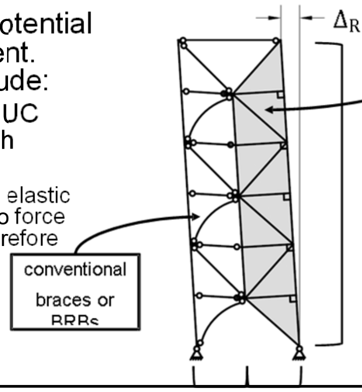
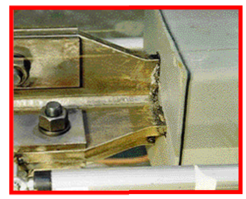
Buckling Restrained Braces

- Concept Originally Developed in Japan
  - Better hysteretic behavior than typical braces – LOTS of energy dissipation capacity!
- Widely used system for major steel buildings including hospitals
- Some concern about potential for residual displacement. Ways to avoid this include:
  - Strongback system – UC Berkeley research with applications
    - Combines stiff/strong elastic element with BRB's to force uniform drifts and therefore avoids weak stories







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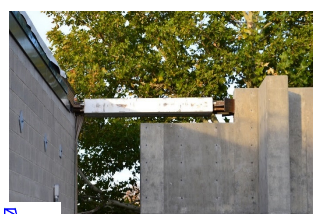
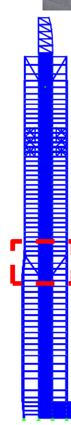
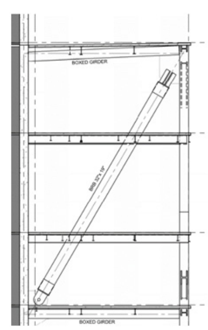
Other Uses of BRB or Dampers

- BRB's or Dampers can be for more than just as diagonal elements in vertical frames
- Across building joints or isolation planes to limit displacements and dissipate energy
- Outriggers to limit loads to columns in tall buildings







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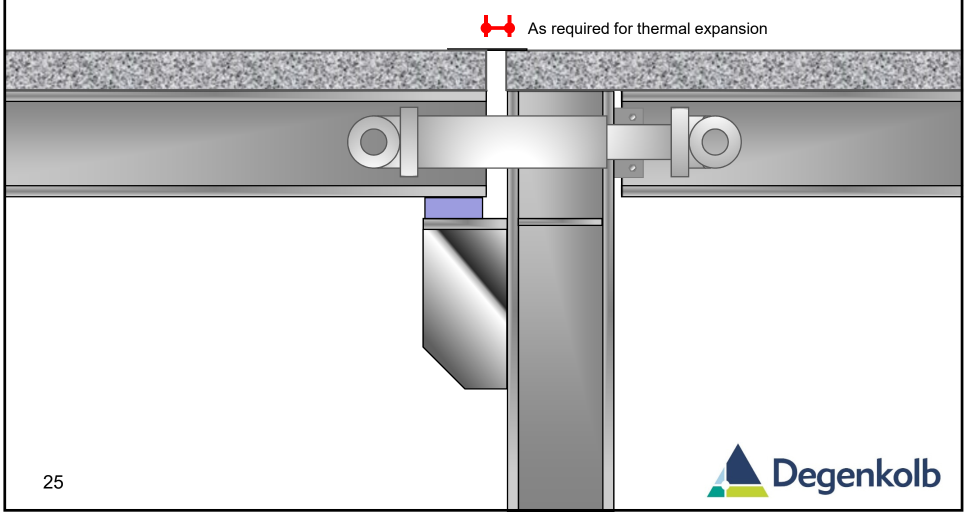
Dampers Across Thermal or Seismic Isolation Joints



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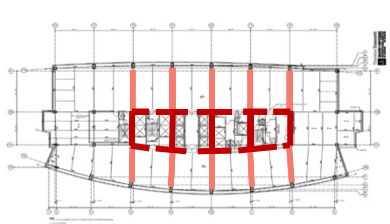
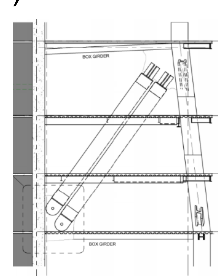
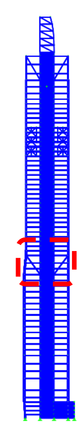
Use of Outriggers – W-Grand, e.g.

