Improving Functional Recovery Using Replaceable Fuses

Dr. Justin D. Marshall, PE, PhD
President, DuraFuse Frames, LLC

Structural Engineers Association of Alaska
Webinar
March 16, 2022

Outline

- Code Compliant Seismic Design
- Functional Recovery
- Designing for Functional Recovery
  - Response Modification Devices
  - “Better than Code” Designs
  - Replaceable Fuses

Seismic Design State of the Practice

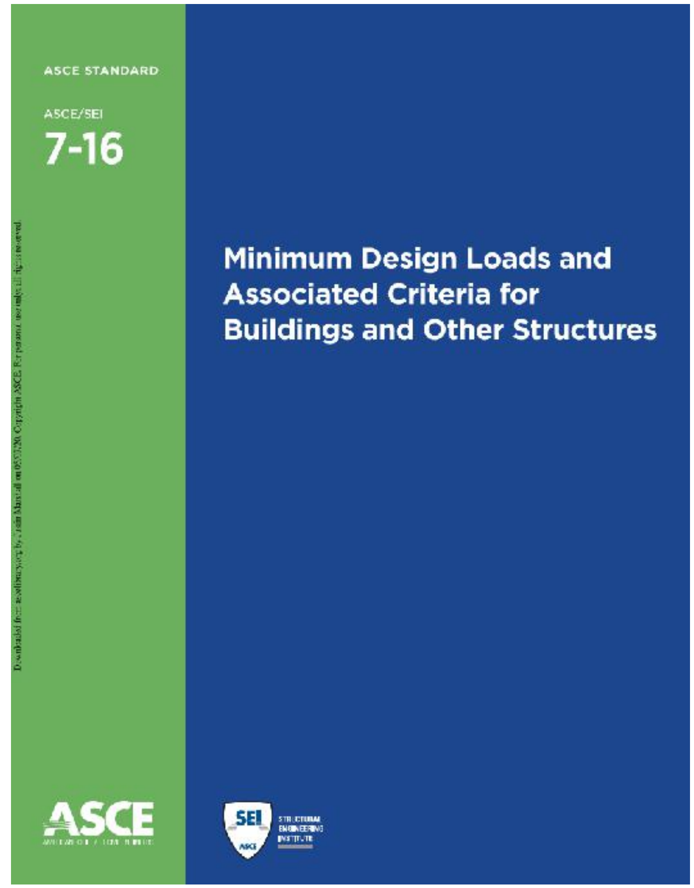
Table 1.3-2 Target Reliability (Conditional Probability of Failure) for Structural Stability Caused by Earthquake

Risk Category	Conditional Probability of Failure Caused by the MCE_R Shaking Hazard (%)
I & II	10
III	5
IV	2.5

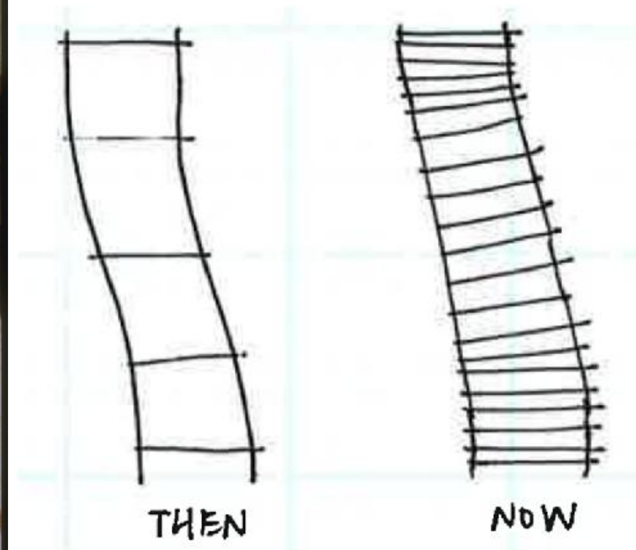
C11.5. Structures designed in accordance with the standard are likely to have a low probability of collapse but may suffer serious structural damage if subjected to the risk-targeted maximum considered earthquake (MCE_R) or stronger ground motion.

ASCE 7 seismic design targets

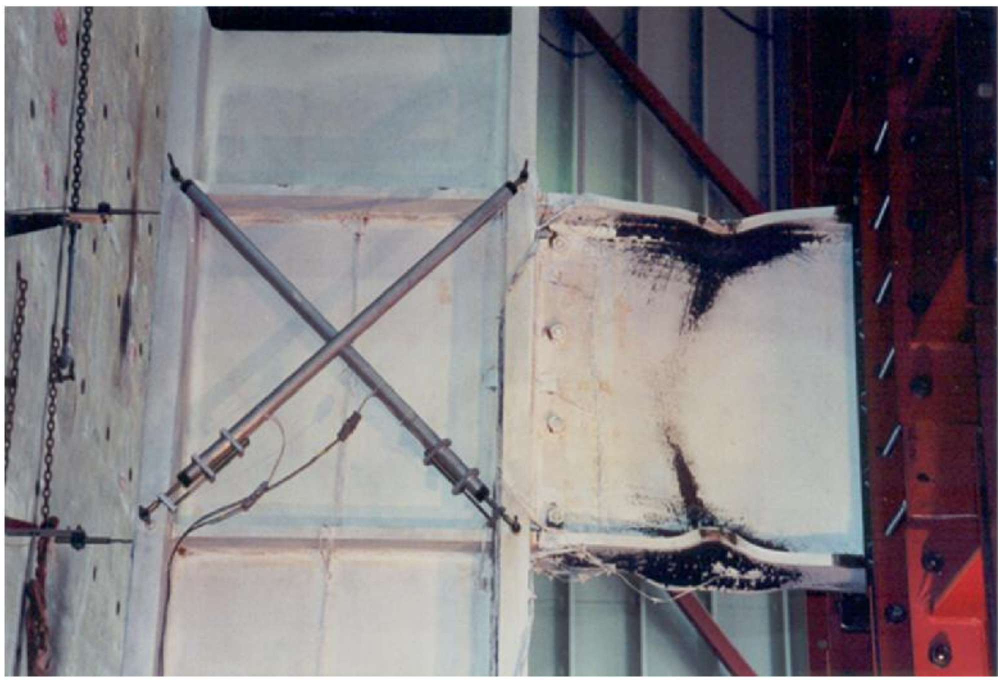
Ductility-Based Life-Safety Design Provisions

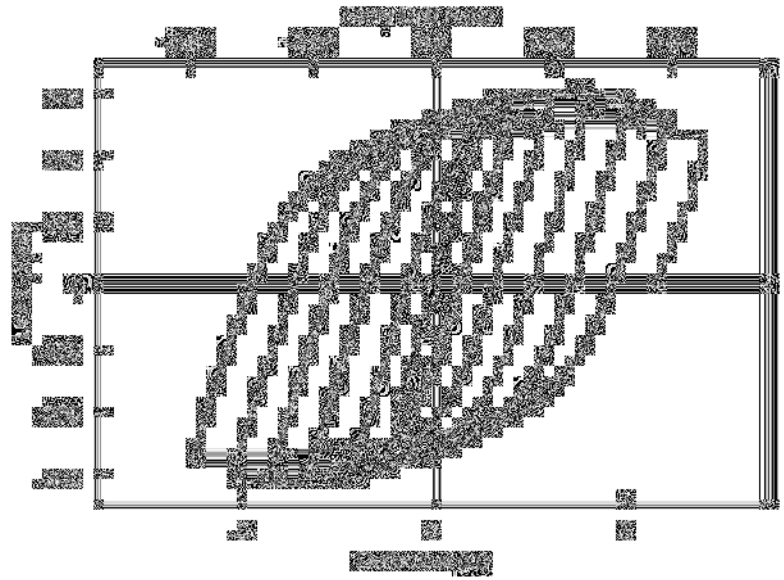


Prior to Ductility-Based, Life-Safety Building Codes



“Code Compliant” Behavior of Ductile Systems





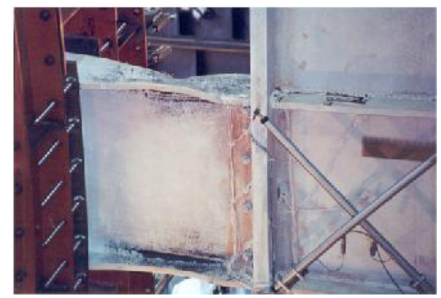
Post-Earthquake Repairs

1. Excessive residual drift

- Easy to quantify
- Very challenging to rectify

2. Fatigue in ductile elements

- Very challenging to quantify
- Very challenging to rectify



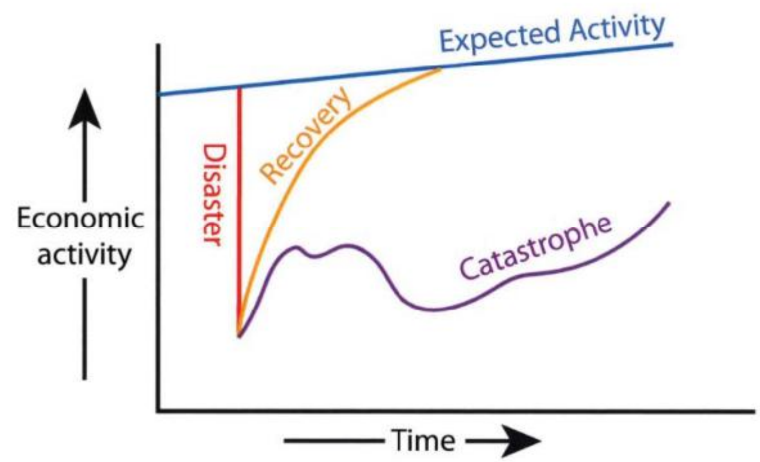
Life Safety versus Functional Recovery

"The building did what it was supposed to do," Mr. Devereux says. "But this building is coming down for economic reasons - it was just too expensive to repair."

https://www.nzherald.co.nz/nz/quake-city-landmark-will-soon-be-rubble/LQHGDLBPKJZKUPHQ66PYM5CUIY/

Life Safety versus Functional Recovery

Resilience curve



Updating the Code to Include Functional Recovery


U SMART
UTAH SMART ENERGY LAB
Department of
City and Metropolitan Planning
COLLEGE OF ARCHITECTURE + PLANNING | THE UNIVERSITY OF UTAH

Utah Resilience Webinar Series
Infrastructure

David Bonowitz
Structural Engineer
EERI, Distinguished Lecturer, 2020

Functional Recovery: What it Means to Design for Community Resilience

Thursday, November 12, 2020 - 4:00 to 5:00 pm MST
Connect via Zoom: https://utah.zoom.us/j/99991564928

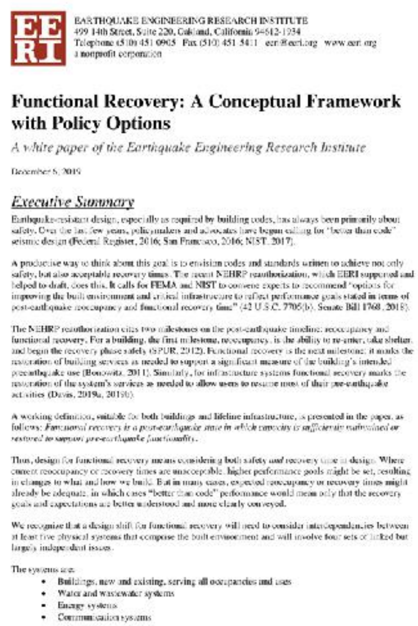
Abstract

This lecture will focus on the emerging concept of functional recovery as a basis for earthquake-resistant design. Designing buildings and infrastructure for limited downtime - or an acceptably functional recovery - is not new, but is receiving new attention through state and federal legislation, and showing new feasibility through research and technology. Most intriguing is the recognition that designing for functional recovery is a necessary tool for achieving community-wide earthquake resilience. And if progress is to be measured at the community level, functional recovery will also be a matter of public policy. The lecture will look at the roles EERI members can play in shaping this thinking into design practice with four sets of questions: definitional, technical, policy, and implementation.

