2022 SEAOC Convention

HYATT REGENCY INDIAN WELLS
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Practical Design Procedure for Steel Moment Frames with Fluid Viscous Dampers

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Outline

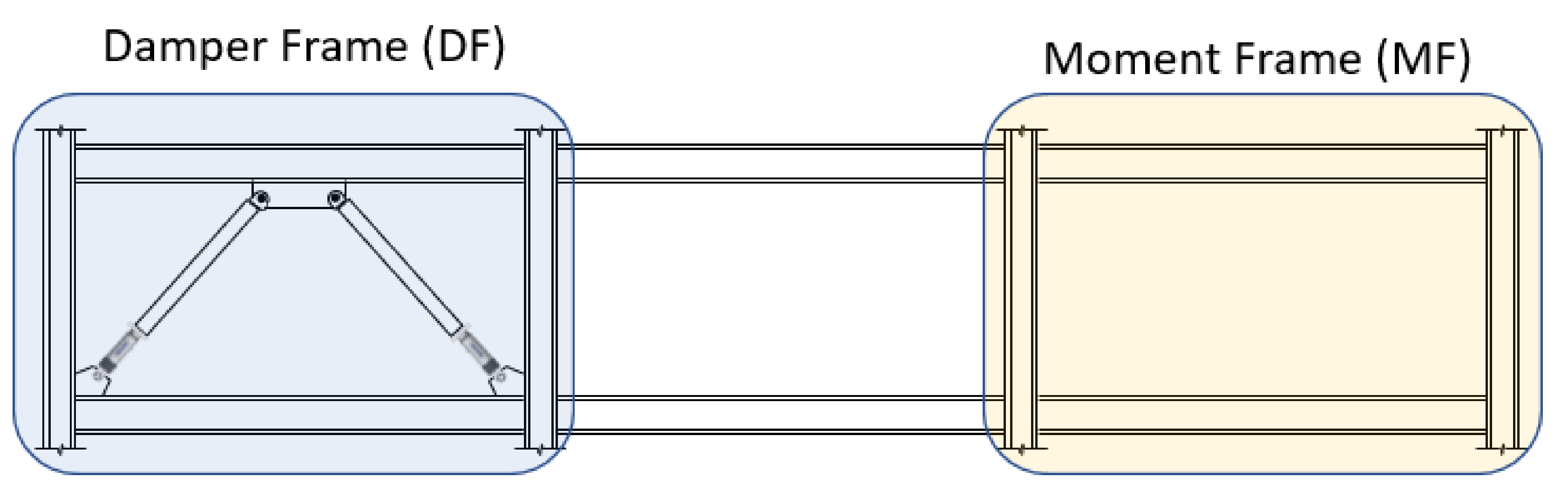
- Motivation for the new TDMF design Methodology
- Summary of the TDMF System and Design Procedure
- Overview of AC 494 and FEMA P-695 system approval process
  - Archetype Design Space for P-695 Assessment
  - Example Application of the P-695 Methodology
- Performance Summary using the new Design Procedure
  - Collapse Performance
  - Comparison to Traditional Steel MRF
- Conclusion

Motivation for A New Design Method

- Current design standards for steel moment frames with supplemental damping (ASCE 7-16)
  - Linear design procedures allowed, but rarely used in practice (Complex/impractical)
  - Nonlinear time history design procedure is most common, but this is a barrier to many design professionals
  - Peer review required

- Objective - Standardized design method that:
  - Is relatively straightforward to execute (based on ASCE 7, ch. 12)
  - Does not require a nonlinear model
  - Reduces design iteration (beyond what is typical for linear design)
  - Does not require peer review
  - Produces building designs that consistently meet ASCE 7 collapse performance objectives (using FEMA P-695 / AC 494)… and resilient!

