New Resilient Structural System in SP3: Taylor Damped Moment Frame (TDMF™)

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Part 1: Background

- Benefits of supplemental damping

- Barriers for damper use in practice

Part 2: Taylor Damped Moment Frame (TDMF™) System Description

Part 3: Overview of Design Procedure

Part 4: AC494 / FEMA P-695 System Validation

Part 5: TDMF Implementation in SP3

- Structural properties

- Response prediction engine

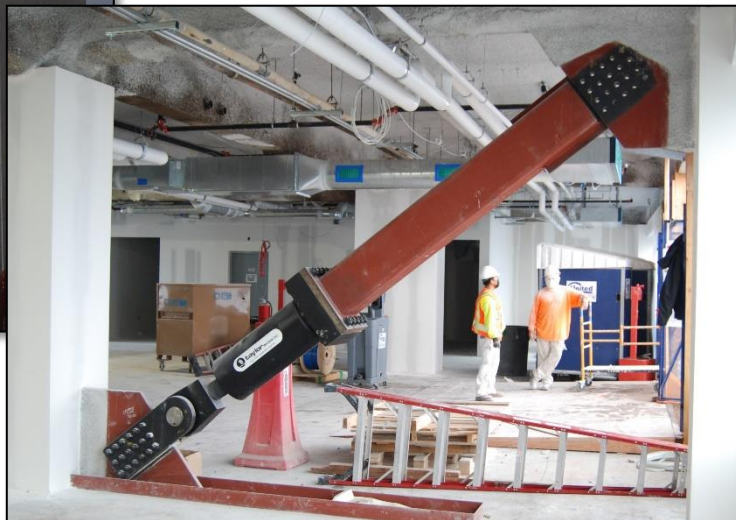- Brief comparison to undamped steel SMF (8-story in LA)

Part 6: Q & A

Current Practice for Damper Use

TDMF Applications

New Construction

Retrofit Applications

Base Isolation with Supplemental Damping

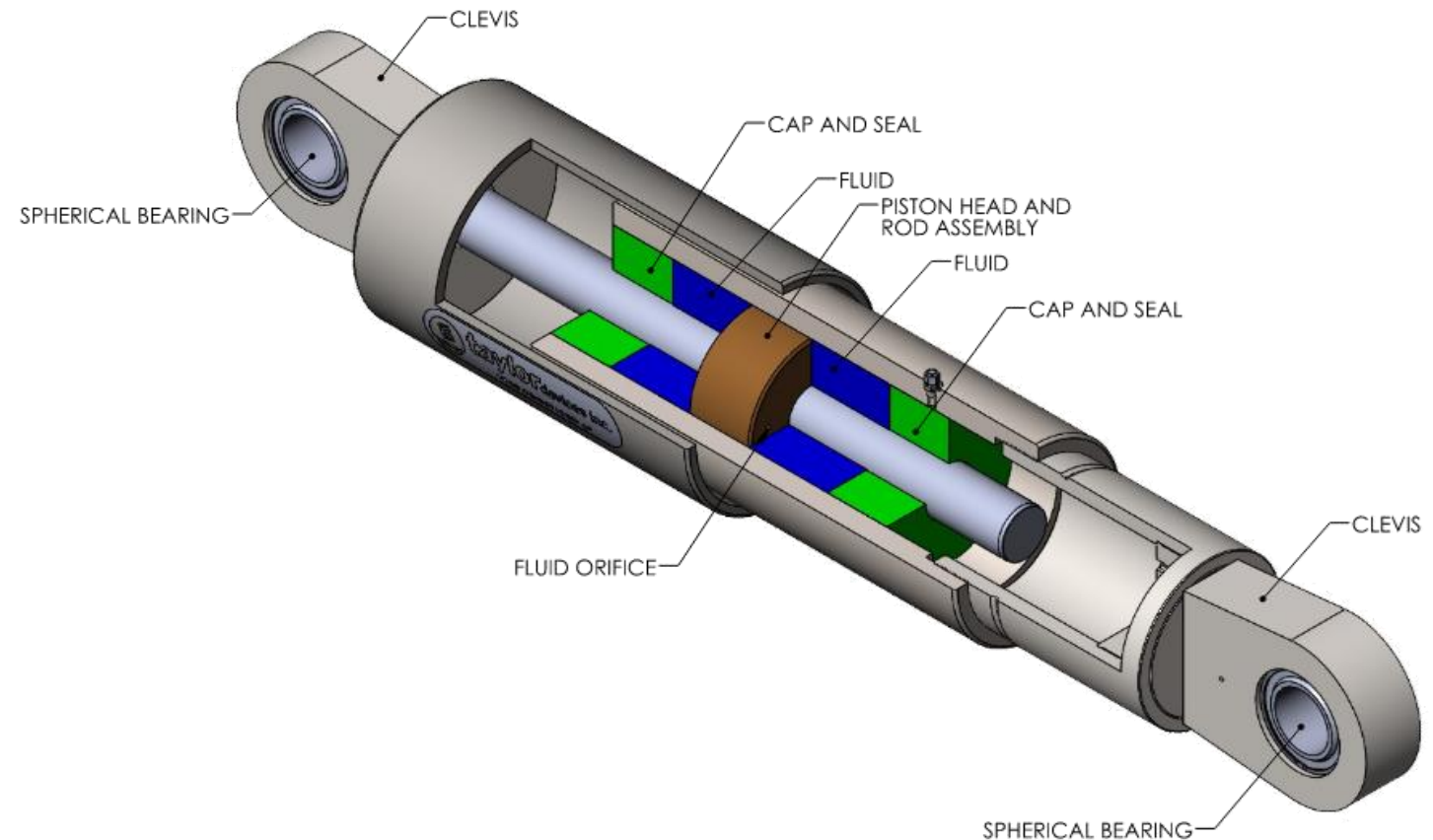© HB Risk Group

Damper Fundamentals

Damper Output Force, F

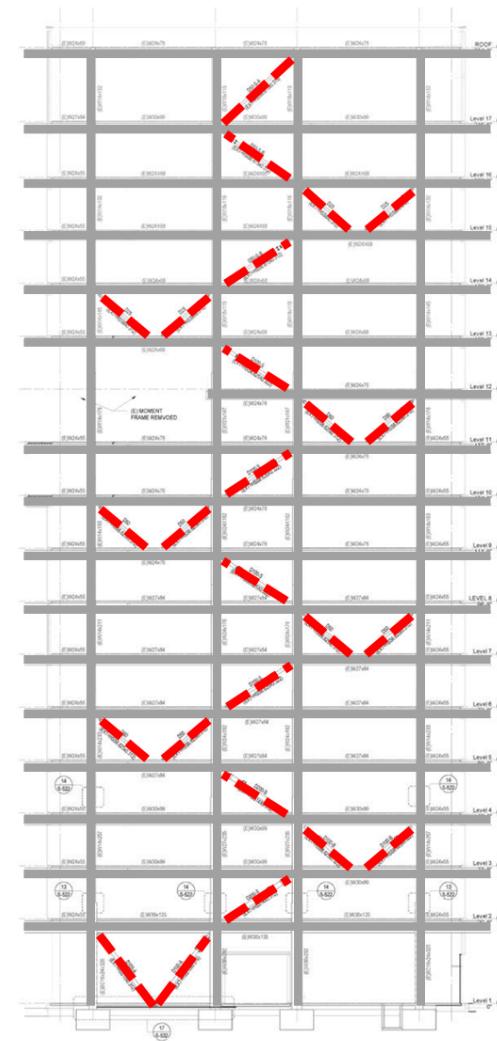$$F = CV^\alpha$$
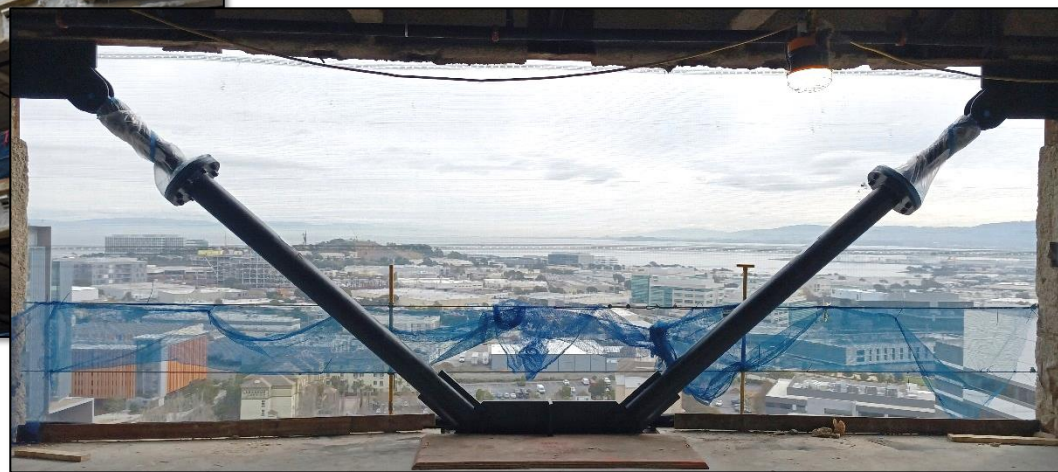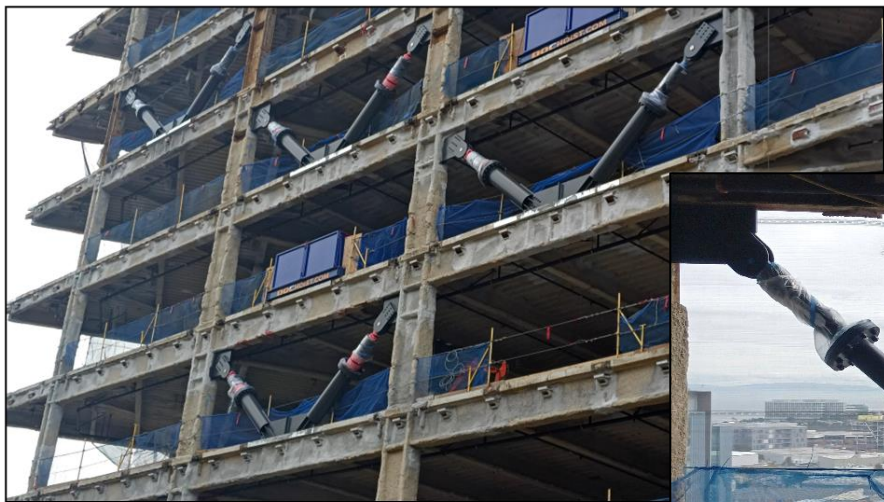
C = damping constant

V = velocity

α = velocity exponent

Key Advantages of Dampers

- Reduce floor drifts and accelerations

- Dampers don't add stiffness to the structure

- Damper bays don't have to stack vertically

- Dampers reduce base shear and foundation loads

Current Practice – ASCE 7 Ch. 18

- Nonlinear Response History Analysis (practically) required
- Peer Review
- Open-Ended and Interwoven design process between Moment Frame and Damper design
- No guidance on initial damper property selection (C & alpha)

Taylor Damped Moment Frame^{TM}

- Based on Modal Response Spectrum Analysis
- Removes Peer Review Requirements
- Decouples the design procedure for the Moment Frame from the Dampers
- Prescriptive approach to determining damper properties
  - Alpha is fixed at 0.4
  - Damping Ratio is set to 25%
  - C values are determined in a simplified way, based on MRSA results

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ICC-ES Evaluation Report
ESR-4769

Issued May 2023

This report is subject to renewal May 2024.

DIVISION: 05 00 00—METALS
Section: 05 12 00—Structural Steel Framing

REPORT HOLDER:

TAYLOR DEVICES INC.