Bio

David Bonowitz (M. EERI, 1994) is a leading structural engineer in San Francisco and is a member of the new working group of the Federal Emergency Management Agency - National Institute of Standards and Technology on Functional Recovery of the Built Environment and Critical Infrastructure. He is co-author of Functional Recovery: A Conceptual Framework, an EERI white paper and lead author of "Resilience-based Design and the NEHRP Provisions", now under review by the Provisions Update Committee of the National Earthquake Risk Reduction Program. Among other awards, he received the Distinguished Lecture Award 2020 from the EERI of the United States, award given to EERI members who have made outstanding contributions to reducing the risk of earthquakes.

Earthquake Engineering Research Institute


EARTHQUAKE ENGINEERING RESEARCH INSTITUTE
499 14th Street, Suite 220, Oakland, California 94612-1934
Telephone (510) 451 0905 Fax (510) 451 5411 eeri@eeri.org www.eeri.org
a nonprofit corporation

Functional Recovery: A Conceptual Framework with Policy Options

A white paper of the Earthquake Engineering Research Institute

December 5, 2019

Executive Summary

Earthquake-resistant design, especially as required by building codes, has always been primarily about safety. Over the last few years, policymakers and advocates have begun calling for "better than code" seismic design (Federal Register, 2016; San Francisco, 2016; NIST, 2017).

A productive way to think about this goal is to envision codes and standards written to achieve not only safety, but also acceptable recovery times. The recent NEHRP reauthorization, which EERI supported and helped to draft, does this. It calls for FEMA and NIST to convene experts to recommend "options for improving the built environment and critical infrastructure to reflect performance goals stated in terms of post-earthquake reoccupancy and functional recovery time" (42 U.S.C. 7705(b), Senate Bill 1768, 2018).

The NEHRP reauthorization cites two milestones on the post-earthquake timeline: reoccupancy and functional recovery. For a building, the first milestone, reoccupancy, is the ability to re-enter, take shelter, and begin the recovery phase safely (SPUR, 2012). Functional recovery is the next milestone; it marks the restoration of building services as needed to support a significant measure of the building's intended preearthquake use (Bonowitz, 2011). Similarly, for infrastructure systems functional recovery marks the restoration of the system's services as needed to allow users to resume most of their pre-earthquake activities (Davis, 2019a, 2019b).

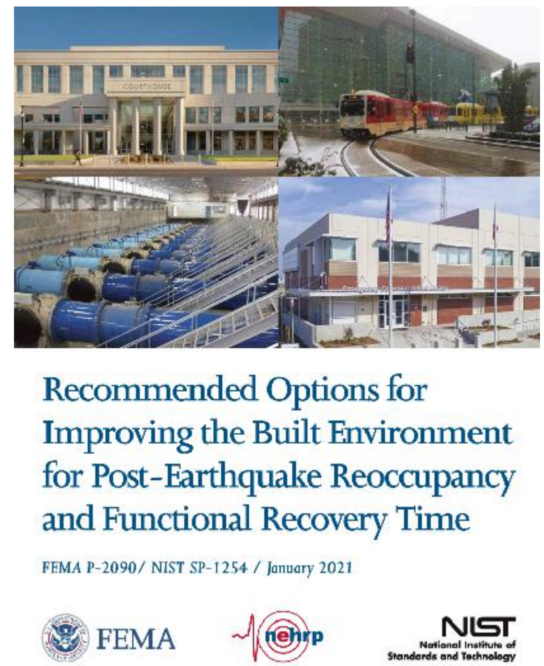
A working definition, suitable for both buildings and lifeline infrastructure, is presented in the paper, as follows: *Functional recovery is a post-earthquake state in which capacity is sufficiently maintained or restored to support pre-earthquake functionality.*

Thus, design for functional recovery means considering both safety *and* recovery time in design. Where current reoccupancy or recovery times are unacceptable, higher performance goals might be set, resulting in changes to what and how we build. But in many cases, expected reoccupancy or recovery times might already be adequate, in which cases "better than code" performance would mean only that the recovery goals and expectations are better understood and more clearly conveyed.

We recognize that a design shift for functional recovery will need to consider interdependencies between at least five physical systems that compose the built environment and will involve four sets of linked but largely independent issues.

The systems are:

- Buildings, new and existing, serving all occupancies and uses
- Water and wastewater systems
- Energy systems
- Communication systems


Recommended Options for Improving the Built Environment for Post-Earthquake Reoccupancy and Functional Recovery Time

FEMA P-2090/ NIST SP-1254 / January 2021

FEMA
nehrp
NIST
National Institute of Standards and Technology

"Functional recovery is a post-earthquake state in which capacity is sufficiently maintained or restored to support pre-earthquake functionality"

Updating the Code to Include Functional Recovery

- Performance States
  - Reoccupancy – a building is maintained or restored to allow re-entry for providing shelter or protecting contents.
  - Functional Recovery – a building or lifeline is maintained or restored to support the basic intended functions associated with pre-earthquake occupancy
- Recovery-based objectives
  - Target recovery times based on shaking level
  - Vary based on building use and occupancy

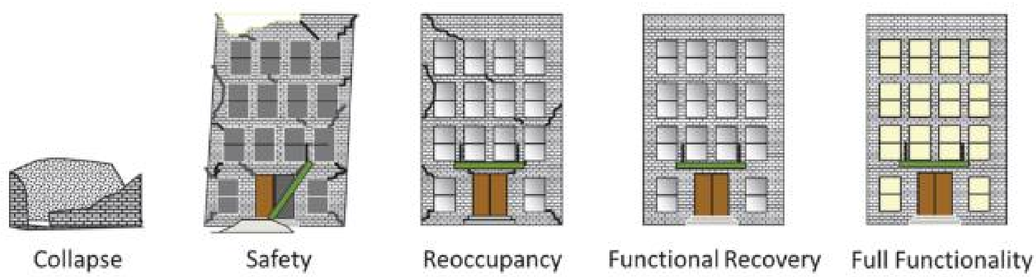
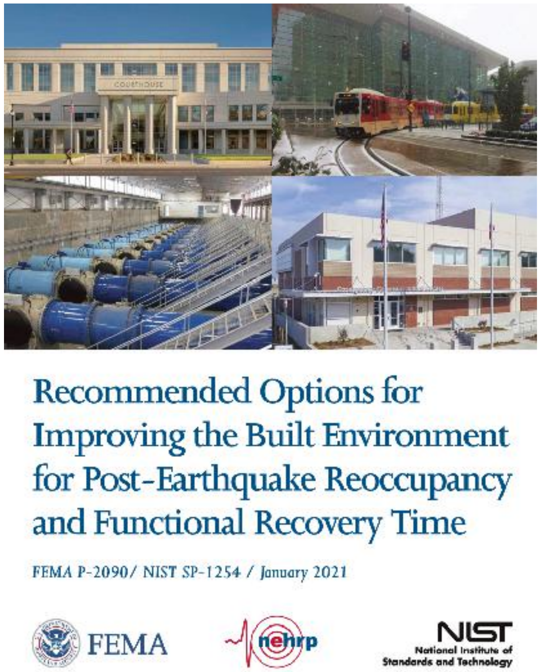


Figure 1-2 Theoretical range of building performance and relative placement of safety-based and recovery-based goals (courtesy of R. Hamburger).



Methods to Design for Functional Recovery

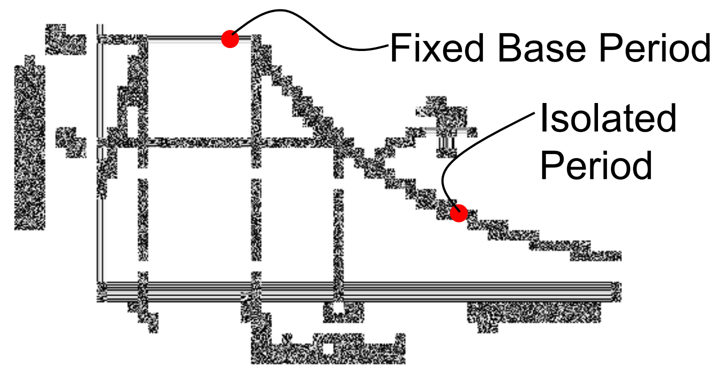
- Seismic or Base Isolation
- Energy Dissipating Devices
  - Viscous Dampers
  - Viscoelastic Dampers
  - Hysteretic Energy Dissipaters
- "Better than Code" Design
- Replaceable Fuses

(Seismic or Base Isolation and Energy Dissipating Devices: Response Modification Devices)

Seismic Isolation

Seismic Isolation

- Building is supported on vertically stiff, horizontally flexible supports
- This is accomplished typically by rubber bearings or friction bearings
- The long period of vibration for the isolation system results in large displacements at the isolation plane and low accelerations on the building
- Adds additional cost and complexity to design and construction but provides improved performance

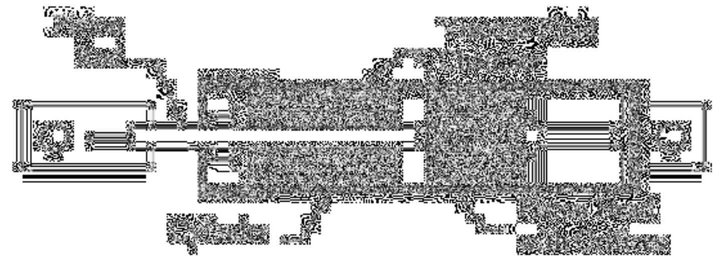


Oregon State Treasury Resilience Building

- Critical infrastructure that needed to be functional post-earthquake
- Base isolation provided the best assurance at meeting the functional recovery targets

https://www.oregon.gov/treasury/news-data/the-ledger/Pages/Coming-in-2022-Treasury-Will-Move-to-New-Resilient-Building.aspx

Fluid Viscous Dampers



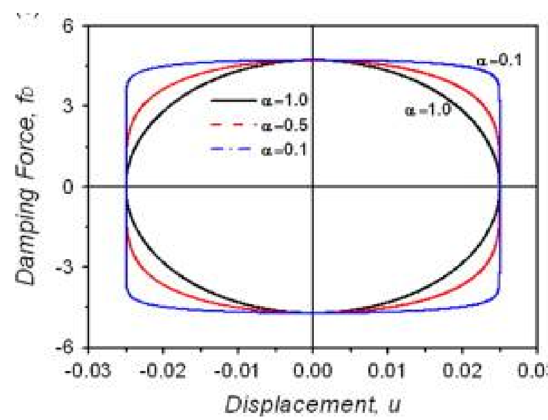
- Energy dissipation through a viscous fluid contained in a cylinder with a piston head with specially machined orifices
- Damping force is based on the velocity across the device and the exponent in the equation
- The exponent (α) ranges from 0.2 – 2.0 and is based on the application
- For seismic building applications, α is typically in the range of 0.2 – 0.5

$$F = C \cdot sign(V) \cdot |V|^{\alpha}$$

F = Force in the damper
C = Damping constant
V = Velocity across the device
α = Velocity exponent

Fluid Viscous Dampers

- A primary lateral system is still required for the structure
- The supplemental energy dissipation reduces the displacements and forces that develop within the system
- Due to the phase difference between the velocity and displacement, damper forces are out of phase with maximum structural forces
- Adds additional cost and complexity to design and construction but results in improved performance of the structure



Narkhede, D.I., and Sinha, R. (2014). Behavior of nonlinear fluid viscous dampers for control of shock and vibrations. *Journal of Sound and Vibrations*, 333(1), 80-98.