- Triples effective width from of lateral system
- 2.5 factor on transverse stiffness (1^{st} mode period reduced from 11 sec to 7 sec)
- Buckling Restrained Braces (BRB's) limit demand on Outrigger Columns







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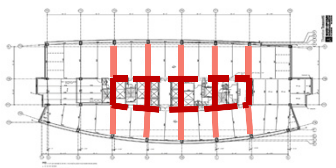
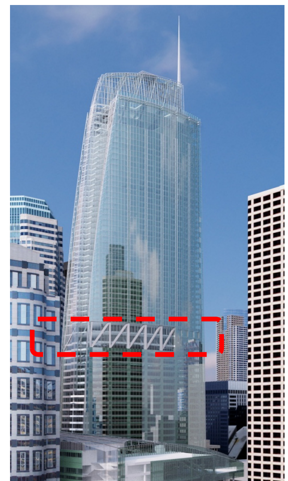
Use of Belt Trusses to Engage More Dead Load

- Engage all perimeter columns
  - Spreads load to more of structure
  - Column shortening strains
  - Column overturning strains
  - Reduces potential for net tension on large columns, saving on foundation costs
- Expressed by glazing
  - Architectural feature





Image– Wilshire Grand Design Team

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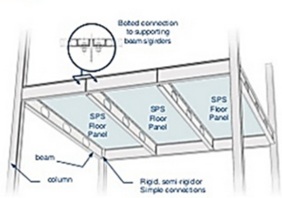
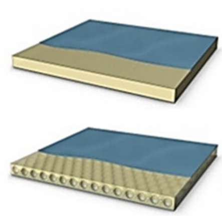
SPS Floor Systems to Reduce Mass

- Composite material comprising two metal plates bonded with a polyurethane elastomer core (developed in Canada)
  - Replaces Metal Decking and Concrete Fill and some floor framing
  - SPS delivers a **lightweight** floor system with **high strength and stiffness**.
  - Used on first commercial project in 1999. **Over 180 projects have been completed in ships, bridges, buildings, and stadiums.**



SPS Floors



Core Configuration

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What about Multi-Component Braces?

- Combine BRB's or BRB's with Dampers
- In series or parallel, or both
  - Multi-Core BRB's for added capacity up to 5000 kips
  - 181 Fremont Mega-Braces had BRB's, elastic element and damper in series
  - Dual Core BRB's of different capacity in parallel for multi-level stiffness and yielding

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D. Structural Analysis Techniques/Modeling

- Many Advances in Techniques for Structural Analysis, Design and Modeling Have Facilitated Innovation, Many Driven by Computer Speed Increases
  - Capacity Design
  - Nonlinear Analysis
  - Response History Analysis
  - Ground Motion Simulations
  - Building Information Modeling (BIM)

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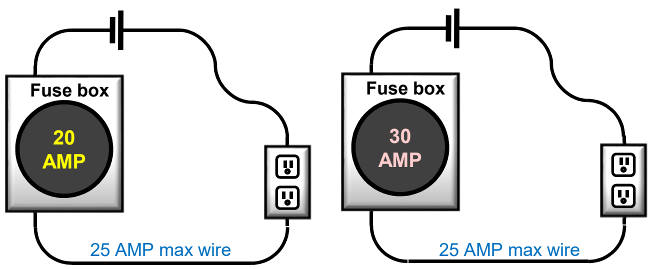
Capacity design (system): Fuse concept

Which is the better system?