EVALUATION SUBJECT:

TAYLOR DAMPED MOMENT FRAME SYSTEM (TDMF™)

1.0 EVALUATION SCOPE

Compliance with the following codes:

- 2021 and 2018 *International Building Code®* (IBC)

For evaluation for compliance with codes adopted by the Los Angeles Department of Building and Safety (LADBS), see ESR-4769 LABC Supplement.

are located in separate bays and there are no common elements. In a Type II system, the DF is located within the same bay as the SMF. In a Type III system, the SMF and DF are in adjacent bays and share some common elements. Elements common to the DF and SMF are designed for combined demands from the two systems. The DF need not be located along the same line of resistance as the SMFs, as shown in Figure 2. Buildings utilizing the TDMF system may include any combination of Type I, Type II and Type III.

Taylor Dampers are arranged in Diagonal, Chevron, V-type, or Two-story X configurations as shown in Figure 3, where dampers are in-line with the inclined extender braces between work points within a DF, or in modified Chevron or V-type configurations as shown in Figure 4, where dampers are placed horizontally within a DF.

The Taylor Damped Moment Frame System (TDMF™) is evaluated as an alternative structural system in accordance with Section 12.2.1.1 of ASCE/SEI 7 and ICC-ES AC494
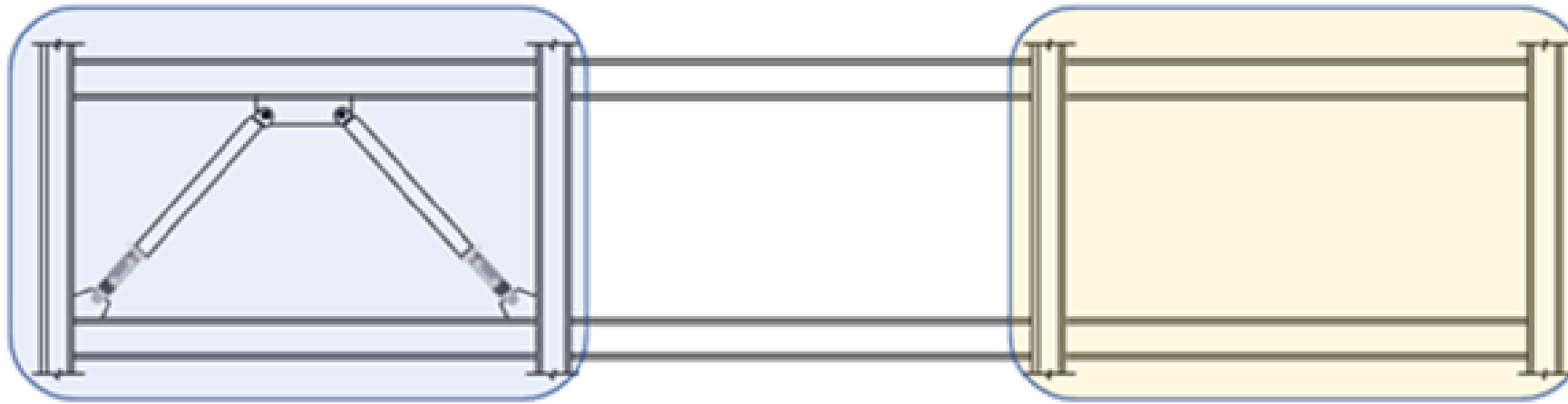
Damper Frame (DF)

- Taylor Fluid Viscous Dampers

- Gusset-to-Gusset Assembly

- Supporting Beams & Columns

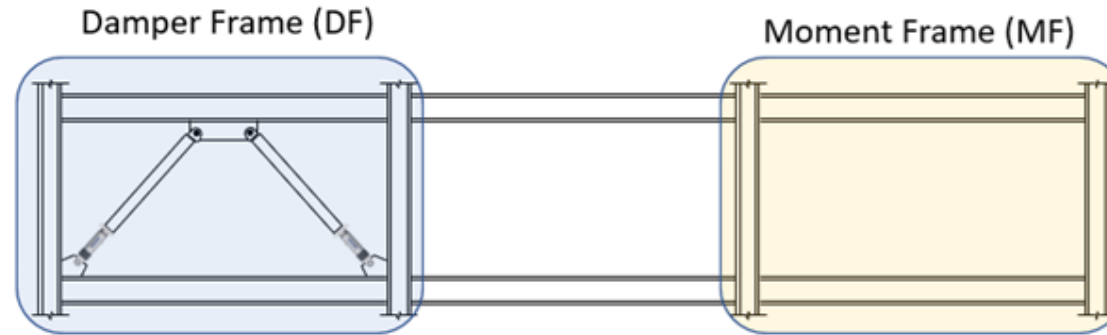- Reduces seismic response through energy dissipation

Moment Frame (MF)

- Steel Special Moment Frame (SMF) in alignment with ASCE 7, AISC 341, 358 & 360.
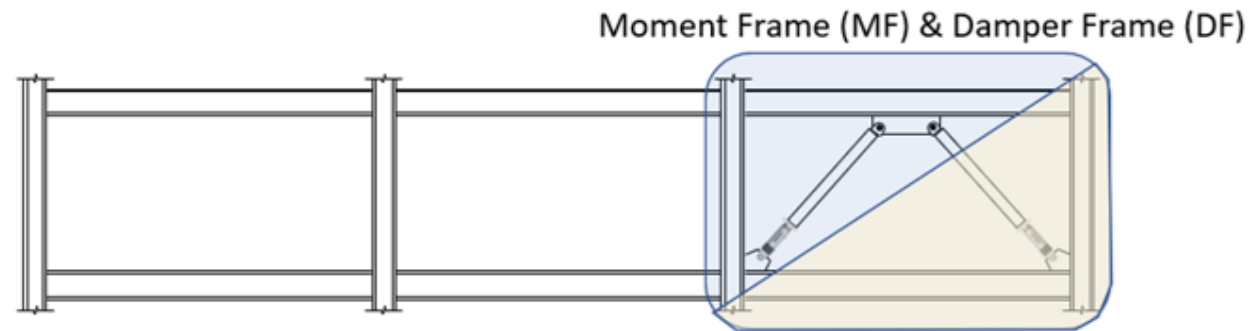
- Serves as main lateral force resisting system

Three main configuration types (elevation)

System Description: Configurations
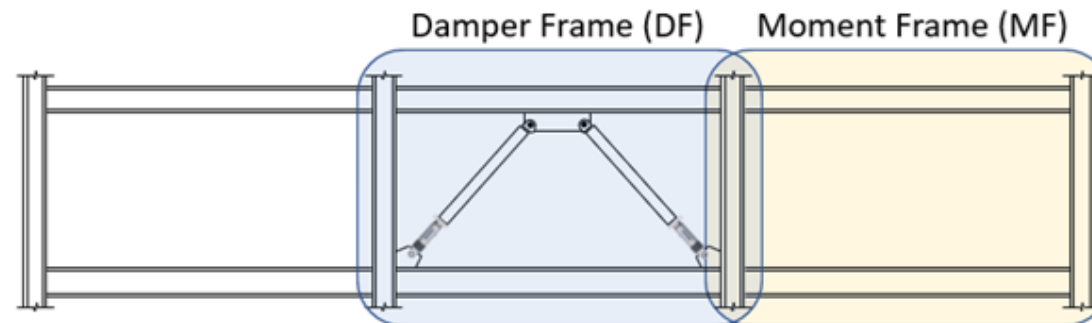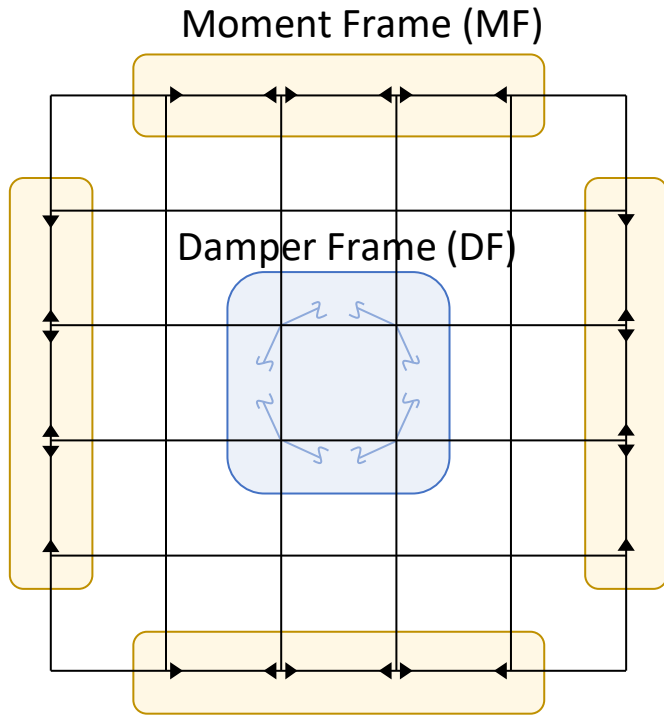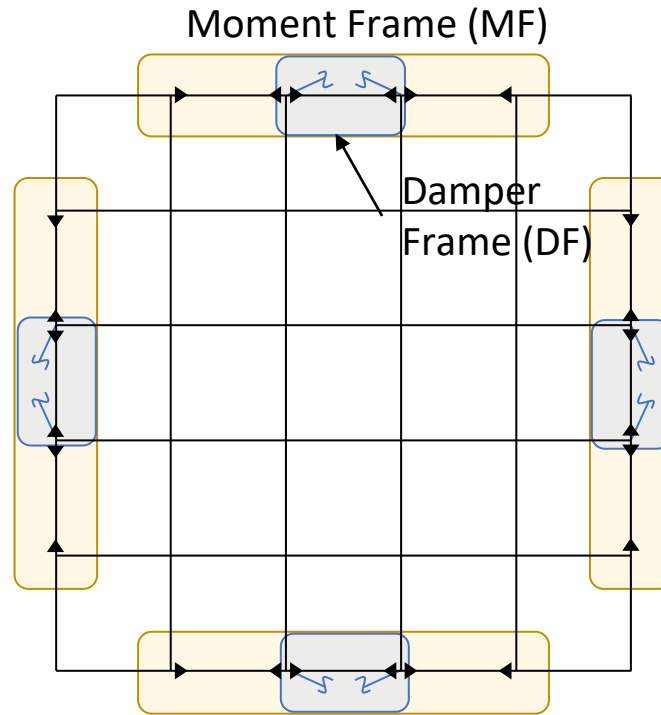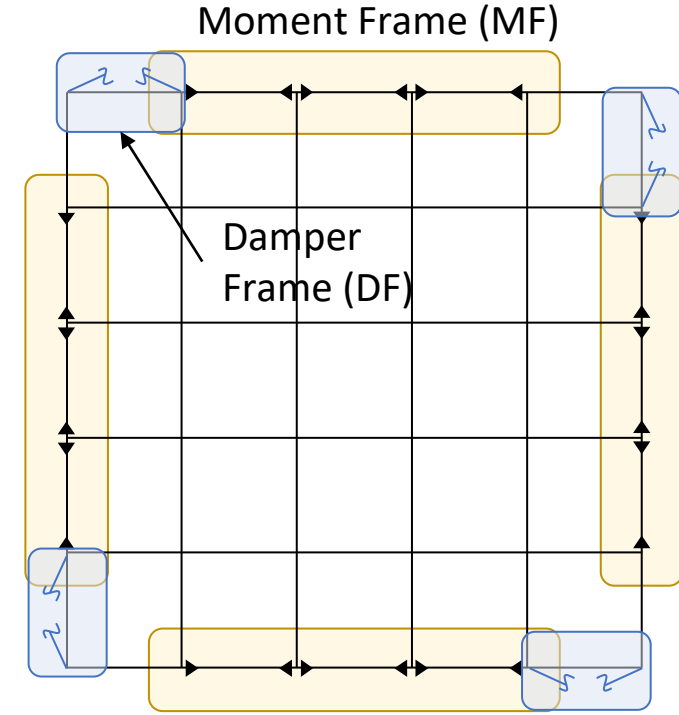
Three main configuration types (plan)