Hysteretic Energy Dissipaters

- Supplemental energy dissipation through metal yielding or friction
- Typically added to supplement the hysteretic energy of the primary lateral resisting system
- Numerous examples of these systems have been developed through research but applications are limited
- Adds additional cost and complexity to design and construction but have capability to significantly improve performance

Casa Adelante
Mission District
San Francisco, CA

Figure 17 - Completed photo of the building

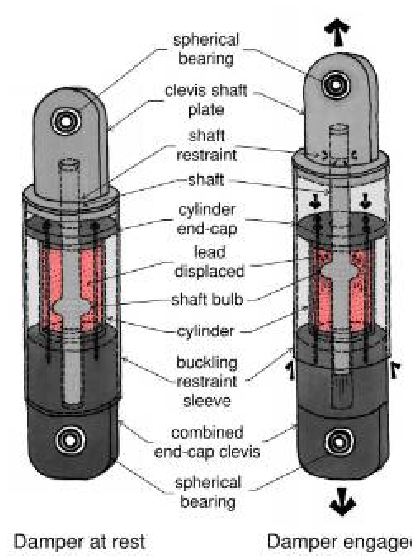


Figure 4 - Lead extrusion damper shown in an at rest and elongated state

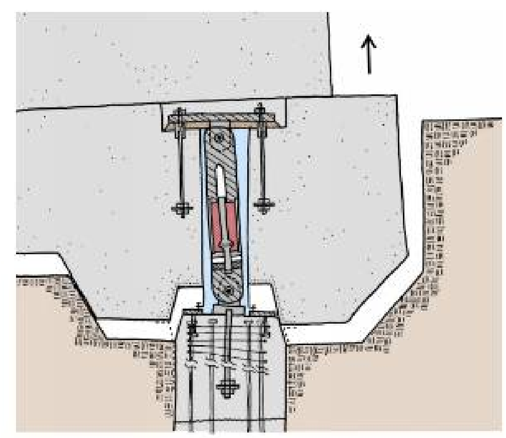


Figure 3 - Enlarged view at the lead extrusion damper during mat foundation rocking

https://www.marstructuraldesign.com/files/uploads/Publications/CasaAdelante.pdf

"Better than Code" Designs

- One approach to achieving Functional Recovery is designing to a higher Risk Category than the code requires
- Design impacts:
  - Increased design forces ($I_e = 1.25$ or 1.50)
  - Decreased drift limits ($\Delta_a = 0.015h_{sx}$ or $0.010h_{sx}$)
- Additional construction costs are incurred

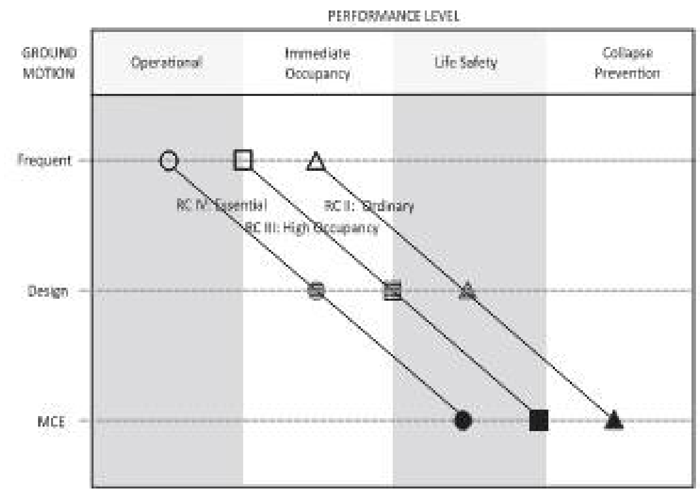
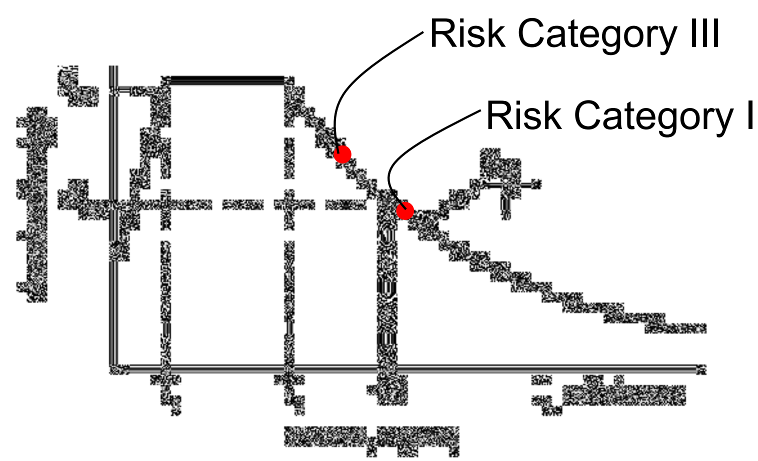
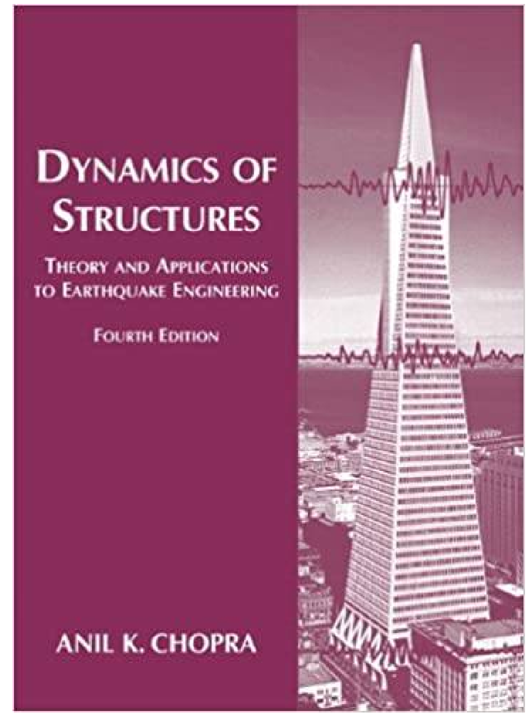


FIGURE C11.5-1 Expected Performance as Related to Risk Category and Level of Ground Motion

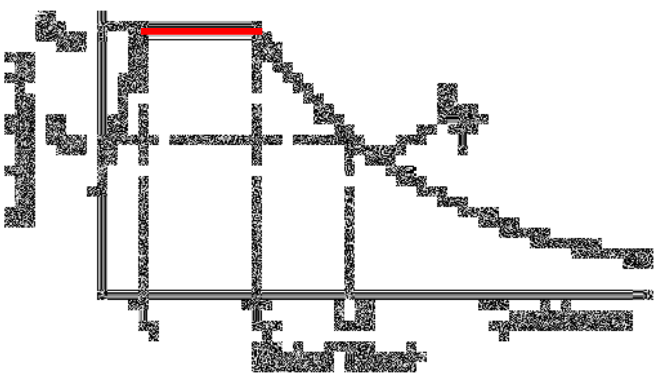


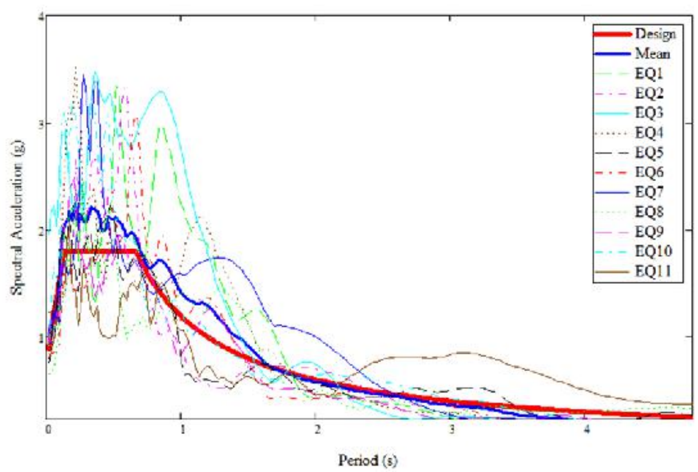
“Better than Code” Designs

“For systems in the acceleration-sensitive region of the spectrum...the ductility demand can be much larger than R_y. This result implies that ductility demand on very-short-period systems may be large even if their strength is only slightly below that required for the system to remain elastic.” –Chopra, *Dynamics of Structures*



Acceleration sensitive region



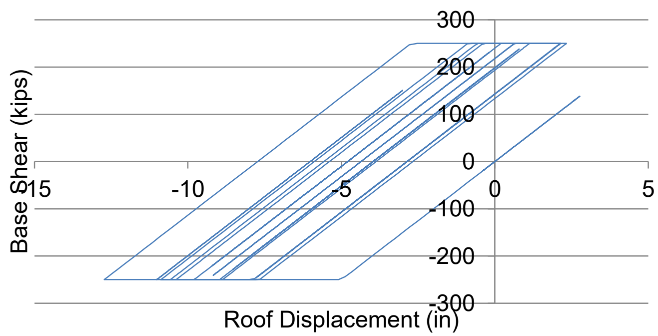


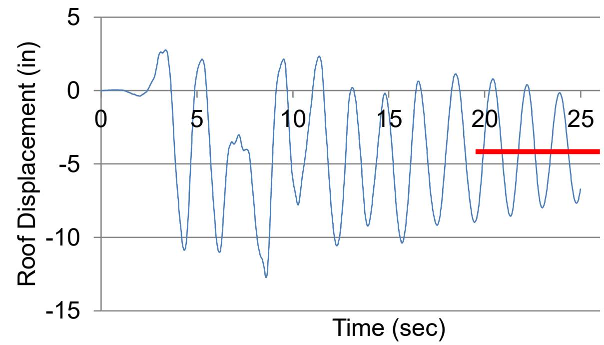
“Better than Code” Designs

components. Stiffer buildings, with lower fundamental periods, experience lower interstory drifts and higher peak floor accelerations. These buildings typically have higher nonstructural losses, because fragilities of most nonstructural components are correlated to peak floor accelerations. When

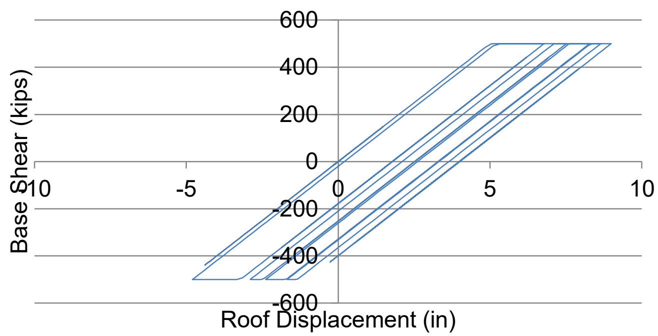
“Better than Code” Designs

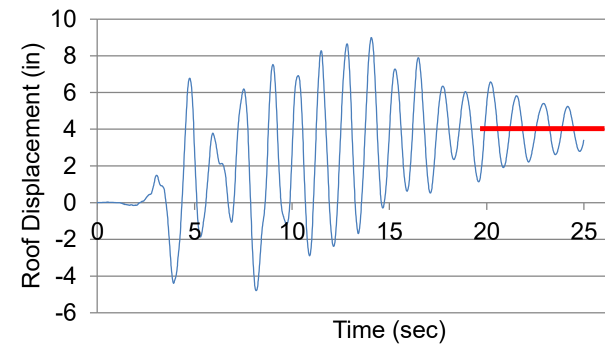
Stiffness: 50 k/in
Strength: 250 kips
T: 1.78 sec
Max Roof Disp: 12.7 in
Resid. Roof Disp: 4 in.