System quality is not only due to strength;
Proportioning is key to good behavior

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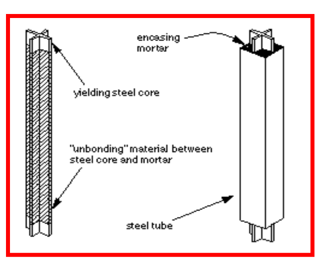
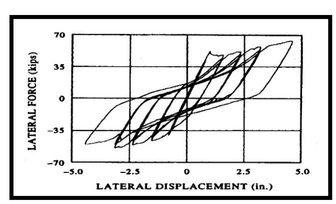
Think About Your Seismic System as Having Fuses

- A Reduced Design Seismic Force Can Be Used IF Sufficient Ductility Is Built into the Structure
- Certain Elements Are Strategically Designated to Serve as Structural Fuses, i.e., Deformation-Controlled Elements





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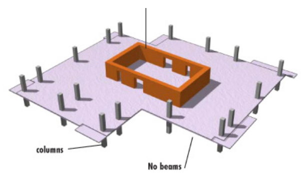
Expanded Use of Nonlinear Analysis

- Becoming Common for PBEE in Tall Buildings and Major Seismic Retrofits
- Advantages Primarily for More Accurate Estimation of Column Demands
  - ➢ Capacity design overly conservative due to higher mode effects
- Typically Used in Conjunction with Peer Review
- Concentrated plasticity model for beams and columns and fiber elements for walls are most common
- All other elements and components that in combination significantly contribute to or affect the total or local stiffness of the building should be included in the mathematical model.



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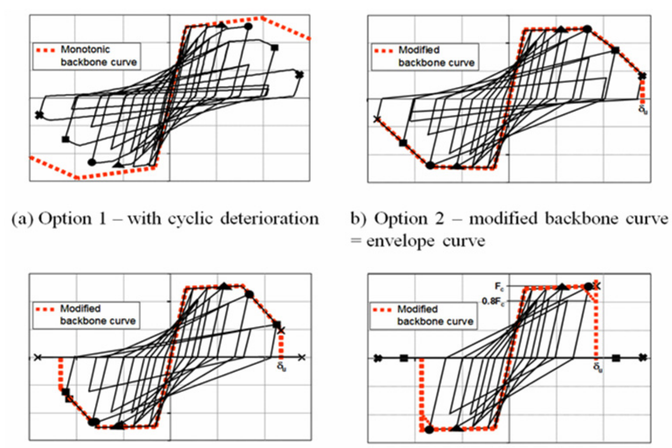
Nonlinear Modeling Options



(a) Option 1 – with cyclic deterioration

b) Option 2 – modified backbone curve = envelope curve

(c) Option 3 - modified backbone curve = factored monotonic backbone curve

(d) Option 4 – no strength deterioration

Figure courtesy of Prof. Helmut Krawinkler

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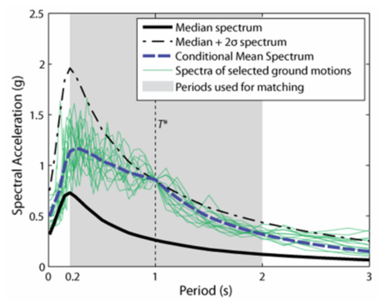
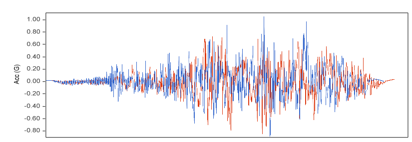
Response History Analyses/ Ground Motion Simulation

- Typically use recorded motions to match demand spectrum
- Can simulate motions for events for which motions are not available (M9 PNW Events, e.g)
- Still ***great*** uncertainty as to character of future events
  - Need to do many simulations to capture range of behavior