Type I

Type II

Type III

SP3

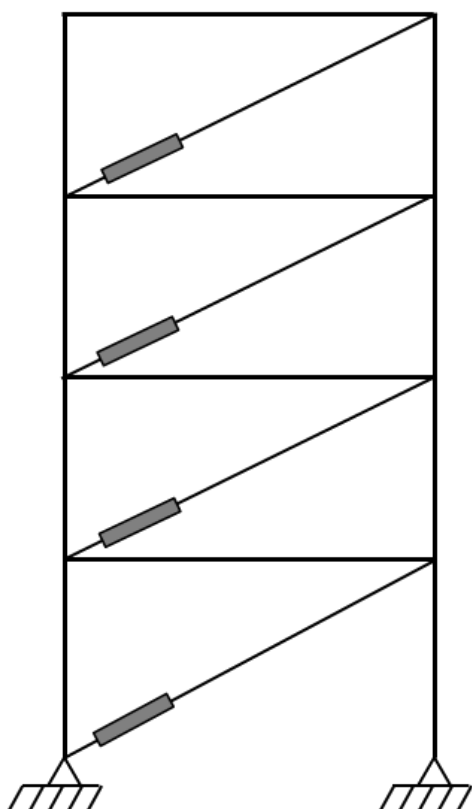- Common DF configurations (others possible)
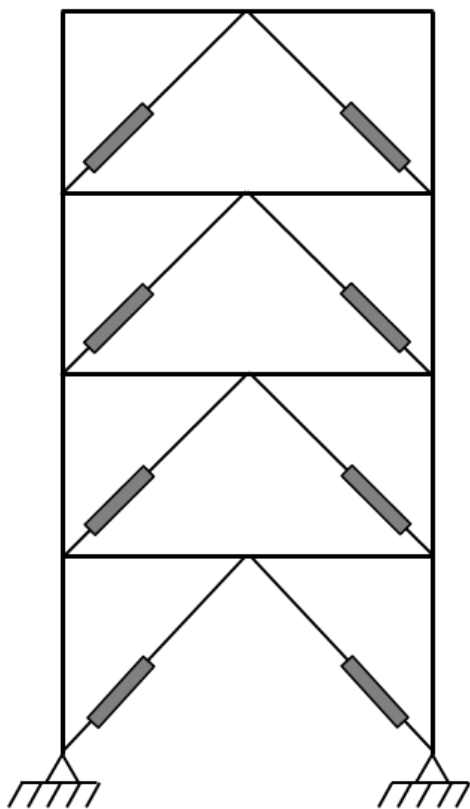
Chevron   Diagonal   2-Story X   MCHD

SP3
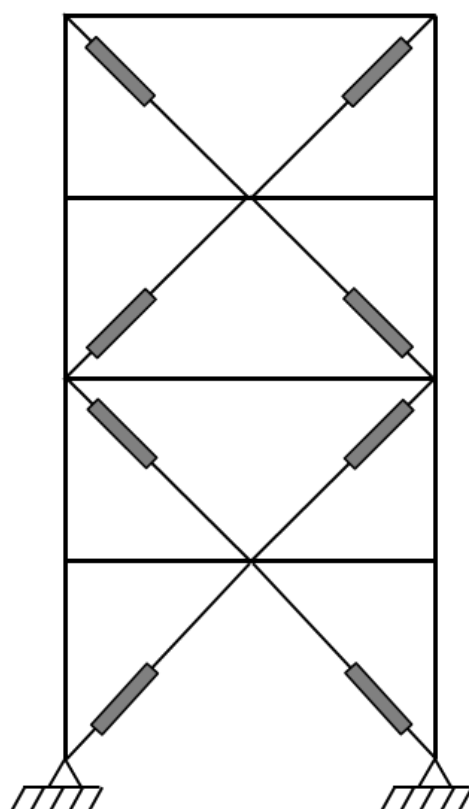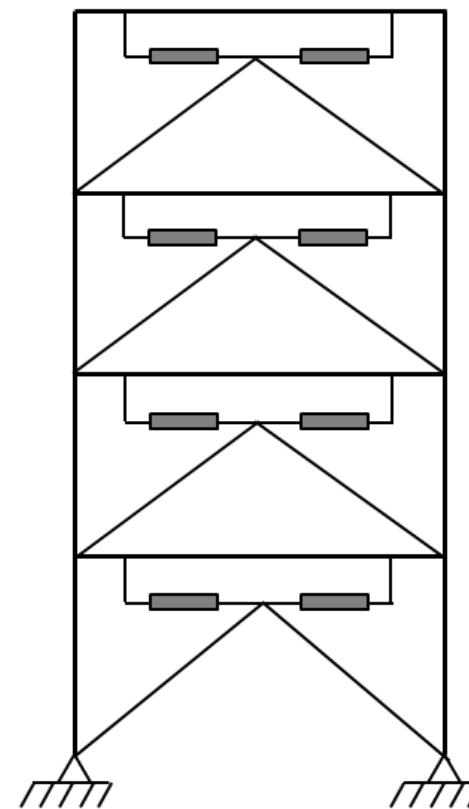
- ## Building configuration requirements
  - Height Limit: 300 ft.
  - Diaphragms not flexible according to ASCE 7 classification
  - At least two dampers in each principal direction at each story above the base, configured to resist torsion
  - Extreme Torsional Irregularity (TIR > 1.4) not allowed

- ## Moment Frame:
  - Steel Special Moment Frame, in accordance with AISC
    - Proprietary connections are allowed!

- ## Dampers: Taylor Devices fluid viscous dampers
  - 25% Damping at DE intensity
  - Damper Force-velocity relationship: $F = CV^\alpha$
    - C = Damping Constant
    - V = Velocity
    - α = Velocity Exponent = 0.4

$$F_{TD} = C(v)^\alpha$$

Force

Velocity, v
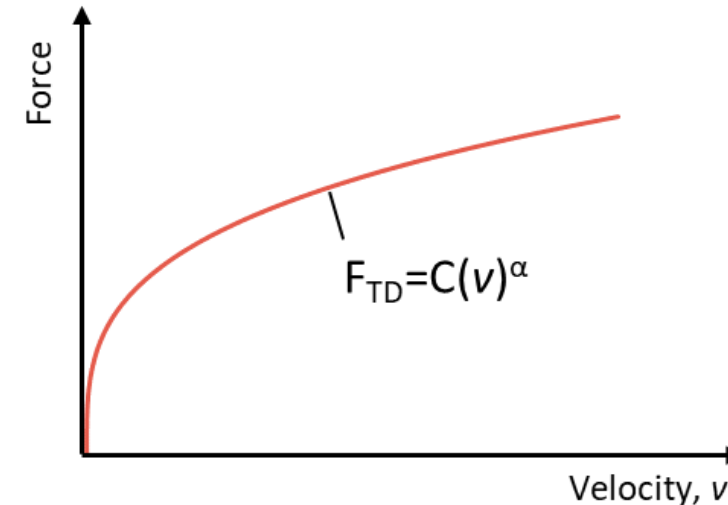
- Objective → Standardized design method that:
  - Is relatively straightforward to execute
  - Does not require a nonlinear model
  - Does not require iteration (beyond the typical MF design process)
  - Does not require peer review
  - Produces building designs that consistently meet ASCE 7 collapse performance objectives
    - And resilient!

- Moment Frames
  - Follow ASCE 7 Chapter 12 linear design procedures as closely as possible
  - <u>Decoupled</u> from the damping system design, to avoid iteration

- Damping System
  - Highly standardized (simple)
  - 25% damping at DE intensity

- **Steel Design Req's: No changes**
  - AISC 341, 358, and 360

- **Loading: ASCE 7 MRSA with the following modifications:**
  - $C_d = 4.5$, $\rho = 1.0$
  - Reduce base shear by 25% (strength)
  - Section 12.8.7 Stability Coefficient: $\theta_{max} = 0.25$
  - New min base shear equation for checking drifts:
    - $C_{s,d} = 0.35 S_{D1}/(R/I_e) \leq 0.5 S_1/(R/I_e)$