Stiffness: 100 k/in
Strength: 500 kips
T: 1.26 sec
Max Roof Disp: 9.0 in
Resid. Roof Disp: 4 in.





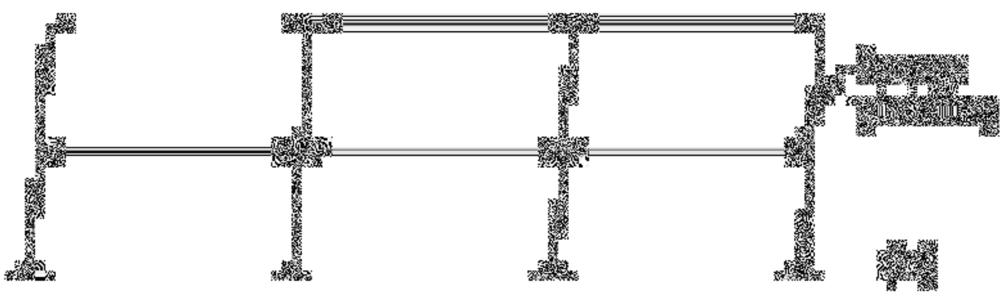
1994 Northridge Canoga Park record used for analysis.

Replaceable Fuses in Research

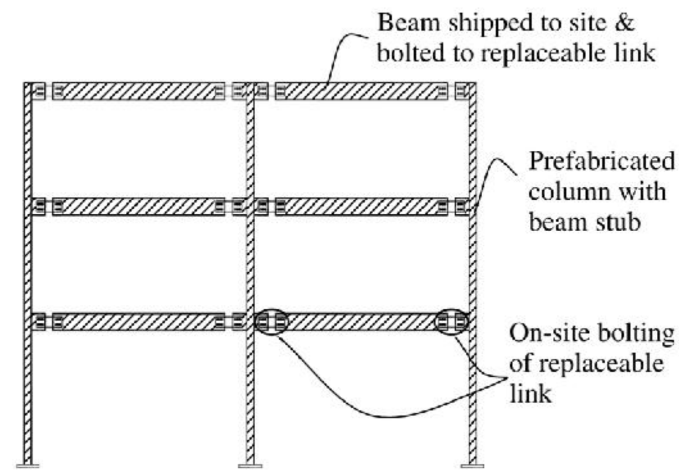
Repairability is the key factor to designing a ductility-based lateral system that can meet Functional Recovery targets without incurring additional design and construction costs.

- Mechanical Fuses
  - Moment Frames with Replaceable Connections
  - Replaceable Shear Links
- Friction Fuses
  - Sliding Hinge Joints
  - Sliding Brace Joints

Moment Frames with Replaceable Connections



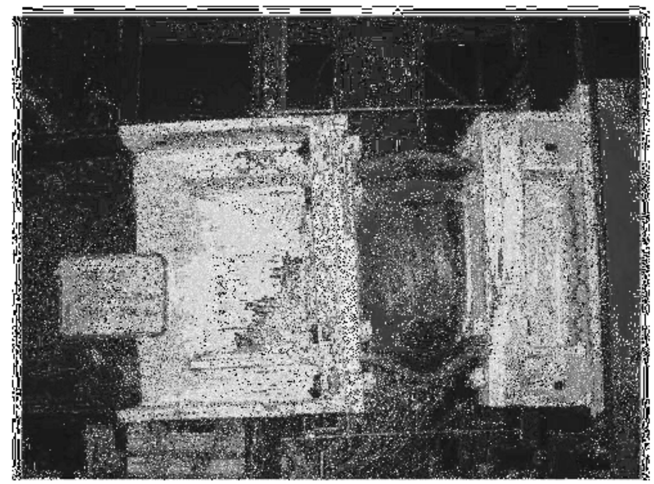
Old Concept

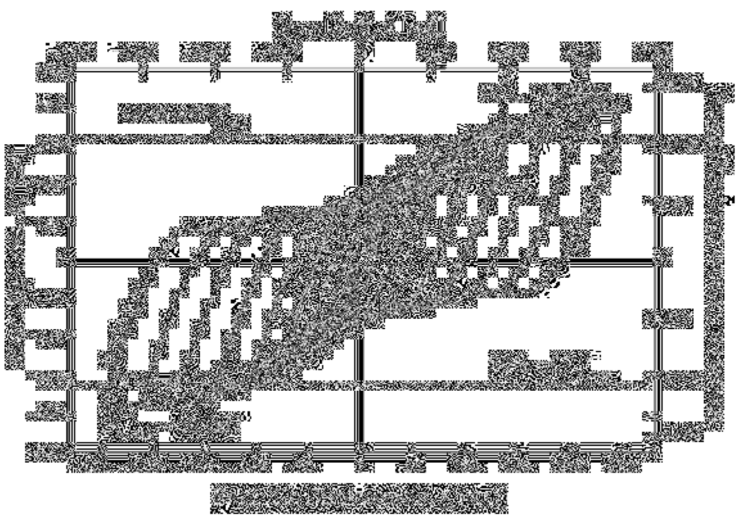


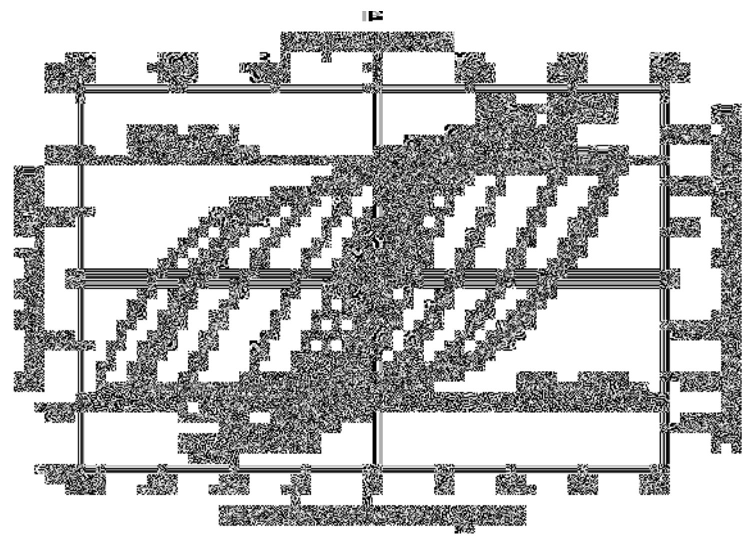
New Concept*

* Shen, Christopoulos, Mansour, and Tremblay (2011). “Seismic Design and Performance of Steel Moment-Resisting Frames with Nonlinear Replaceable Links,” *Journal of Structural Engineering*, 137 (10).

Results

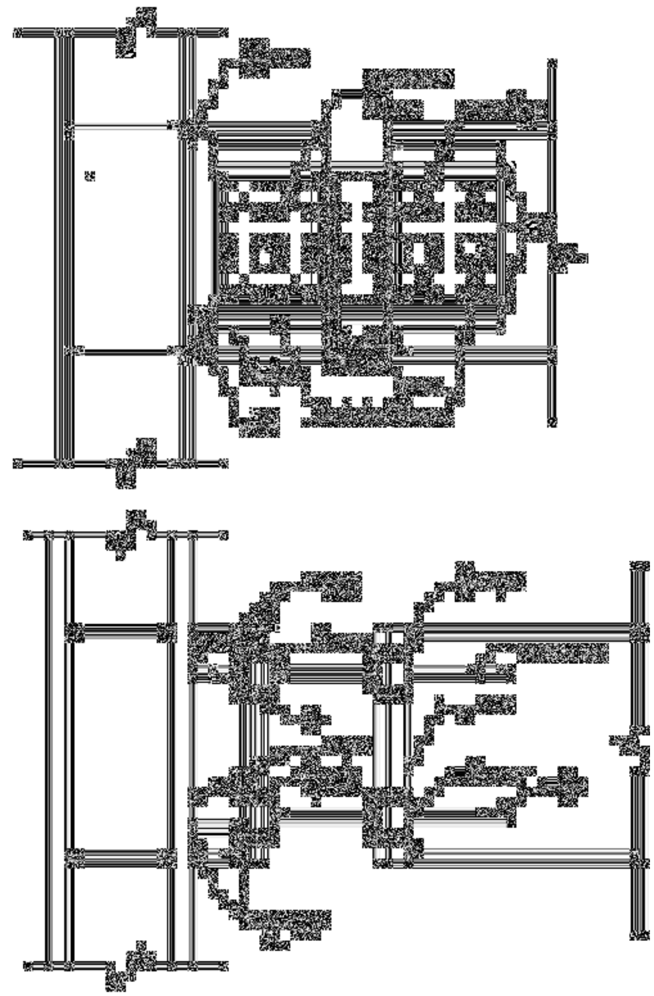




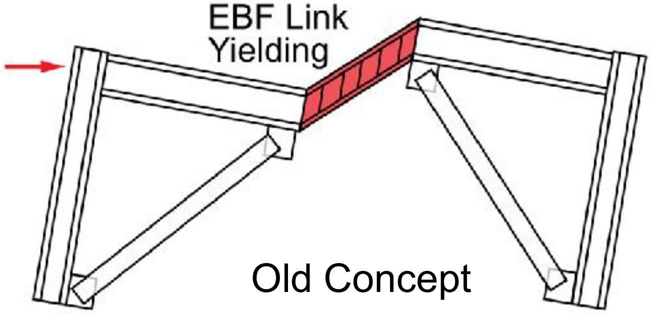


Practical Challenges

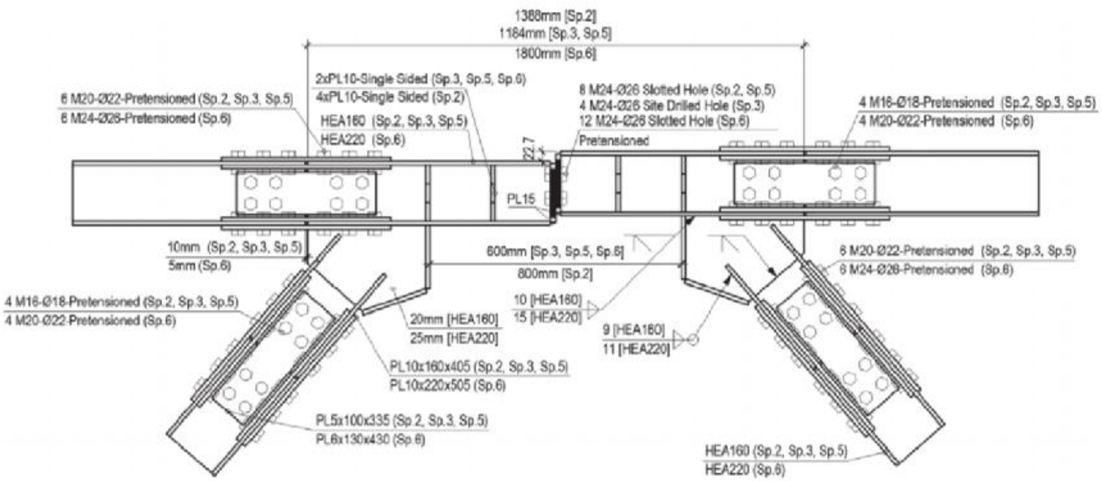
- Details more expensive (additional CJP welds or doubler plates)
- Stiffness loss near connections (heavier overall frame weight)
- Lower strength as compared to other SMFs (moment capacity of links was only 33-40% of the beam).
- Difficulty in removing/replacing a link beam (e.g. beam shoring)