System Description: General



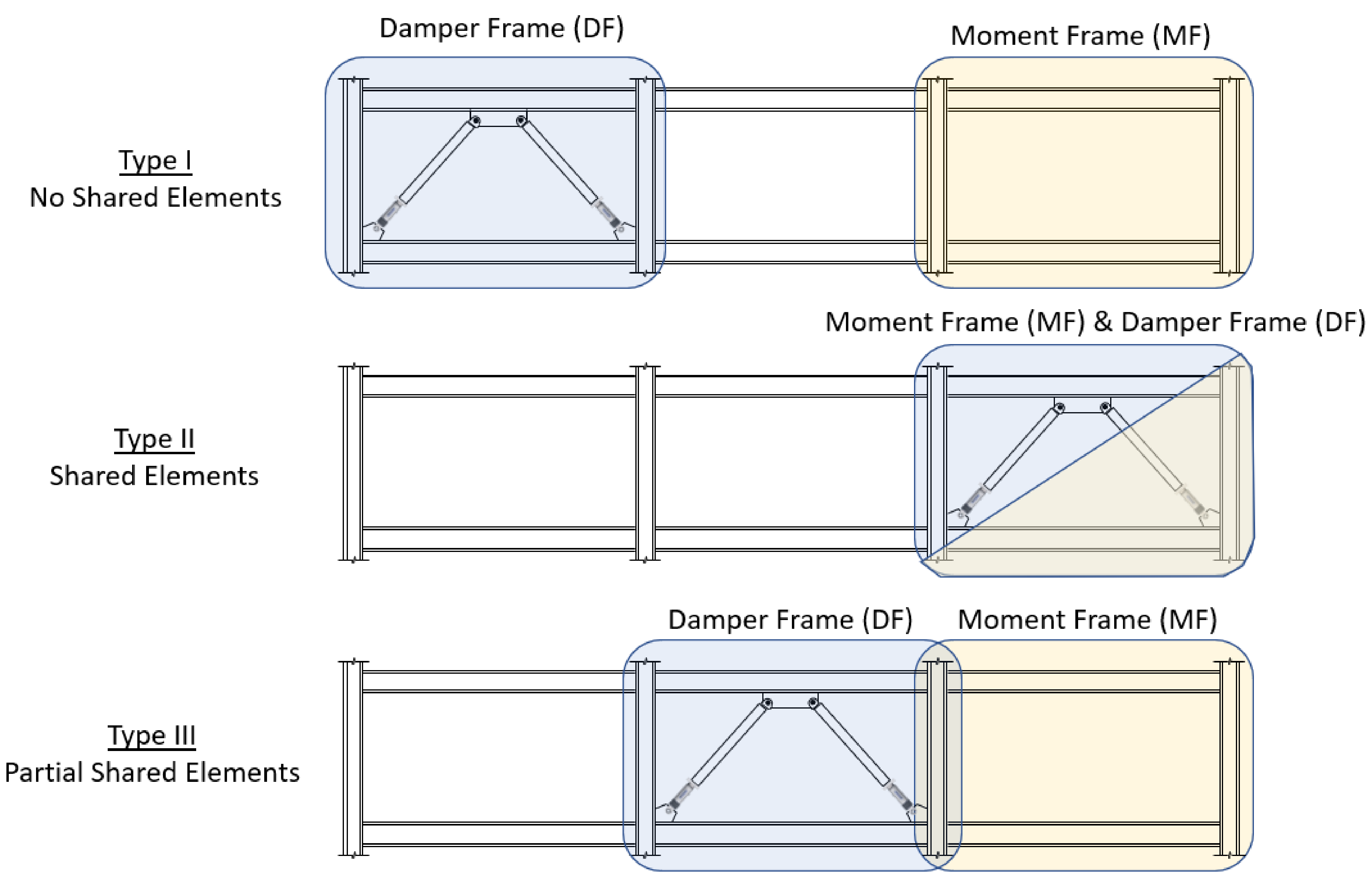
Damper Frame (DF)

- Taylor Fluid Viscous Dampers (FVDs)
- Gusset-to-Gusset Assembly
- Supporting Beams & Columns
- Reduces seismic response through energy dissipation