- **Note: MF design is <u>decoupled</u> from the DF design**

Ch. 11
Ch. 12
Ch. 13
~~Ch. 18~~
Ch. 20

Damper Frame (DF) Design
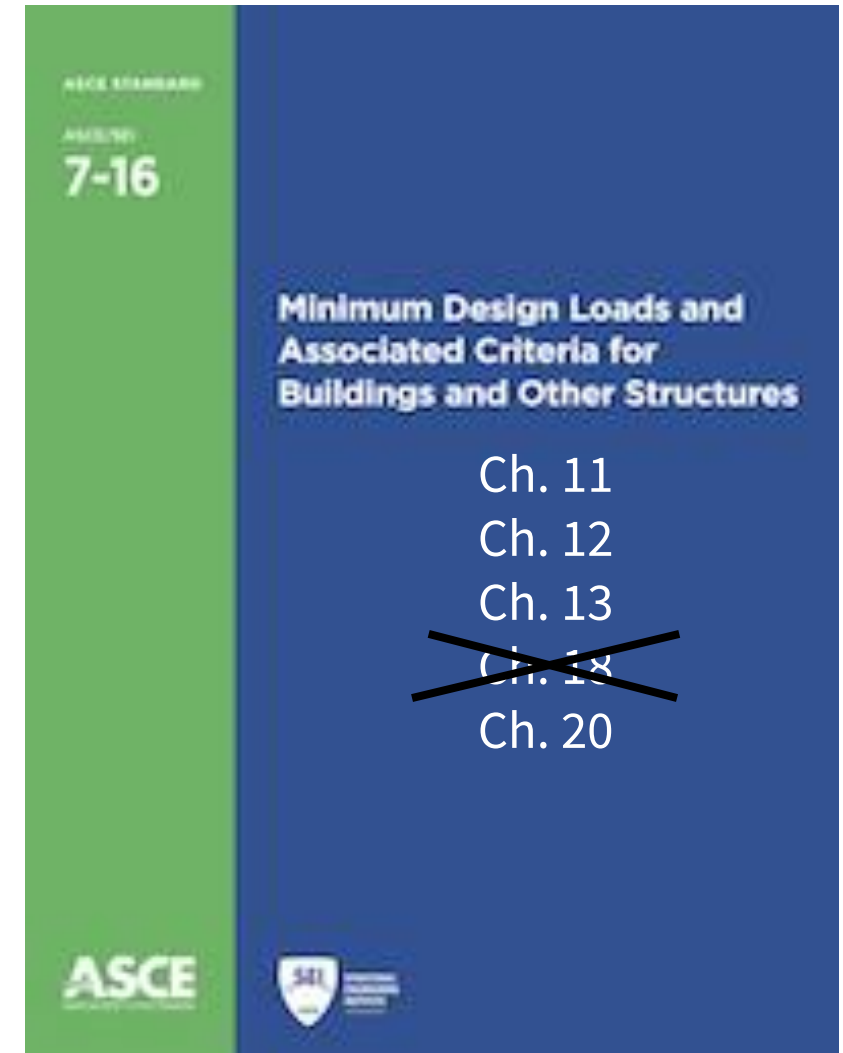
- Damper Frame (DF) is designed based on Moment Frame (MF) response
  - MRSA drift profile
  - Story stiffness from ELF loading
- Damper Properties
  - 25% damping at DE intensity (prescriptive)
  - Amplify stroke capacity to prevent exhausting the stroke in an MCE event
- User overstrength damper forces for capacity-based design of beams, columns, connections, etc.
  - Design process nearly identical to BRB design
- Highly prescriptive and typically no iteration
  - Can be done in minutes with an Excel spreadsheet
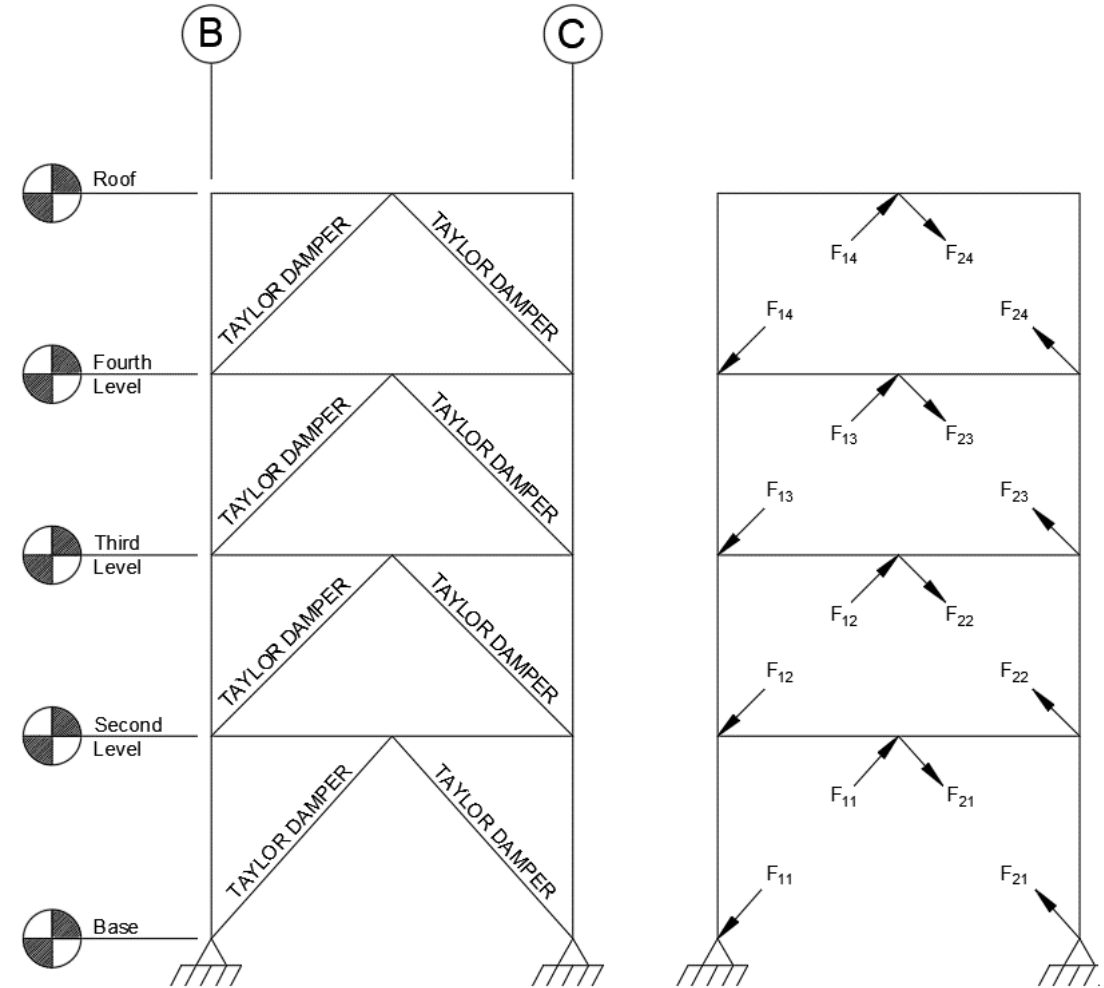
- Portions of foundations that do not require overstrength
  - $E_h = max(E, E_{TD}, \boxed{E \pm 0.7E_{TD}})$
- Shared elements and transfer elements:
  - $E_h = max(E, \boldsymbol{\Omega_F}E_{TD}, E \pm 0.7\boldsymbol{\Omega_F}E_{TD})$

Damper Frame (DF)   Moment Frame (MF)

Shared Column
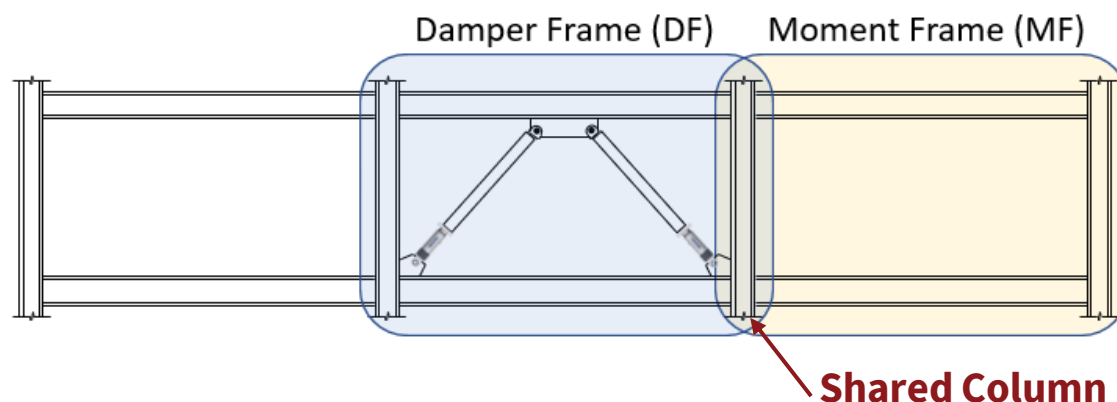
- Shared Elements for which ASCE 7 requires overstrength
  - $E_{mh} = max(\boldsymbol{\Omega_0}E, \boldsymbol{\Omega_F}E_{TD}, \boldsymbol{\Omega_0}E \pm \boldsymbol{\Omega_F}0.7E_{TD})$
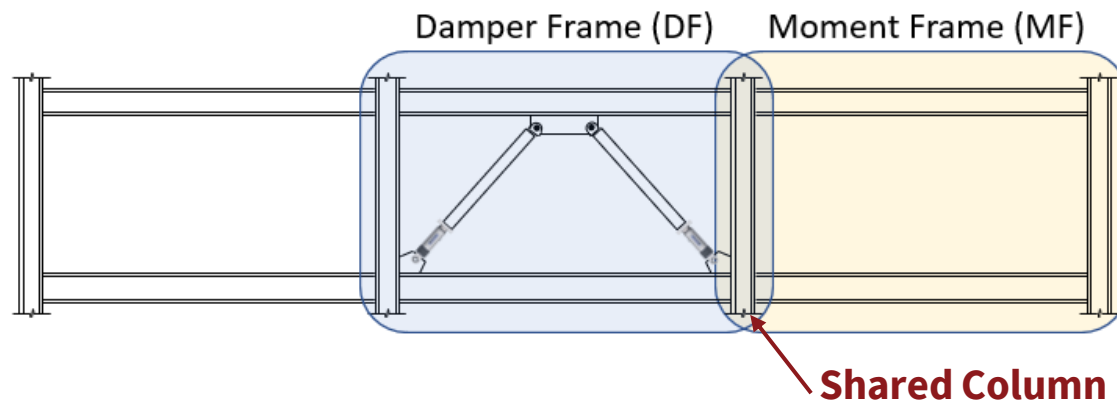
Load Combinations: Actual Notation

- Portions of foundations that do not require overstrength
  - $E_h = max(Q_{MD}, Q_{TD}, Q_{MD} \pm 0.7Q_{TD})$
- Shared elements and transfer elements:
  - $E_h = max(Q_{MD}, \Omega_F Q_{TD}, Q_{MD} \pm 0.7\Omega_F Q_{TD})$

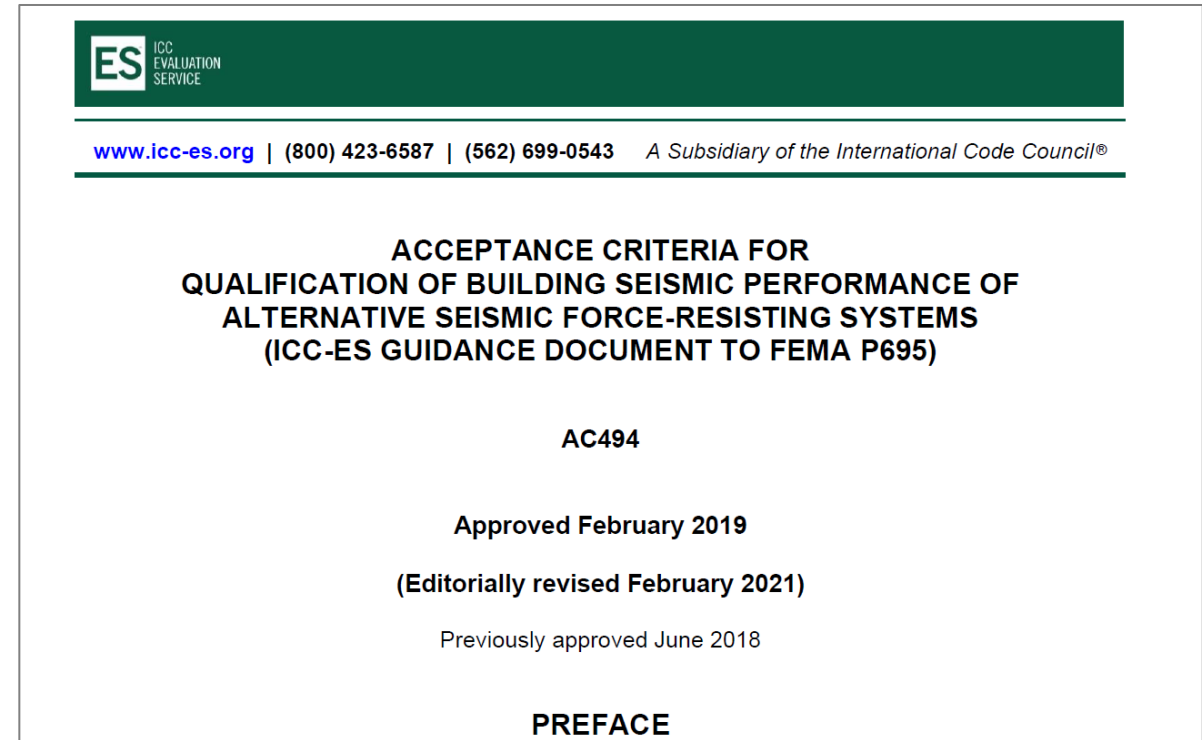Damper Frame (DF)   Moment Frame (MF)

Shared Column

- Shared Elements for which ASCE 7 requires overstrength
  - $E_{mh} = max(\Omega_0 Q_{MD}, \Omega_F Q_{TD}, \Omega_0 Q_{MD} \pm \Omega_F 0.7Q_{TD})$

- **Orthogonal load combination** (e.g. biaxial columns)
  - Damper forces use **100%** in primary direction and **60%** in secondary direction
  - Good practice to do the same for MF members as well