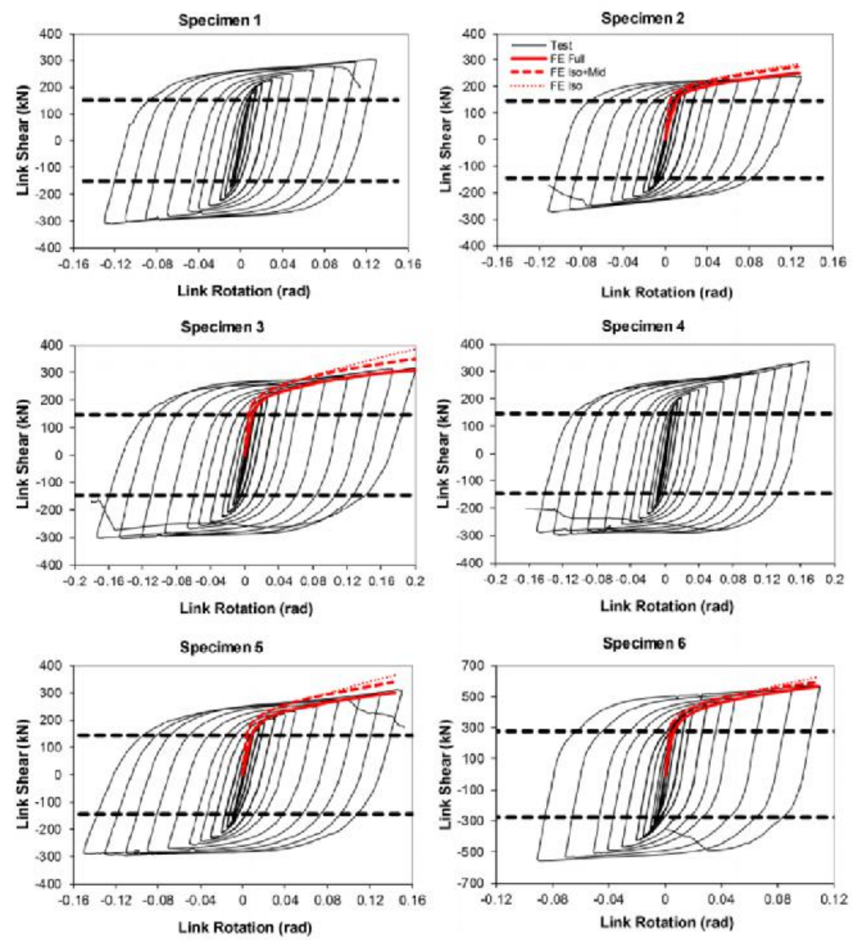


Replaceable Shear Links



Replaceable EBF Detail and Results

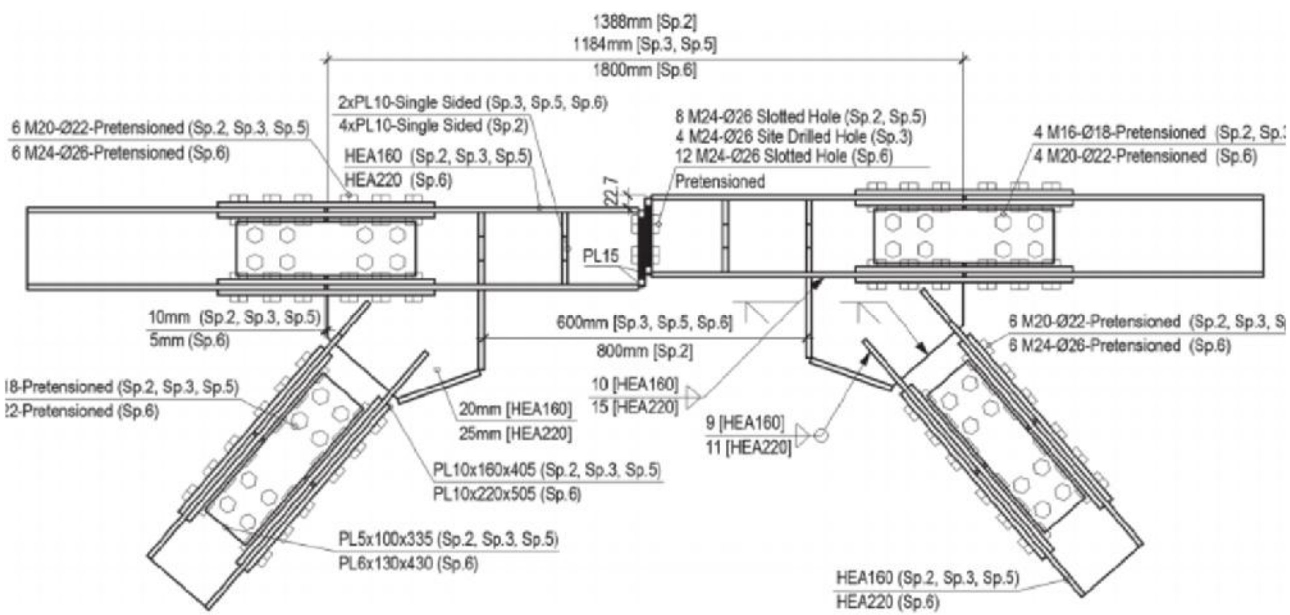




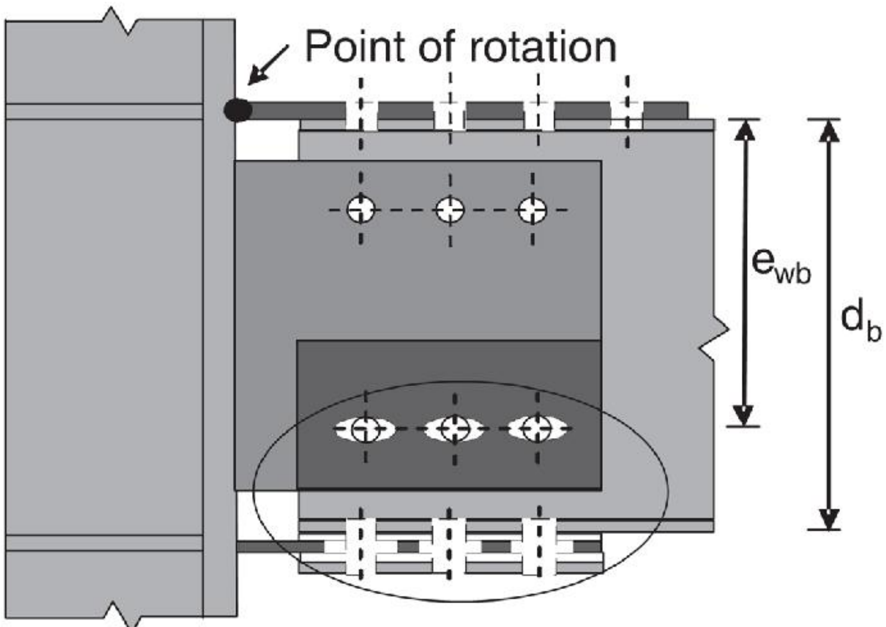
* Bozkurt, Azad, and Topkaya (2019). “Development of detachable replaceable links for eccentrically braced frames,” *Earthquake Engineering and Structural Dynamics,* 48(10).

Practical Challenges for Repairable EBFs

- Even regular EBFs pose design and fabrication challenges
- Slabs would need to be removed to install new links



Sliding Hinge Joint



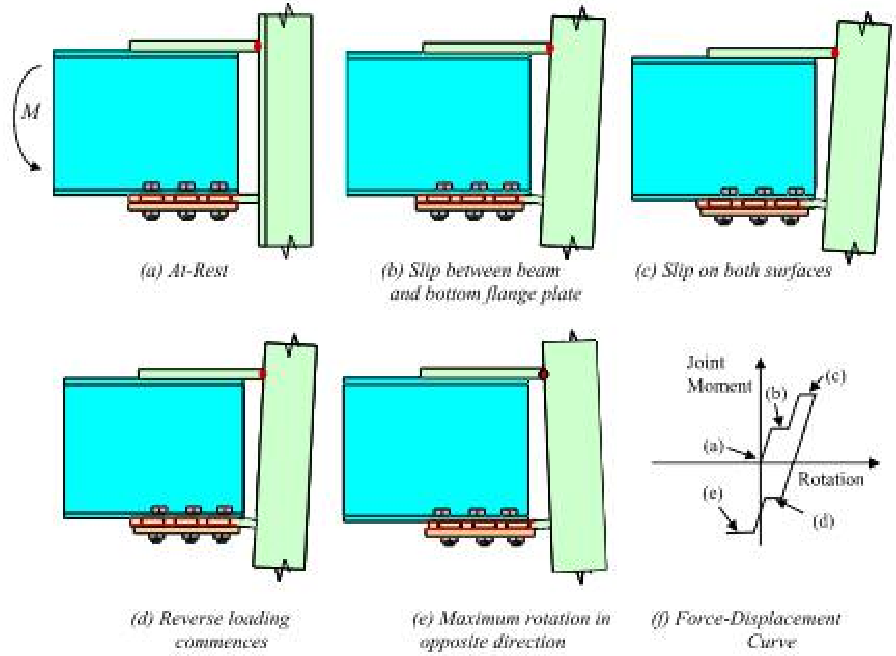


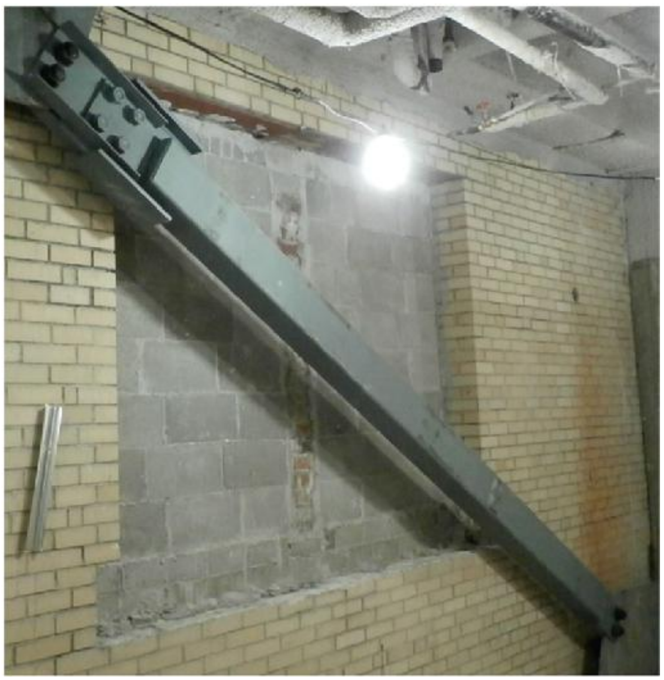
Figure 3. Sliding of Plates Below Beam During Cyclic Deformations

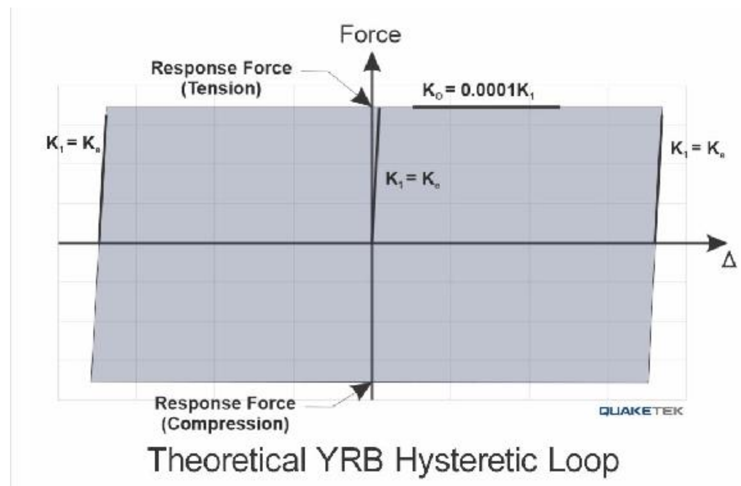
Khoo, H.-H., Clifton, C., Butterworth, J., MacRae, G., Gledhill, S., and Sidwell, G. (2012). "Development of the self-centering Sliding Hinge Joint with friction ring springs." *J Constr Steel Res*, 78, 201-211.