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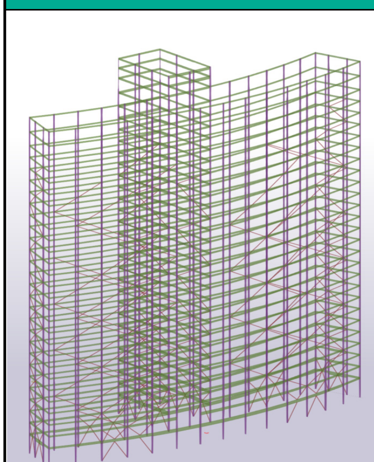
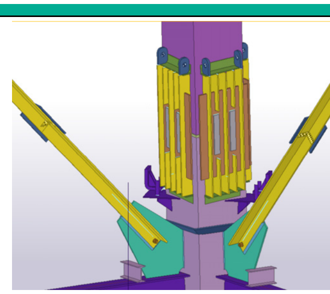
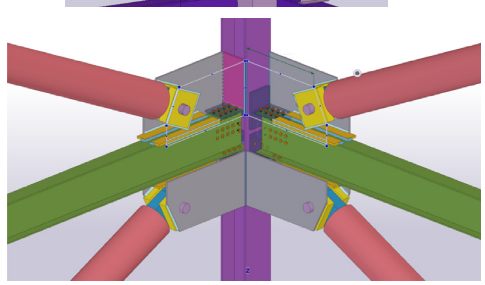
BIM Modeling for Design and Construction







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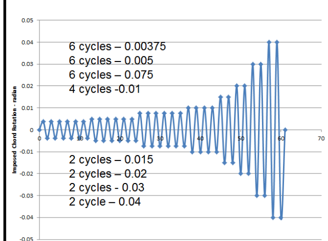
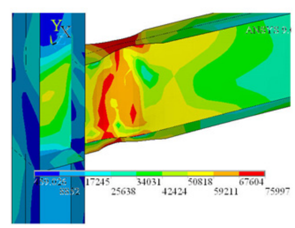
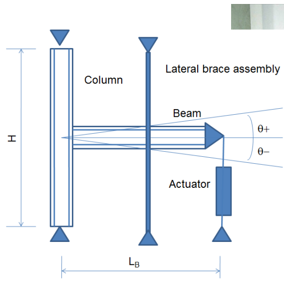
E. Connections

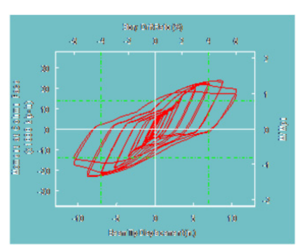
- Connections are Vital to Performance of Steel Structures, Especially for Seismic Performance
  - Generally want connections to be stronger than members, since often hard to provide ductility in connections
  - Industry has pushed toward “pre-qualifying” some connections based on testing/research
  - Also, for unique connections casting techniques can be incorporated. Will printed connections be in the future?
  - Improved understanding can reduce cost
    - PJP Column Splices