- **Torsion:** Damper induced torsion is handled by modifying the accidental torsion equation in ASCE 7, Ch. 12
  - $M_{ta,TDMF} = \underbrace{0.05L * V_{MD,i}}_{\text{ASCE 7 Accidental Torsion}} + \underbrace{0.7 * e_{TD,i} * V_{TD,i}}_{\text{Damping induced torsion}} * \underbrace{\left(1 - \frac{r_{TD,i}}{L}\right)^2}_{\substack{\text{Factor for DF torsional} \\ \text{resistance (0.25 to 1.0)}}}$

- <u>Summary</u>: "Show through nonlinear time history analysis of a suite of archetype designs that the design procedure produces buildings that satisfy ASCE 7 collapse resistance targets"

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**ACCEPTANCE CRITERIA FOR
QUALIFICATION OF BUILDING SEISMIC PERFORMANCE OF
ALTERNATIVE SEISMIC FORCE-RESISTING SYSTEMS
(ICC-ES GUIDANCE DOCUMENT TO FEMA P695)**

AC494

Approved February 2019

(Editorially revised February 2021)

Previously approved June 2018

PREFACE

Part 4: AC494 / FEMA P-695 System Validation

- Summary: "Show through nonlinear time history analysis of a suite of archetype designs that the design procedure produces buildings that satisfy ASCE 7 collapse resistance targets"
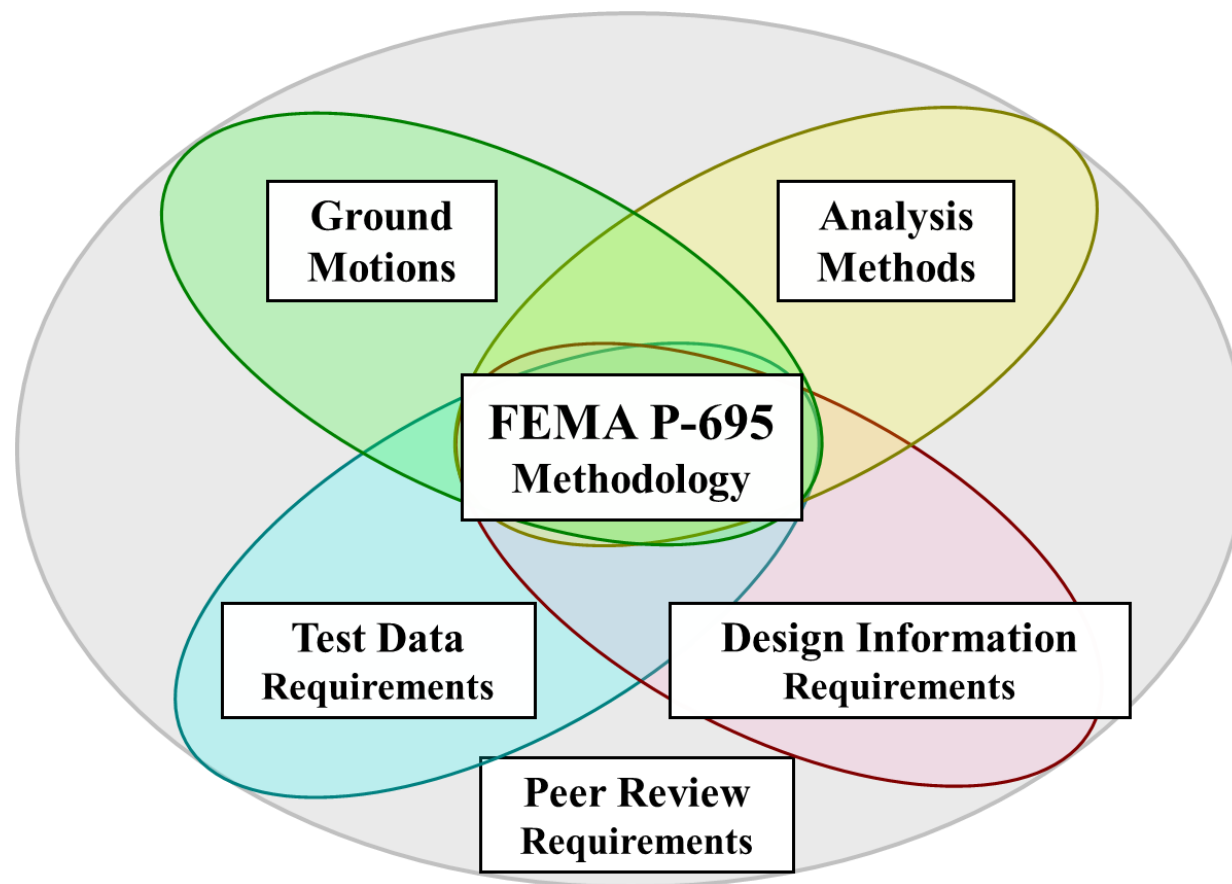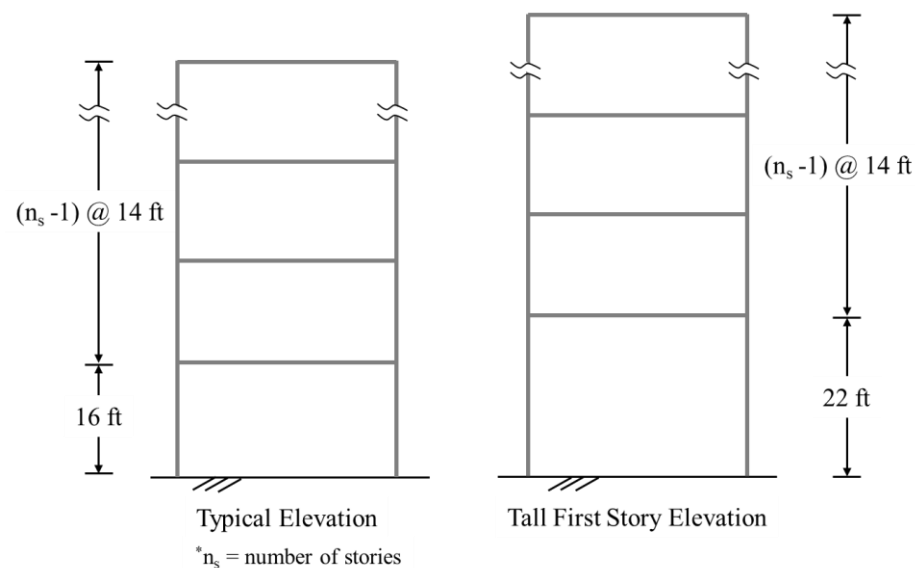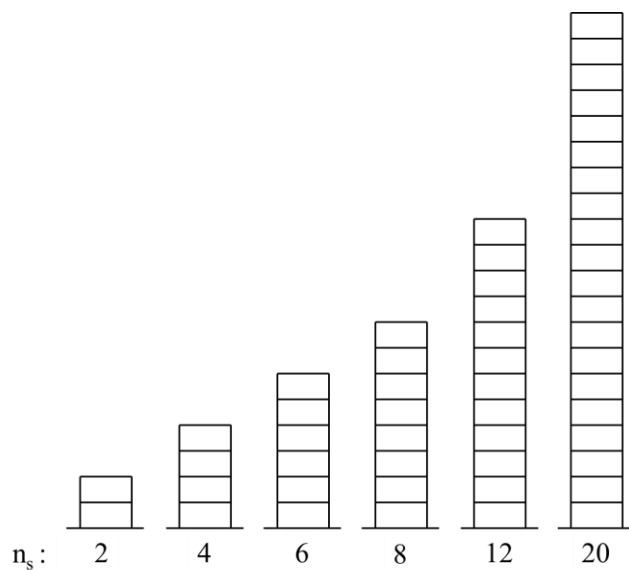
Archetype Design Space

- Approximately 100 designs
- Typically 180 ft by 120 ft in plan
- 2- to 20-story
- Typical story heights are 14 ft with 1st story heights of 16 ft or 22 ft
- Mostly perimeter frames, some space frames

n_s: 2   4   6   8   12   20

$(n_s -1)$ @ 14 ft

16 ft

Typical Elevation

$(n_s -1)$ @ 14 ft

22 ft

Tall First Story Elevation

*n_s = number of stories

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Archetype Design Space

- Bay lengths: 25 ft, 30 ft, 35 ft

- Moment Connections:
  - Reduced Beam Section (RBS) with doubler plates
  - RBS without doubler plates
  - Welded Unreinforced Flange – Welded Web (WUF – W)
  - SidePlate ® Connections

- Damper Configurations:
  - Chevron
  - Diagonal
  - 2-Story X
  - Modified Chevron
   with Horizontal Dampers (MCHD)
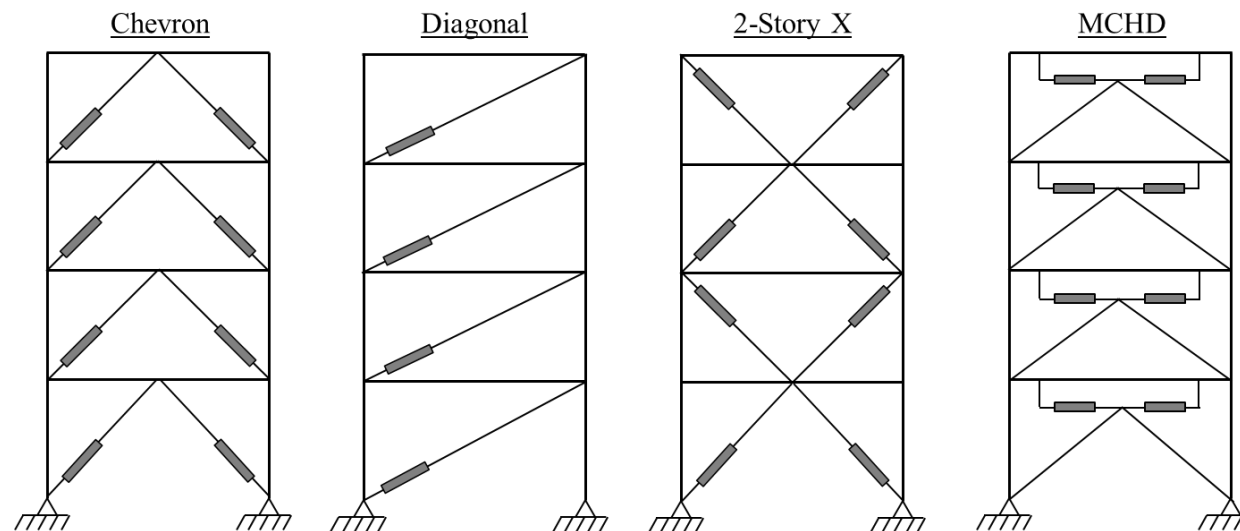
Archetype Design Space

- Seismic Design Category (using P-695 classification):
    - SDC D_{max} (S_{DS} = 1.0, S_{D1} = 0.6) (required by AC494)
    - SDC D_{min} (S_{DS} = 0.5, S_{D1} = 0.2) (required by AC494)
    - SDC E (S_{DS} = 1.5, S_{D1} = 1.0) (*not* required by AC494)

- Risk Category:
    - RC II (required by AC494)
    - RC IV (*not* required by AC494)

Nonlinear Modeling (just a glimpse)