MacRae, G., Clifton, C., Mackinven, H., Mago, N., Butterworth, J., and Pampanin, S. (2010). “The Sliding Hinge Joint.” Bulletin of the New Zealand Society for Earthquake Engineering 43(3) DOI:10.5459/bnzsee.43.3.202-212.

Friction Dampers

QUAKETEK





Practical Challenges for Friction Devices

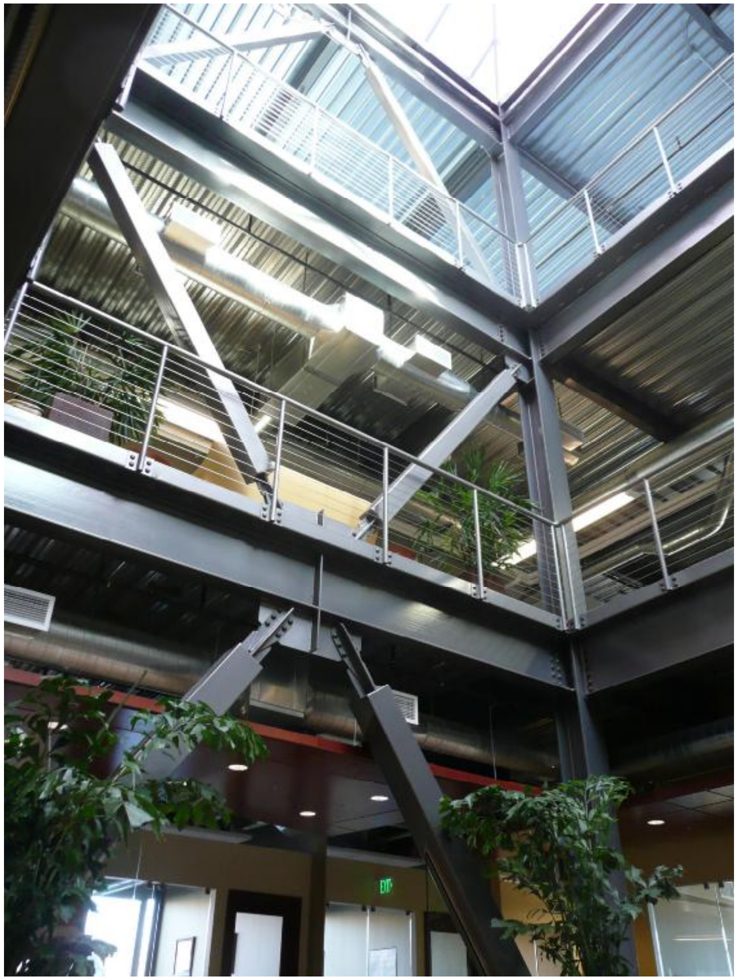
- Concerns about quantifying slip force accurately (over time)
- Strength of the connections can be an issue if friction is the only lateral system
- Inherently disadvantaged by current U.S. codes
- Under ASCE 7, buildings would be designed under §12.2.1.1 (Alternative Structural Systems) or Chapter 18 – Structures with Damping Systems (Peer Review required)

Replaceable Fuses in Practice

Repairability is the key factor to designing a lateral system that can meet Functional Recovery targets without incurring additional design and construction costs.

1. Buckling Restrained Braces
2. Special Moment Frames with Replaceable Fuses

BRBs are Replaceable Fuses



Features that enhance repairability:

- Frames are designed to carry gravity loads without the braces
- Gussets are not designed to go inelastic
- Braces are often bolted
- Instruments can be incorporated to provide data on remaining fatigue capacity

BRBFs are Ductile and Economical

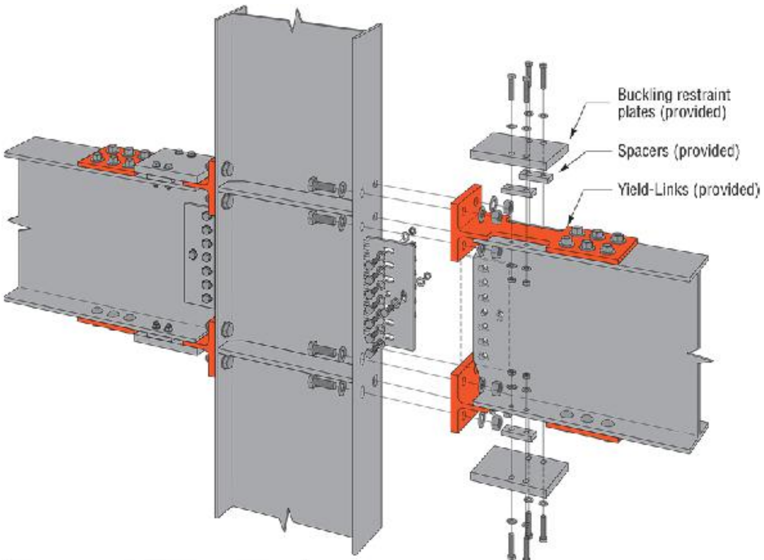
Aspects that make BRBFs low-cost:

- High inherent stiffness
  - Less steel than special moment frames
  - Typically controlled by strength, not drift
- High R-factor
  - Lower strength demands than SCBF
  - Lower demands in beams, columns, foundations.

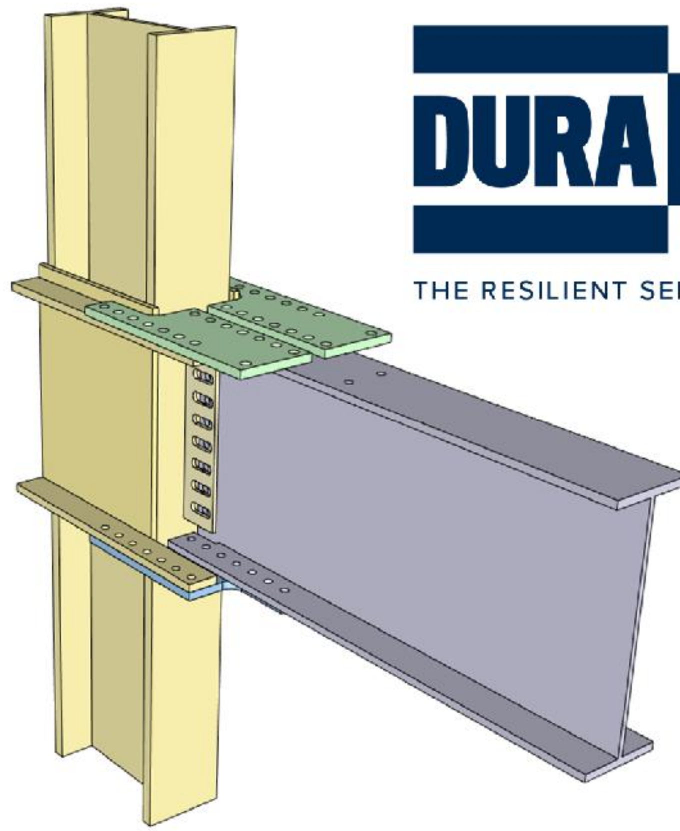
Recent BRB testing demonstrates replaceability.