AISC 358 Conformance Demonstration

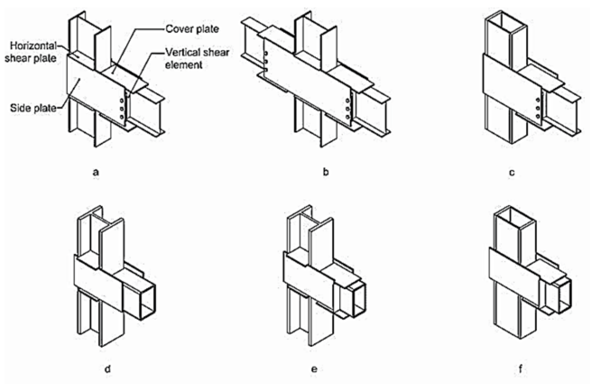








Prequalified Connections in AISC 358



SidePlate uniaxial configurations

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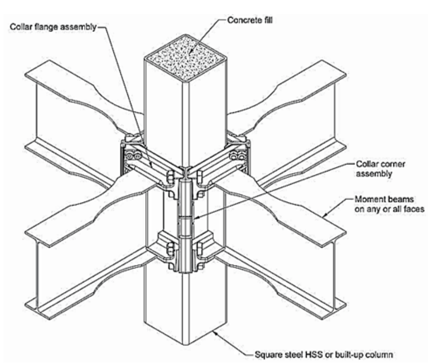
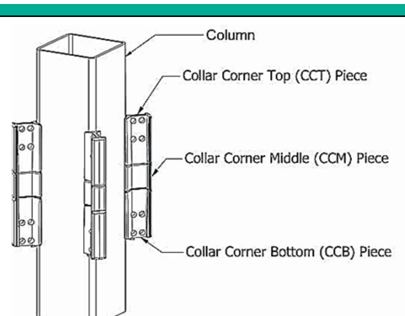
Prequalified connections in AISC 358



Con X Tech



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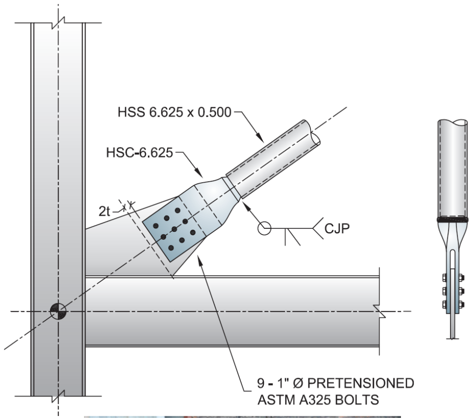
Cast Steel Connections



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3D Printing of Steel Connections is Coming!

- The technical term is "Additive Manufacturing"
- Combines robotic welding, high levels of understanding of weld metal properties, heat flow, BIM, AI, etc.
- Speed is challenge, for large elements, but robots don't get tired!
- Machining is also req'd

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What about Ductile and/or Replaceable Connections?

- Behave similar to BRB’s
- All bolted solutions are desirable
- Many ideas for yielding plate configurations that can be replaced after major EQ
- Friction also

Figure 12 – T-ADAS damper

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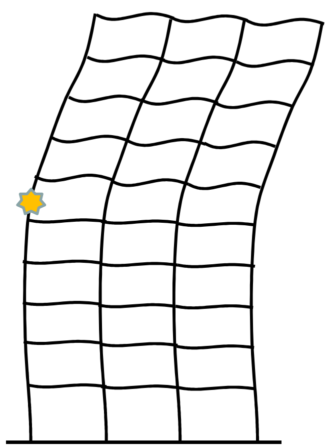
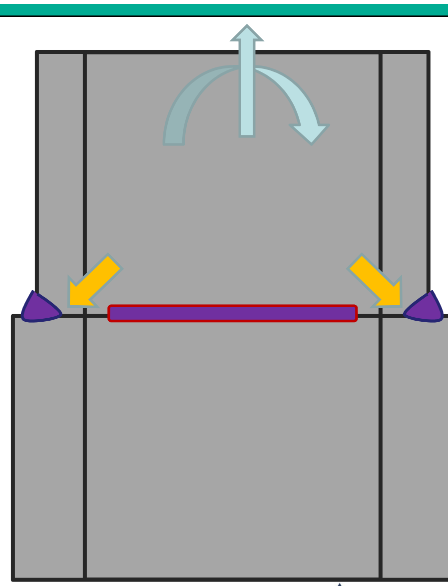
Partial Joint Penetration Welds Are a Concern