- Lumped plasticity models (*OpenSees*):
  - Modeling assumptions are in line with the ATC-114/NIST Guidelines (NIST, 2017)
  - MF behavior based on experimental testing (Lignos *et al.* 2019; Skiadopoulos *et al.* 2021)
  - Viscous damper assemblies capture theoretical dissipation and stiffness characteristics
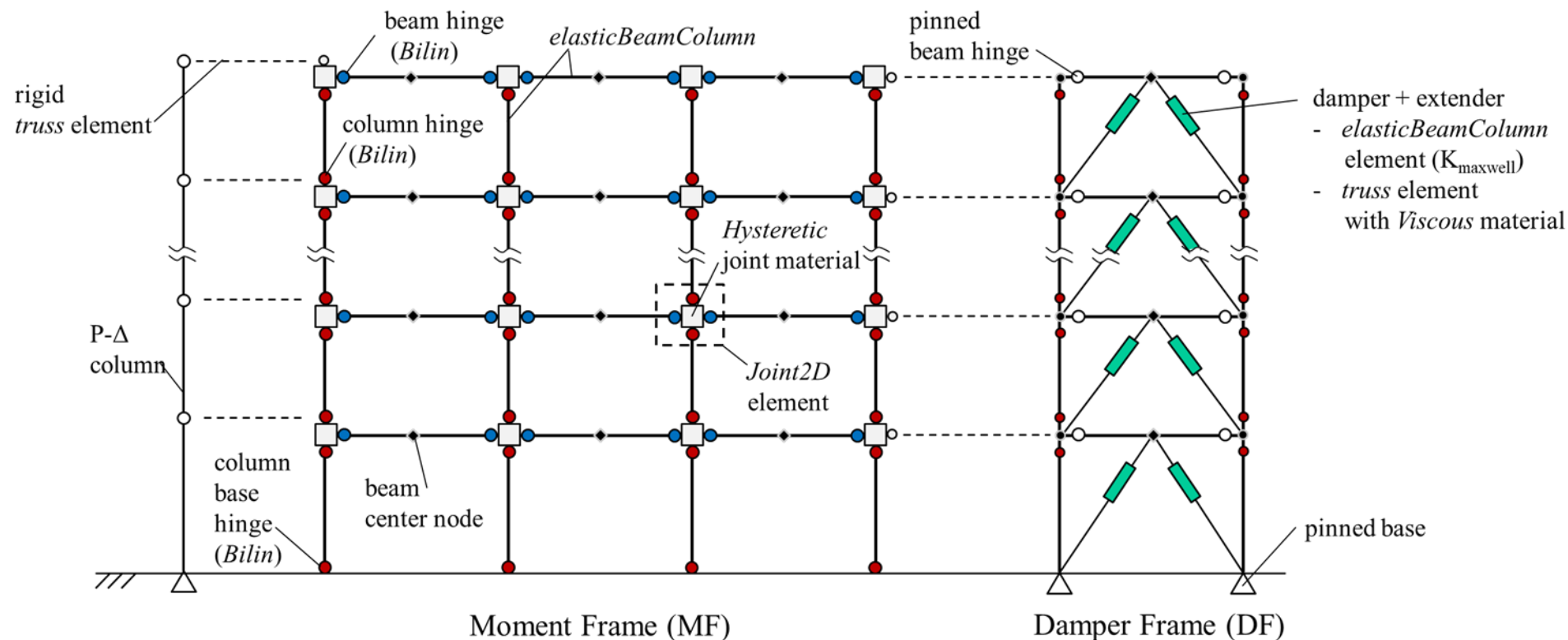
P-695: Incremental Dynamic Analysis and Acceptance Criteria

- Archetypes assembled into performance groups (i.e., number of stories and SDC)
- Acceptance Criteria:
  - < 10% probability of "Collapse" at MCE for *average* of performance group
  - < 20% probability of "Collapse" at MCE for *individual* archetypes within performance group
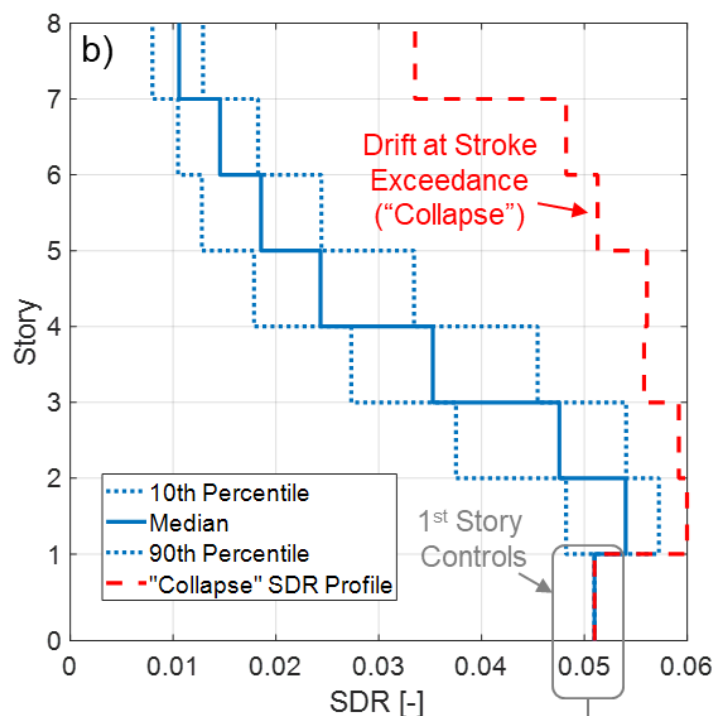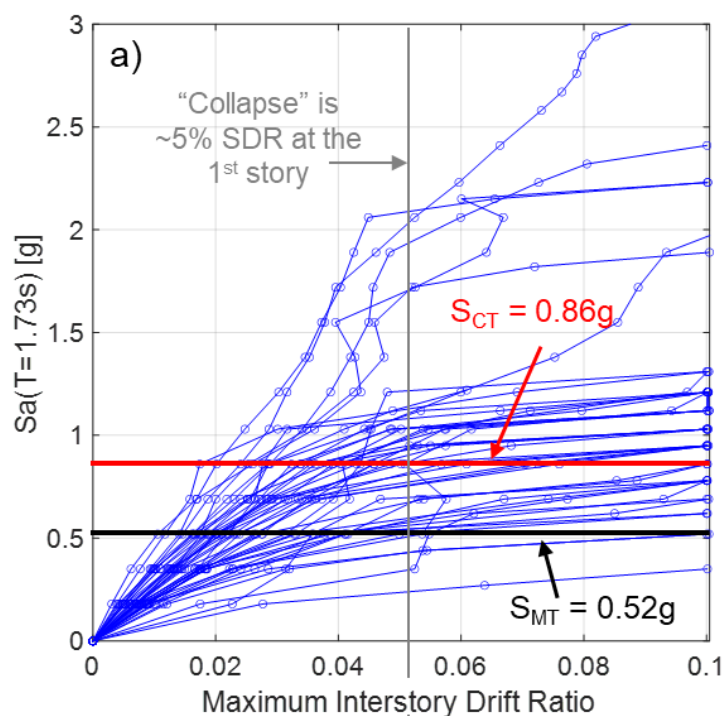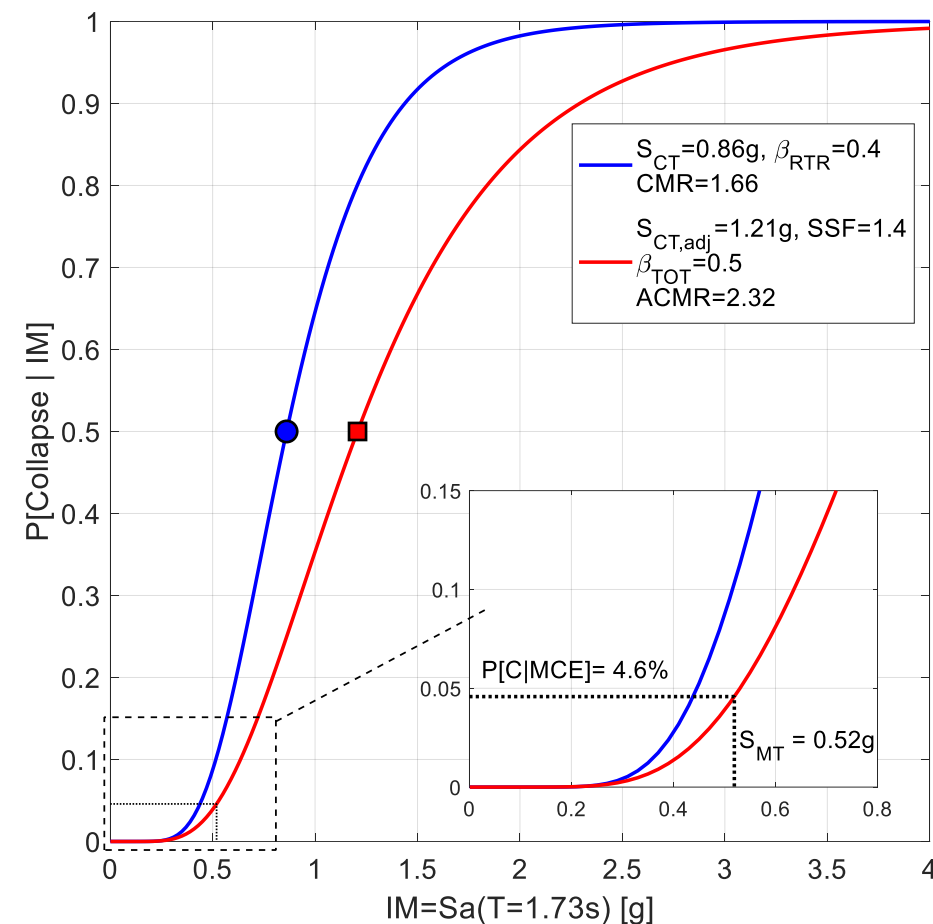

"Collapse" is defined as the intensity that causes the first provided damper stroke to be exceeded

S_{CT} = Median Collapse Intensity
S_{MT} = MCE intensity
S_{CT}/S_{MT} = Collapse Margin Ratio (CMR)

## P-695: Incremental Dynamic Analysis and Acceptance Criteria

- Ground motion suite considers 22 horizontal accelerogram pairs (P-695 far-field set)

- Stroke exceedance considered as collapse:
  - Non-simulated collapse mode per P-695
  - Conservative assumption
  - Avoids calibrating models to capture "bottoming out" behavior
  - Allowed the use of the stroke amplification factor to be adjusted to achieve target performance within design procedure

- Classic collapse mechanisms (e.g., global sidesway) capture, though none controlled

$S_{CT}=0.86g, \beta_{RTR}=0.4$
CMR=1.66

$S_{CT,adj}=1.21g, SSF=1.4$
$\beta_{TOT}=0.5$
ACMR=2.32

P[C|MCE]= 4.6%

$S_{MT} = 0.52g$

IM=Sa(T=1.73s) [g]

P[Collapse | IM]

Red line considers Spectral Shape Factor

Part 4: AC494 / FEMA P-695 System Validation
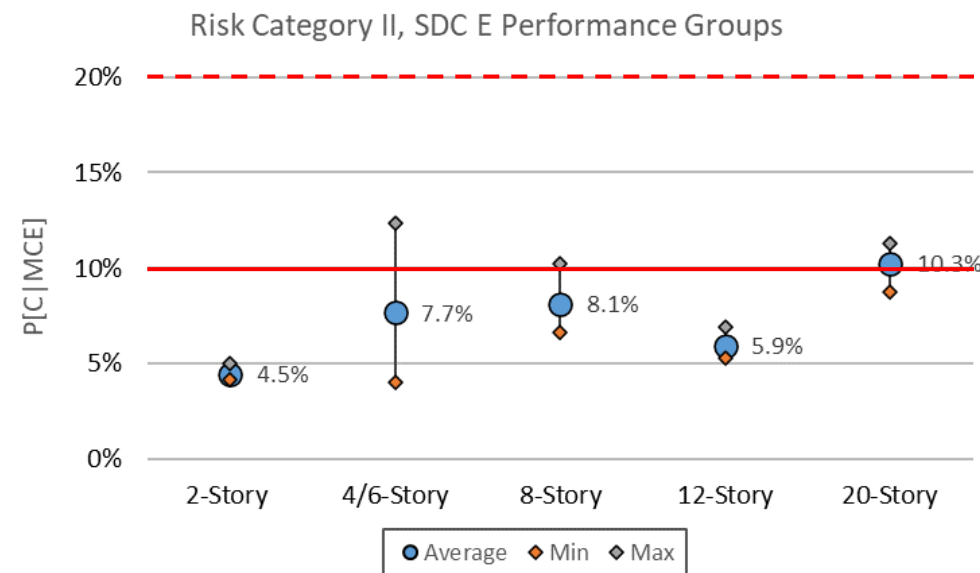
Results Summary