Dr. Chris Pantelides, University of Utah

SMFs with Replaceable Fuses

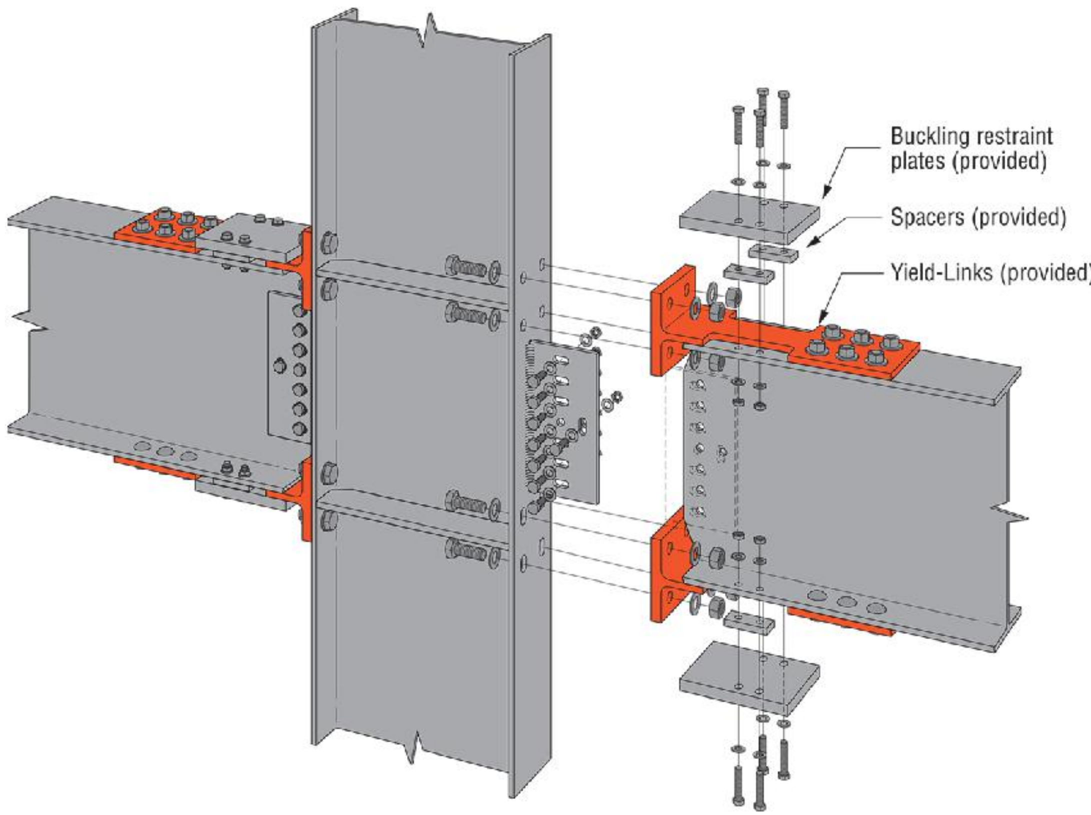


SIMPSON
Strong-Tie



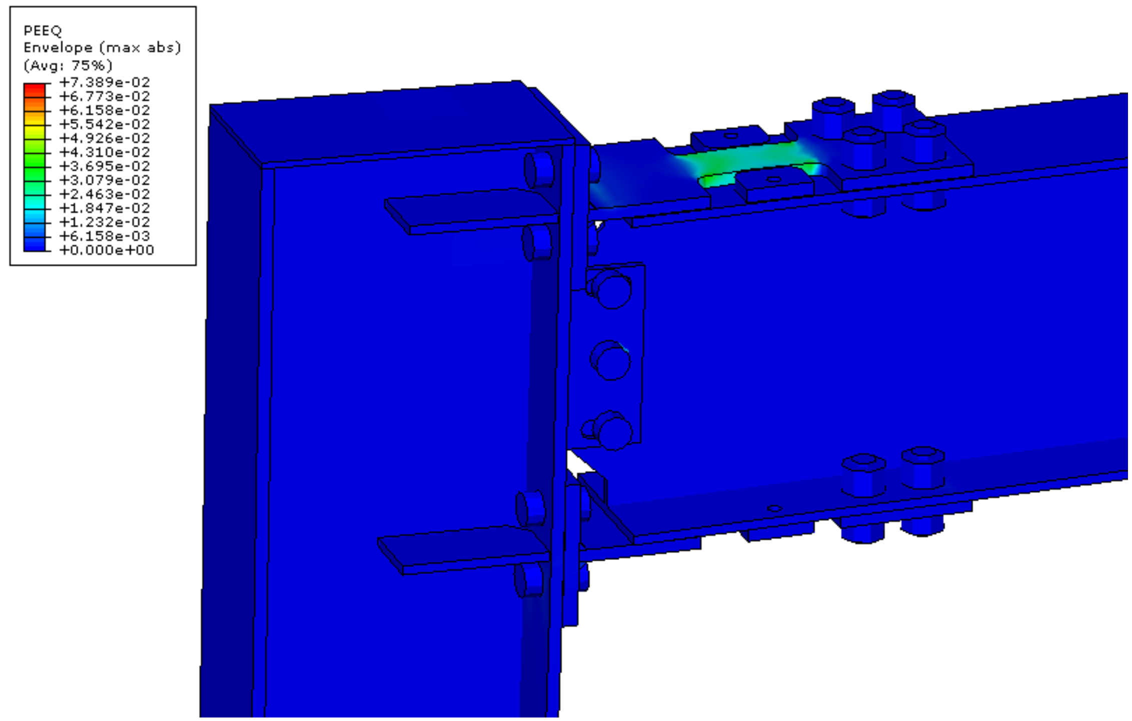
DURA FUSE
FRAMES
THE RESILIENT SEISMIC SOLUTION

Simpson Strong-Tie Yield Link

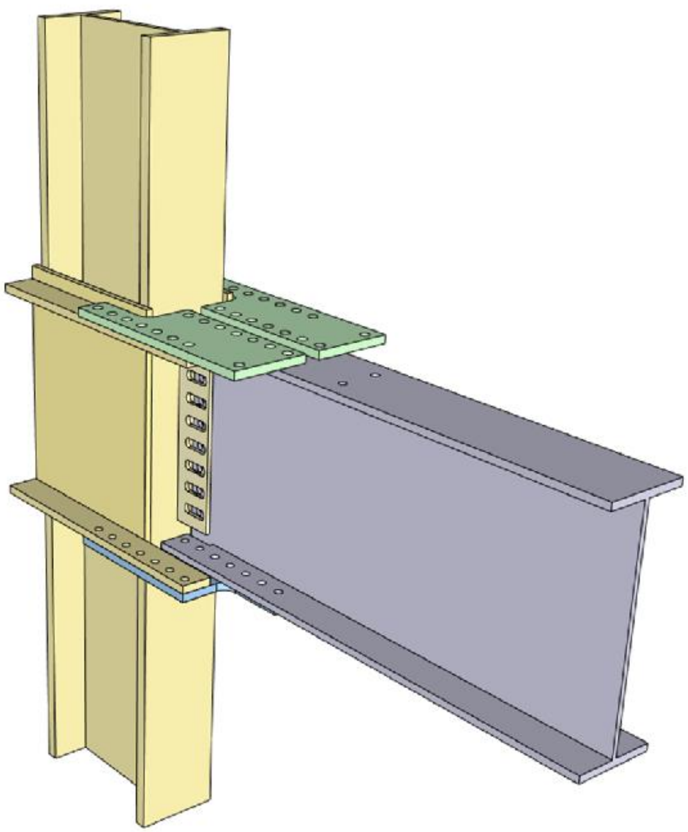


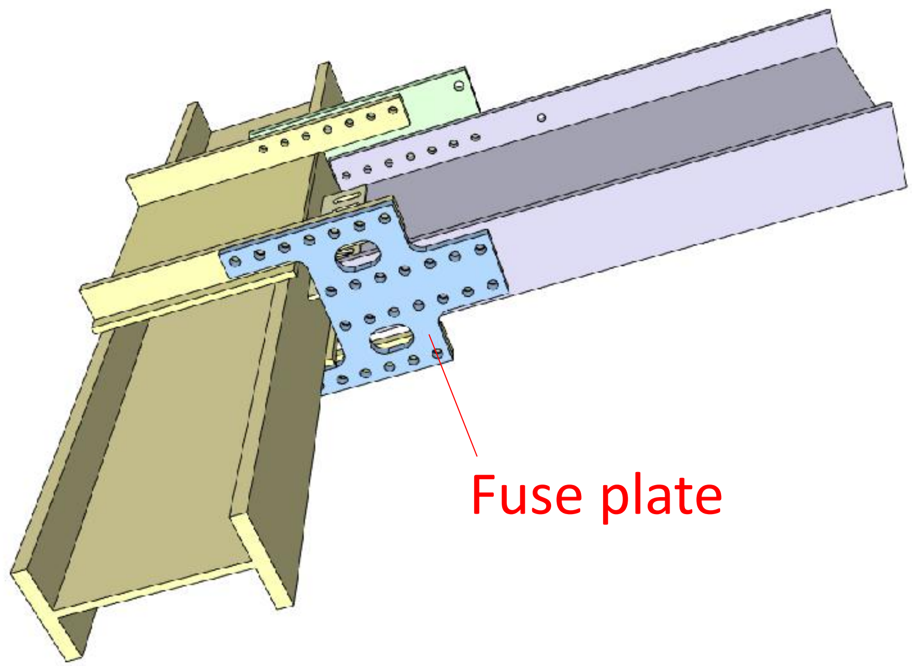
Simpson Strong-Tie Yield Link

- Eliminate yielding in the beam
- Concentrate damage onto replaceable elements
- Mechanical fuse has properties that are predictable
- Classified as a Partially Restrained (PR) moment connection