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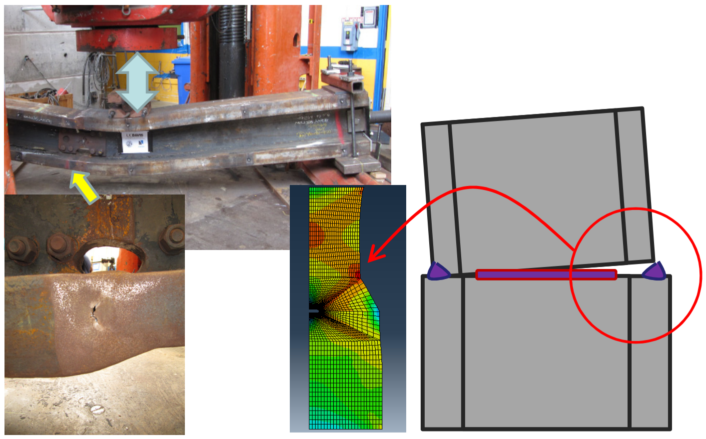
New “Heavy” PJP Splice Detail



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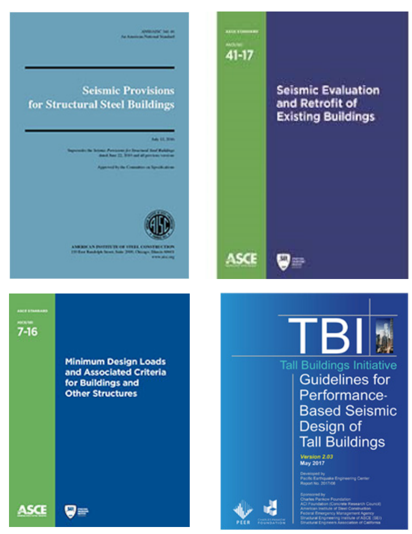
3. Codes/Standards/Guidelines

- Vast Majority of Buildings Designed to Meet Prescriptive Provisions of the Code
  - Can Stifle Innovation due to Their Prescriptive Nature
  - But Codes DO Allow Engineers Alternative Methods to Demonstrate Equivalent Performance!



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The Code Mechanism for Innovation

- Alternative Methods Clause in the Codes
  - Section 104.11 of 2012 IBC:
    - "The provisions of this code are not intended to prevent the installation of any material or to prohibit any design or method of construction not specifically prescribed by this code, provided that any such alternative has been approved. An alternative material, design or method of construction shall be approved where the building official finds that the proposed design is satisfactory and complies with the intent of the provisions of this code, and that the material, method or work offered is, for the purpose intended, at least the equivalent of that prescribed in this code in quality, strength, effectiveness, fire resistance, durability and safety."
  - But, little guidance is provided as to how to do this…

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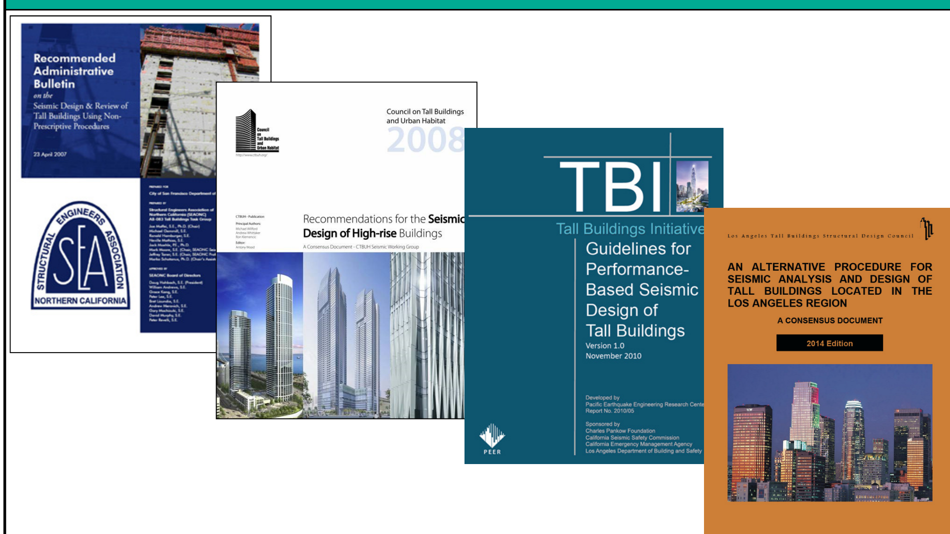
That is where guidelines come in!