- TDMF designs meet the AC494 / FEMA P-695 collapse performance requirements
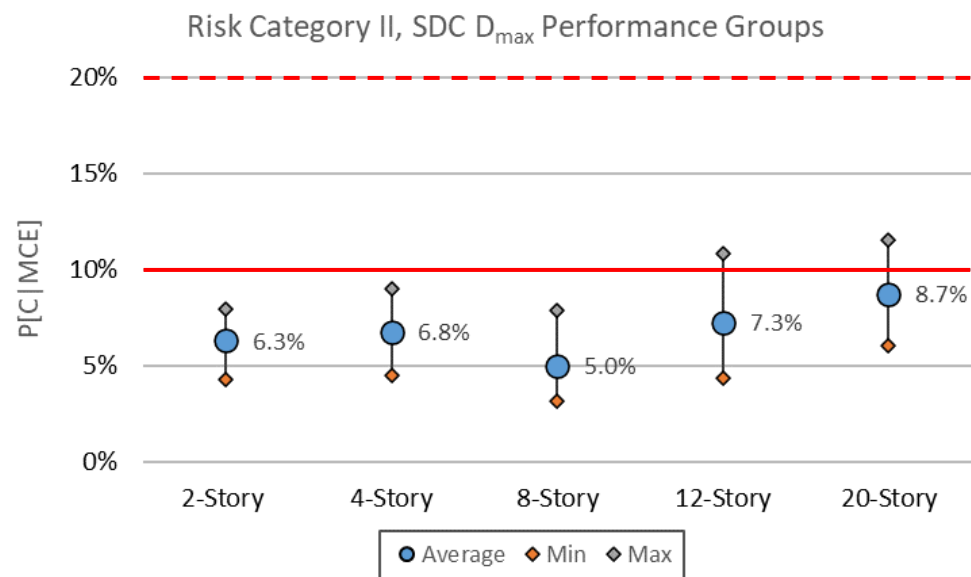
SDC D$_{max}$ (S_{DS} = 1.0, S_{D1} = 0.6)
(required by AC494)
70 archetypes

SDC E (S_{DS} = 1.5, S_{D1} = 1.0)
(**not** required by AC494)
22 archetypes

Structural Properties

- Large data set from AC494 study (~100 archetypes) used to assist in structural property trends:
  - Properly calibrating design model periods (before including nonstructural and gravity system contributions)
  - Obtaining realistic strength to weight ratios for the TDMF system
- TDMF design procedure used to modify automated MF design procedure in SP3
  - Revised base shear requirements
  - C_d = 4.5 (compared to 5.5 for SMF)
- TDMF procedure used for global and local damping system properties:
  - Required story level damping coefficients
  - Individual damper properties estimated based on configuration and structural properties
  - Appropriate damper fragility selection
- SP3 updated to include specific user-inputs:
  - Damper configuration (e.g., chevron, diagonal, modified chevron with horizontal dampers)
  - Damper frame bay length

Structural Response Prediction Engine

- Subset of AC494 archetypes reanalyzed without supplemental damping to compare response reduction with other code-based reduction factors (i.e., ASCE 7 Ch. 18)

- Effective damping ratios consider both frequency and intensity dependencies:

  - 25% supplemental damping assumed at the DE level and at the design model T_1

  - Nonlinear viscous dampers can provide effective damping ratios above and below the target DE value depending on the intensity level

  - Changes in fundamental period when considering nonstructural and gravity system effects results in slight changes in effective damping ratio (compared to bare design model period)

Comparison to Undamped Steel SMF

- 8-story steel frame buildings located in Los Angeles (TDMF and SMF variants)
- High seismicity site: S_{DS} = 1.44g, S_{D1} = 1.23g
- 100 ft by 100 ft in plan
- 15 ft first story height, 14 ft typical story height
- Office occupancy assumed
- All nonstructural inventory the same between both system types

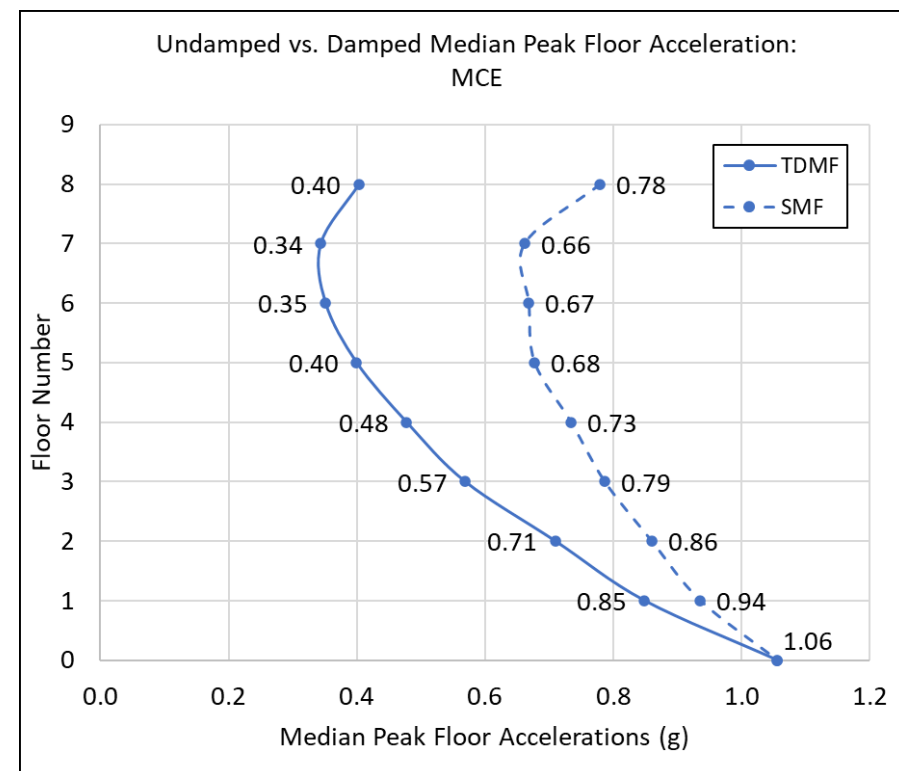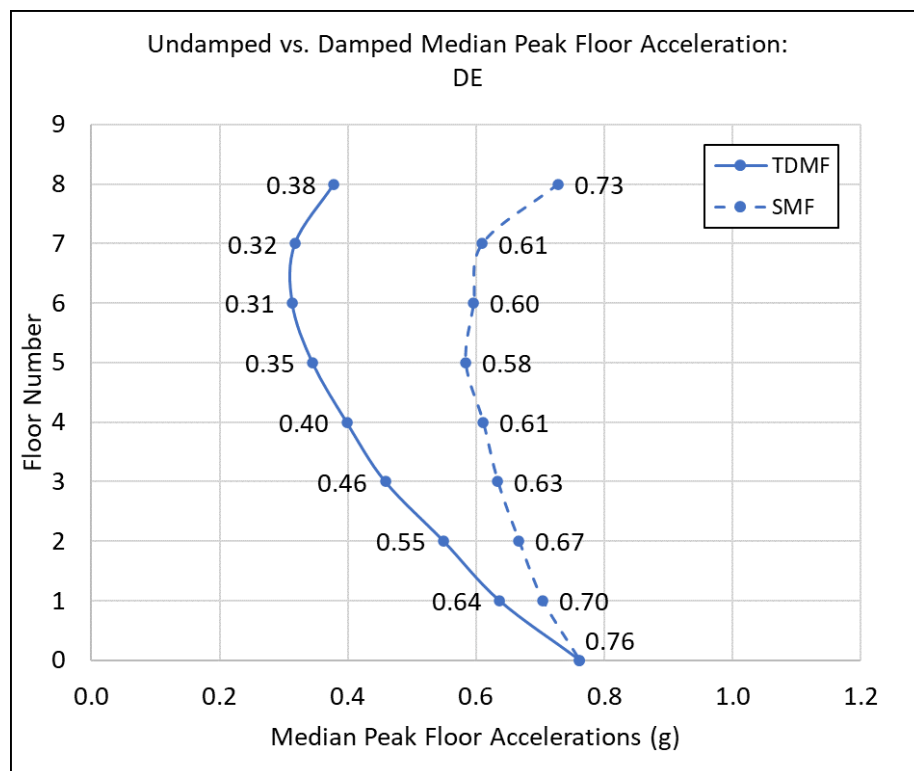## Comparison to Undamped Steel SMF: Structural Properties

- Reduced strength requirements results in TDMF being more flexible with less ultimate strength than an equivalent steel SMF

Structural System	$T_{1,design}$ [s]	$T_{1,final}$ [s]	V_{ult}/W
TDMF	2.30	1.67	0.181
SMF	1.98	1.50	0.226