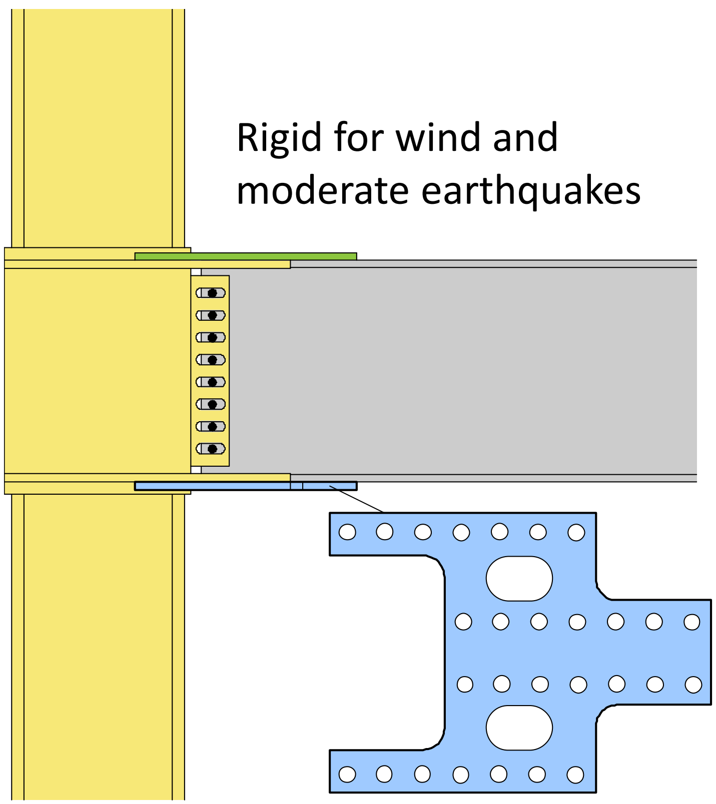


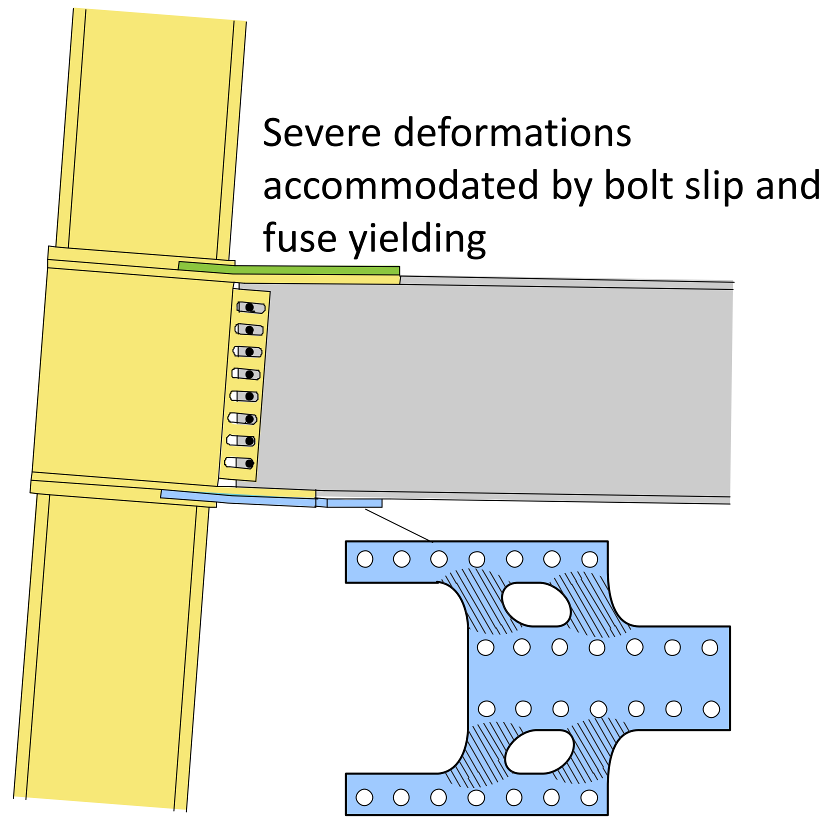
DuraFuse Frame



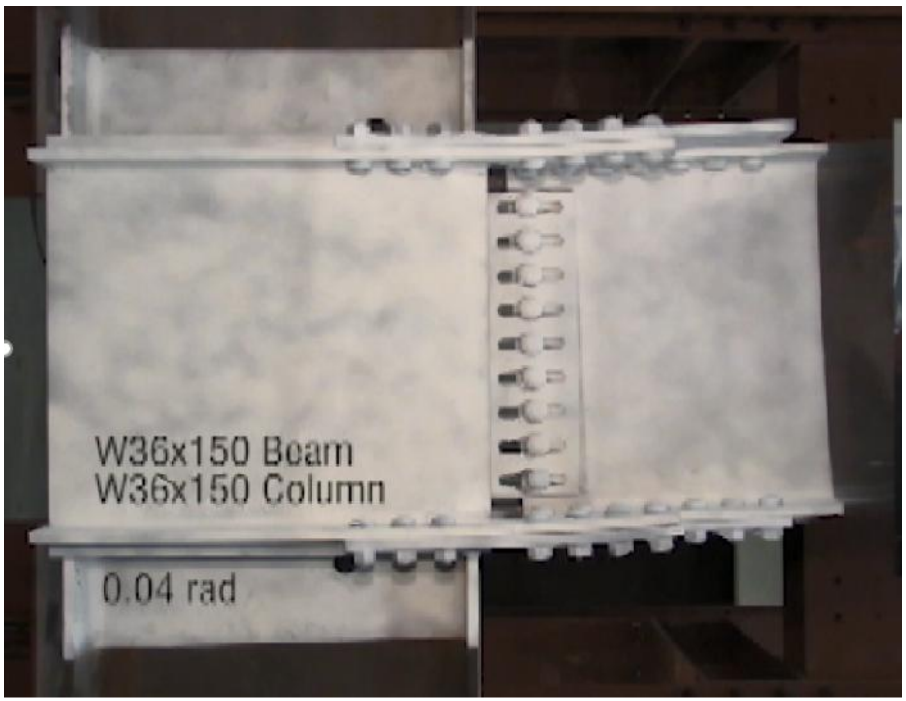


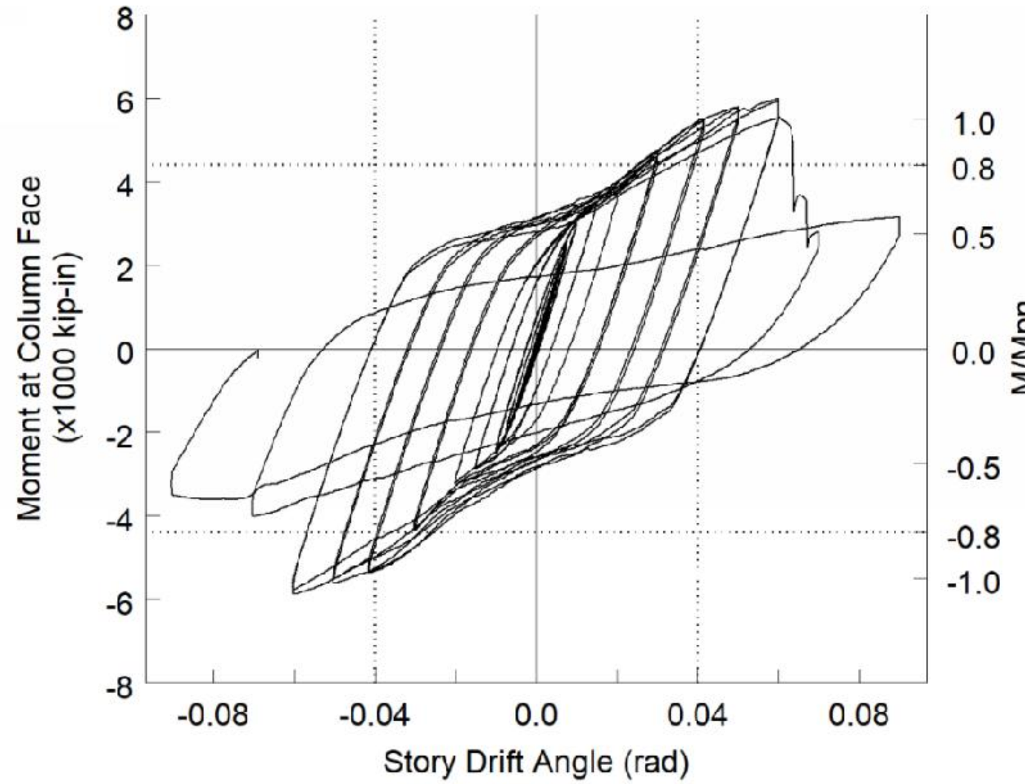
Energy Dissipation through Yielding and Bolt Slip





Hysteretic Response from Qualification Testing

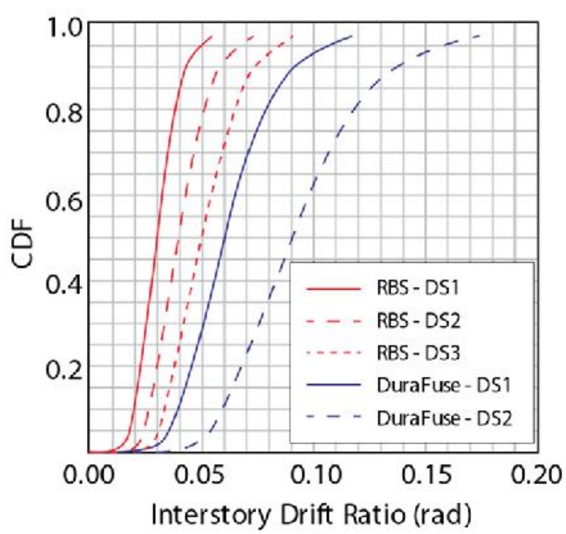




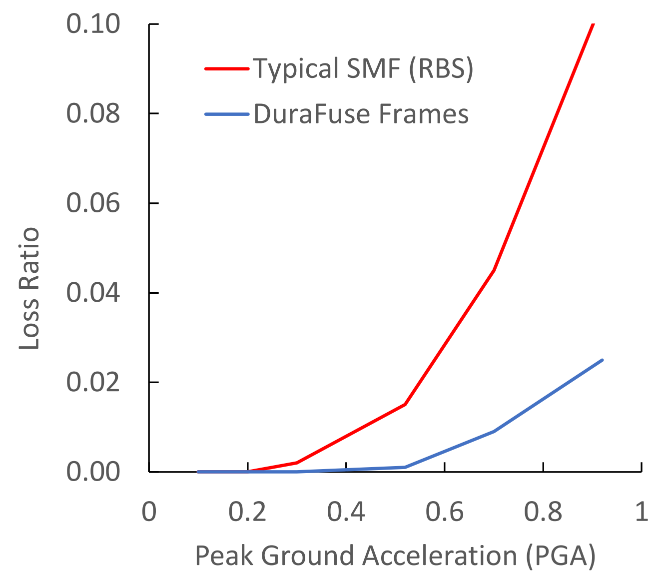
Connection Meets AISC 358 Performance + Repairable

DuraFuse Frames Dramatically Reduce Structural Losses (FEMA P58)

Better Fragility Curves + Lower Connection Repair Cost = Much Lower Structural Losses



RBS – DS2 = $36,625
DuraFuse – DS2 = $15,000

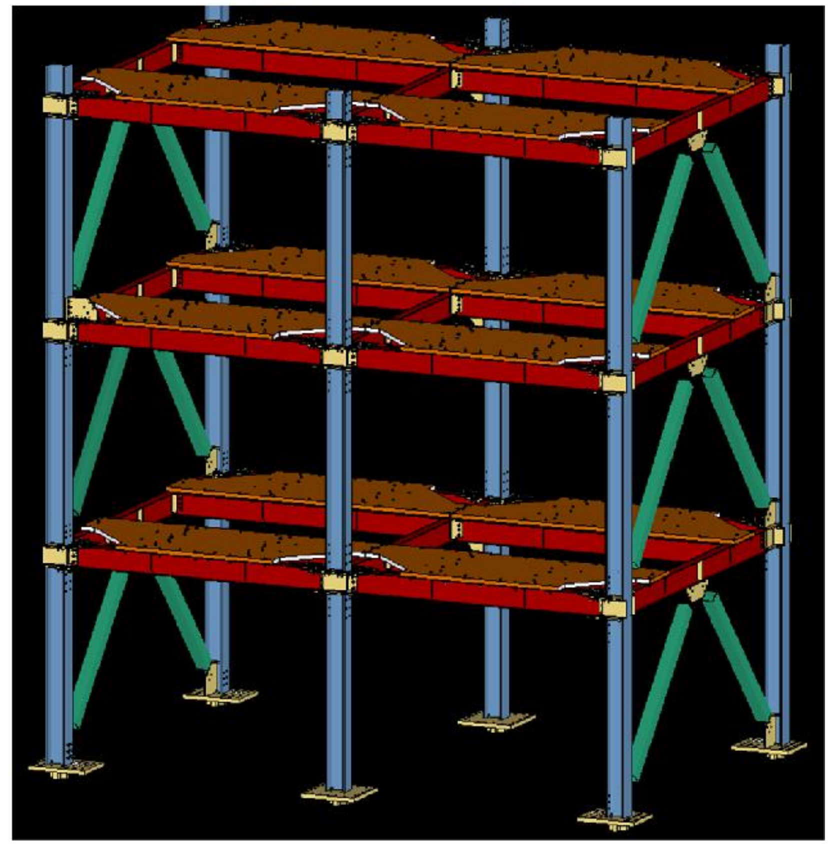


Richards, P.W. (2020). "Reducing seismic losses by using DuraFuse Frames." *Technical Bulletin 15.*

Haselton Baker Risk Group
SP3 Seismic Performance Prediction Program

Modular Test Frame Incorporates DuraFuse Frames Moment Connections and CoreBrace BRBs to Accommodate Repair

http://chei.ucsd.edu/MTB2/index.html



Summary

- Current code compliant designs will be difficult to repair.
- Efforts are underway to have codes include Functional Recovery.
- Response Modification Devices (Base Isolation, Viscous Dampers) are great options to meet Functional Recovery targets but bring added costs.
- “Better than Code” Designs (e.g. RC IV drift limits) can backfire in some cases ($T < 1.0$); they do not guarantee improved functional recovery.

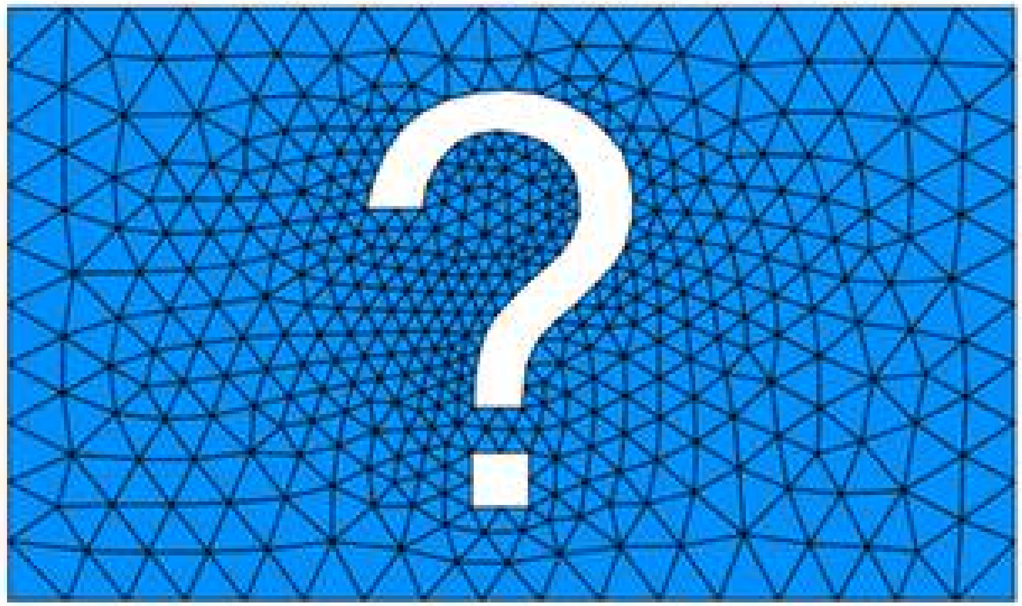
Summary

Replaceable Fuses in **Research**

- Several replaceable fuse concepts have been developed and successfully tested.
- Main obstacles are costs, code requirements and competition with other alternatives.

Replaceable Fuses in **Practice**

- BRBFs and some SMFs incorporate replaceable fuses.
- Systems with repairability are also the low-cost solution in many cases.
- Repairability is a more cost-effective path towards Functional Recovery objectives.



Justin D. Marshall
justin.marshall@durafuseframes.com
801.727.4064