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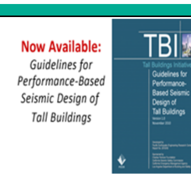
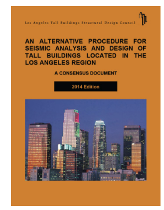
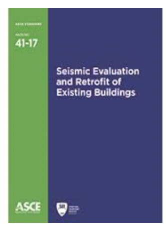
Performance Based EQ Engineering is Here





- Provisions for Performance Based Earthquake Engineering (PBEE)
  - LATBSDC Provisions ('18), City of SF, and PEER TBI Guidelines ('17) focus on Tall Buildings
    - Primarily Used for Code Performance Demonstration
    - Two level (Service and Collapse Prevention) design checks required
    - NLRHA used for Collapse Prevention
    - Peer Review required
  - ASCE 41 can now be used for (N) Building designs
  - FEMA P58 project provides comprehensive approach to PBEE; but use with caution!



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4. Example of Innovative Projects

- The following projects demonstrate some very innovative projects, designed by SE's from San Francisco, Los Angeles and Seattle
- Often focuses on large, tall and/complex buildings (usually all three!)
- Peer Review always performed and important of the process
  - Most of these projects aimed at code equivalent performance but some went for higher levels
  - It was VERY interesting to lead the Peer Review Team on all these projects!

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De Young Museum – San Francisco, CA

- Based Isolated Structure with BRB's above isolation plane
- Extremely complex floor diaphragms for exhibit spaces
- Twisting, leaning Admin/Observation tower with vertical P/T in shear walls
- Huge cantilever over outdoor dining area

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LA Live! – Los Angeles, CA

- At 54 stories, the tallest SPSW in the world
- Composite built-up box columns with up to 4" thick plates as VBE's
- L-shaped for 27 stories created interesting transition challenges
- Podium level diaphragm became almost solid reinforcing steel

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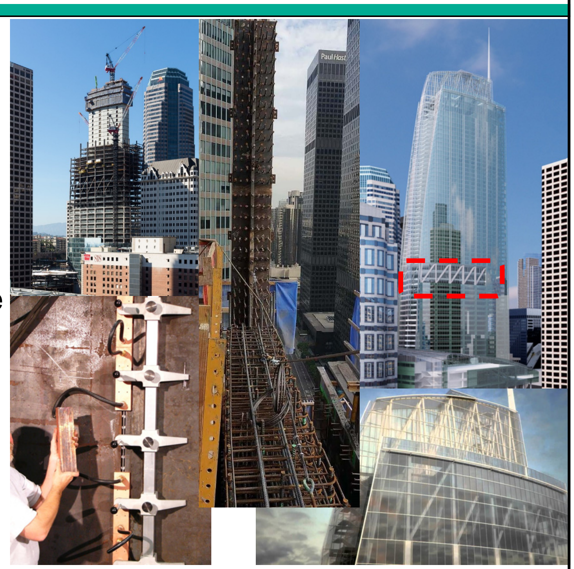
Wilshire Grand – Los Angeles, CA

- Tallest building west of Chicago
- Concrete core with steel gravity framing and composite columns
- Three levels of BRBF outriggers for transverse direction (all unique)
- Belt trusses to balance loading
- First use of field SAW
- Largest R/C pour ever for 21’ thick mat