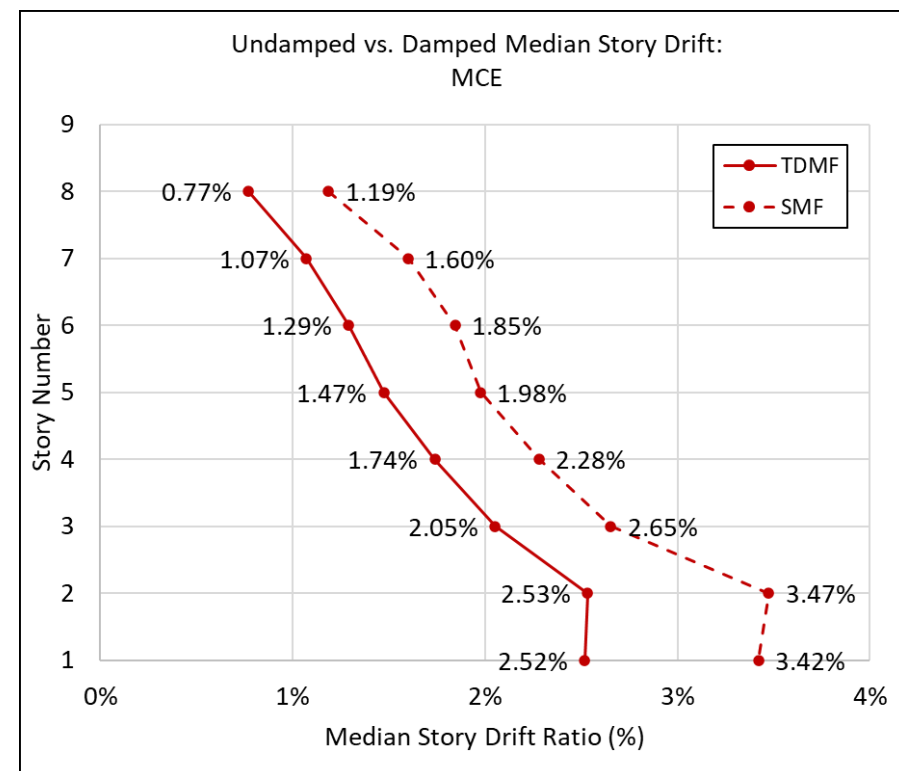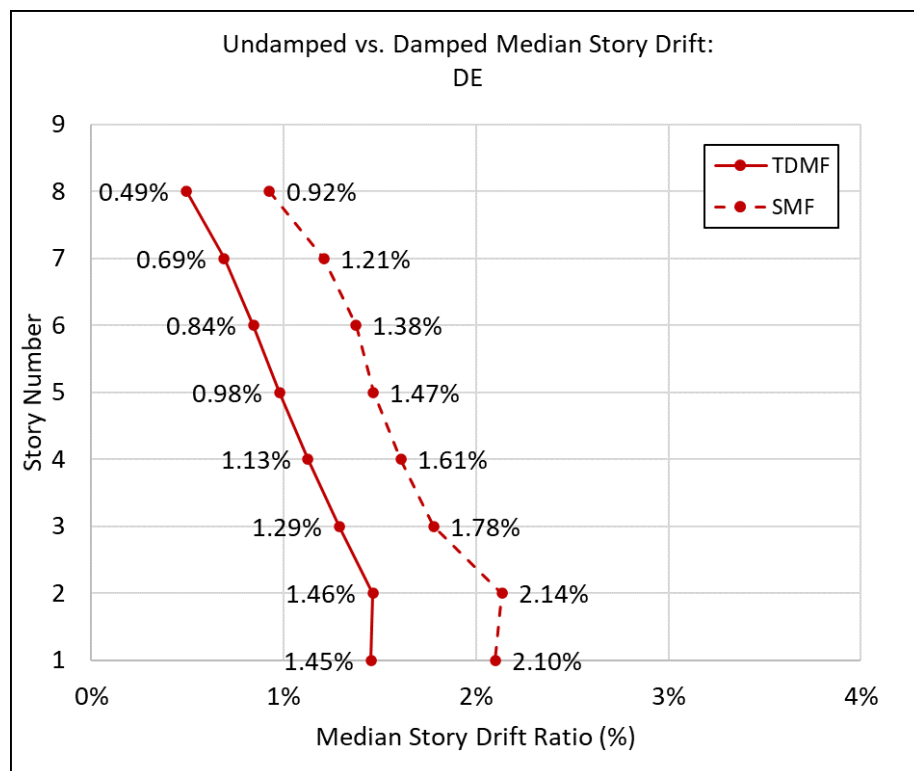## Comparison to Undamped Steel SMF: PFA Responses

- PFA responses are significantly lower for TDMF in the upper stories
- TDMF and SMF are similar in lower stories at high intensity to capture nonlinear demand concentration

Undamped vs. Damped Median Peak Floor Acceleration: DE

Undamped vs. Damped Median Peak Floor Acceleration: MCE
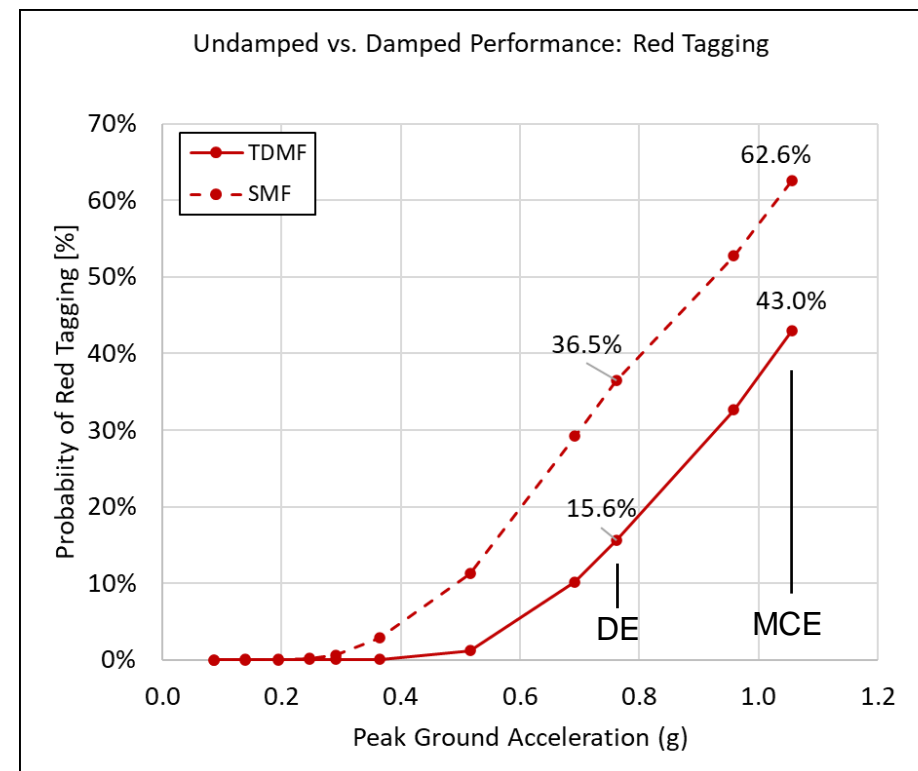
Comparison to Undamped Steel SMF: Story Drift Responses

- Story drift response is consistently lower for TDMF compared to SMF
- Peak story drift ratio is reduced by ~30% comparing TDMF to SMF

Undamped vs. Damped Median Story Drift: DE

Undamped vs. Damped Median Story Drift: MCE

Part 5: TDMF Implementation in SP3

Comparison to Undamped Steel SMF: Performance

- TDMF versus SMF shows significant reduction in mean loss at DE and MCE
- Similar trends are shown for the probability of receiving a red tag

Undamped vs. Damped Performance: Mean Repair Cost

Undamped vs. Damped Performance: Red Tagging

Comparison to Undamped Steel SMF: Recovery
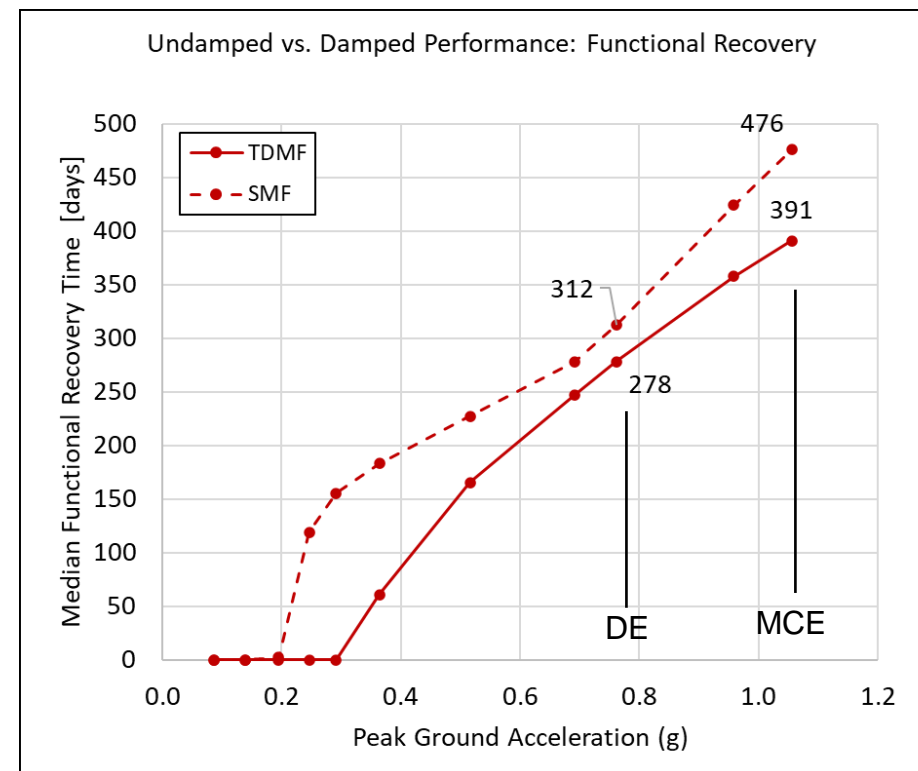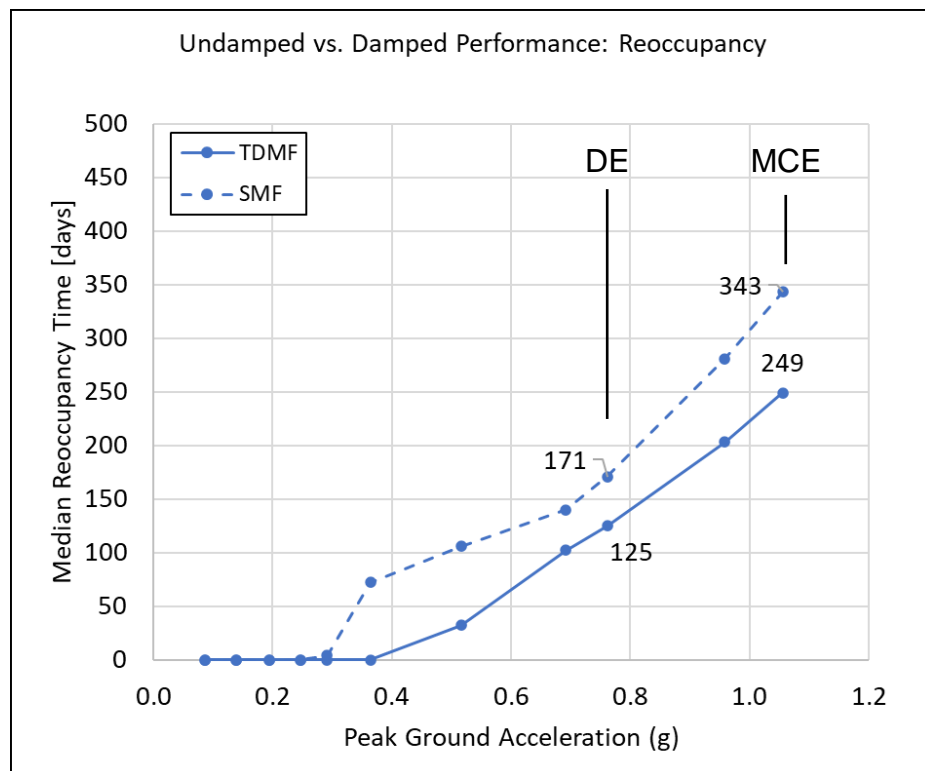
- Onset of non-zero recovery times occurs at larger intensity for TDMF vs SMF
- Largest differences are at moderate seismic intensities

Summary

- The TDMF™ system removes some common barriers for designing steel moment frames with supplemental damping

- The TDMF™ design procedure:

  - Uses ASCE 7 Chapter 12 design methods

  - Decouples the design of the moment frame and the damper frame

  - Does not mandate peer review

- The system has been validated using AC494 and FEMA P-695

- The TDMF™ system has been added to SP3

- Including supplemental damping via the TDMF™ system makes steel moment frames more resilient

Project Participants

- **Project Directors**
  - D. Jared DeBock, PhD, PE
  - Jim Harris, PhD, PE, SE, NAE
- **Project Working group**
  - David P. Welch, PhD
  - D. Jared DeBock, PhD, PE
  - Nathan Canney, PhD, PE
- **Project Advisor**
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- **Moment Frame Design Consultants**
  - Tom Sabol, PhD, PE, SE, RA
  - Henry Burton, PhD, SE
  - Xingquan Guan, PhD

- **Damping Design Consultant**
  - Aaron Malatesta, PE
- **Taylor Devices Management Team**
  - Nathan Canney, PhD, PE – Director of Structural Engineering
  - Stu Buckley – VP of Business Development & Strategy
  - Konrad Eriksen – Structural Products Sales Director
  - Alan Klembczyk - President
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