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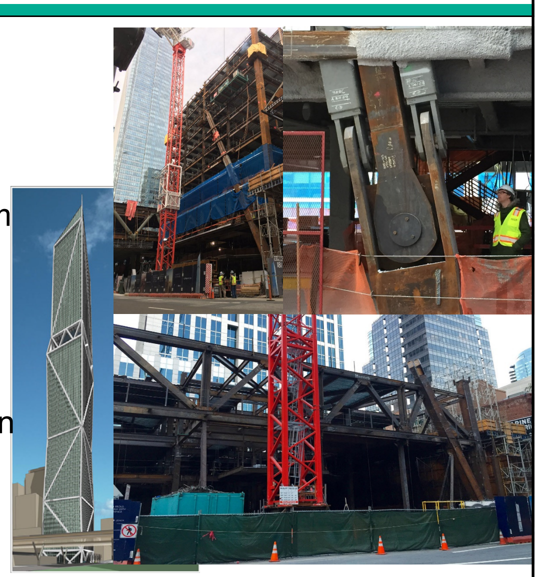
181 Fremont Street, San Francisco, CA

- All steel tower, since too narrow for core system
- Combination of SMF or BRBF and mega-brace/mega column system
- Mega-brace system combines BRB, damper and elastic pieces
- Lateral bracing of mega-braces created huge design challenge
- Transfer truss at Level 2
- Uplifting corner columns



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Rainier Square, Seattle, CA

- 850 foot tower
- Unique architectural shape
- Composite Sandwich Wall system for core walls
  - For speed of erection with all steel floor system
  - Developed for nuclear containment structures
  - First use on ***ANY*** building in the U.S.
- BRBF outriggers, composite columns, transfer podium, etc.

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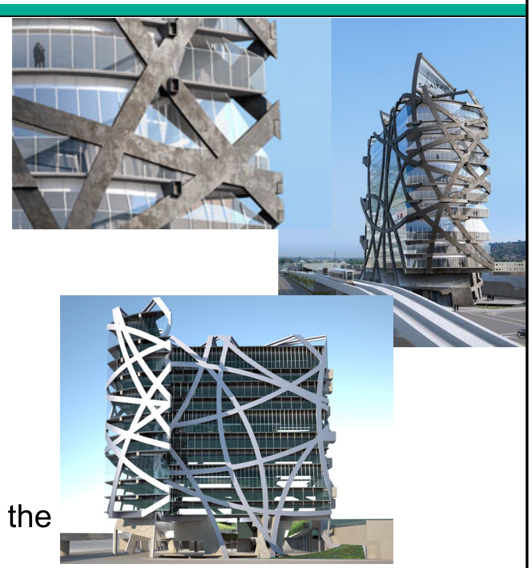
Last, but not least…(W)rapper Tower

- Now, for something completely different…
  - Evokes "Birds Nest" in Beijing for Olympics
- 12"x24" perimeter box elements
- SPSW Core in rear
- Base isolated system (Thank God!)
- ***NO*** interior columns
- Exterior exit tower
- Oh, and it's two miles from the Newport-Inglewood fault…
- ???



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5. How do you get the Innovation Mindset?

- When the Owner/Architect wants to build something that the Code presently doesn't allow (height, configuration, seismic demand, etc.)
- When "true" post EQ functionality is desired
  - I=1.5 presently in the code will likely fall short
  - Multiple EQ buildings, possibly including replaceable fuses
- When an Engineer wants to push improve performance with means not addressed in the code
  - Deliberate design to avoid residual drift
- When there is a LOT of money at stake…
- When the public decides "Community Resilience" is needed

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6. Summary/Conclusions

- There are many mechanisms to deliver innovation into steel building projects
- Innovation is often driven by technology advances in architecture, structural design, analysis and modeling, and construction procedures and techniques
- There are many examples of innovation on recent major projects
- The future may require even more if there is the public move toward "Resilient Communities"
- The resulting cost increases are relatively minor in most cases (except "crazy" architecture)

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Thanks For Your Attention!

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