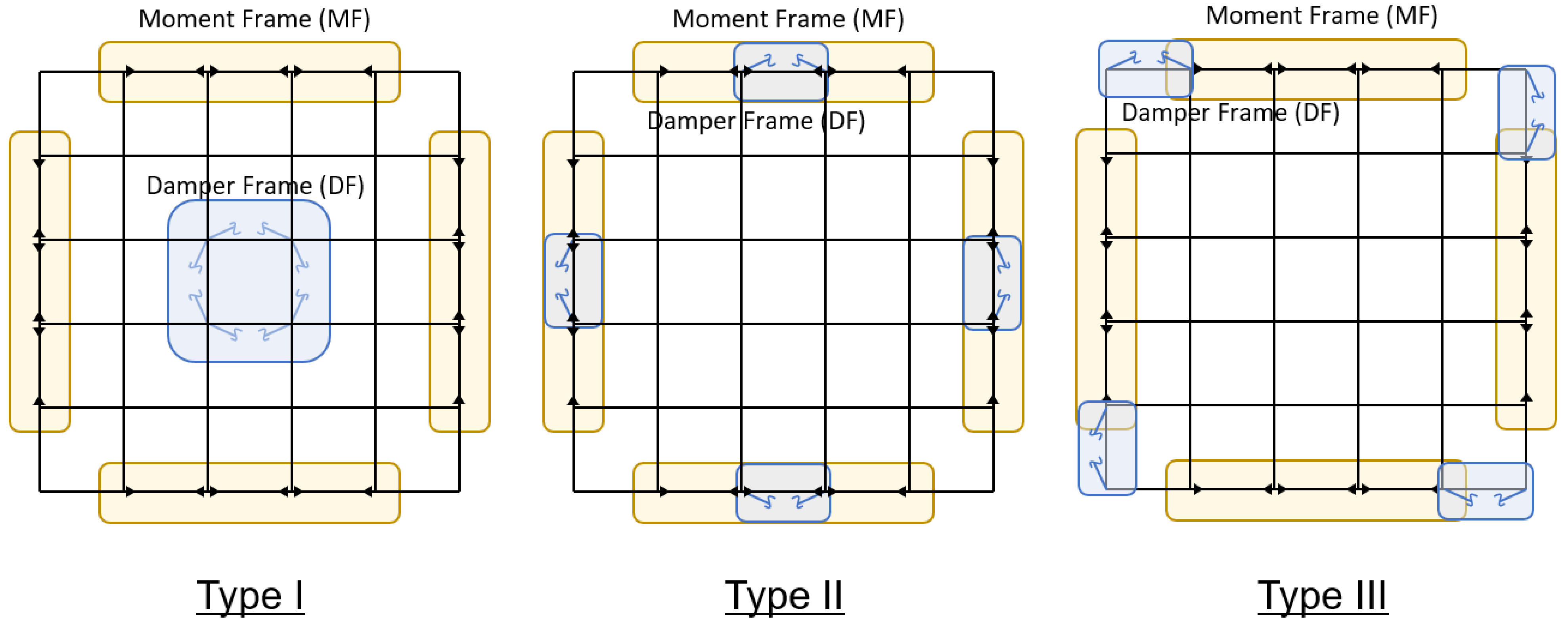
Moment Frame (MF)

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

System Description: Elevation



System Description: Plan



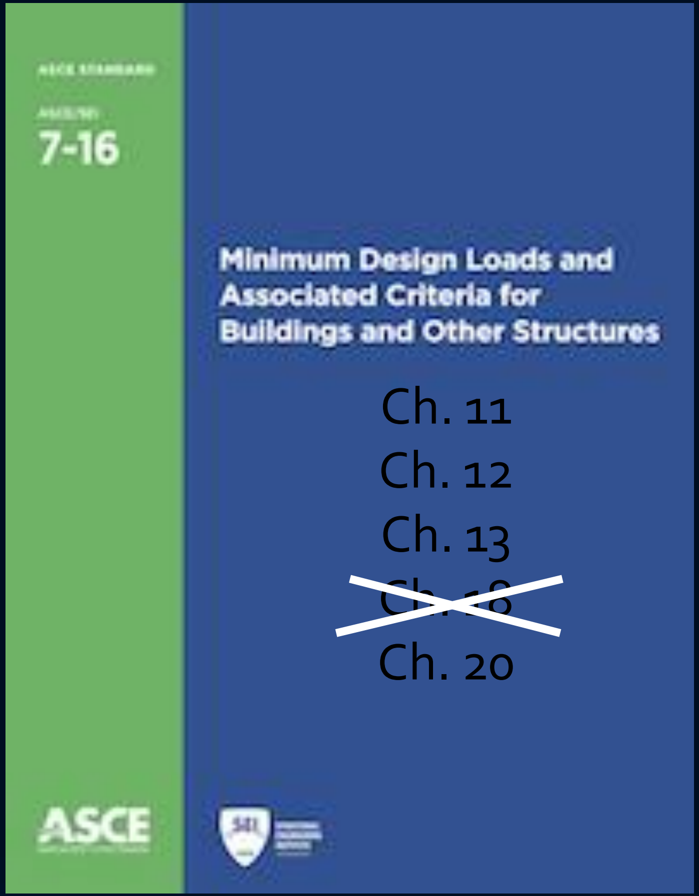
Scope (Limits)

- Building configuration requirements
  - Height Limit: ~20 stories
  - Rigid diaphragms 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 not allowed
- Dampers: Taylor Devices fluid viscous dampers
  - Force-velocity relationship: $F = CV^{\alpha}$
    - C = Damping Constant
    - V = Velocity
    - α = Velocity Exponent (use 0.4)
- Moment Frame:
  - Steel Special Moment Frame, in accordance with AISC

Moment Frame (MF) Design

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

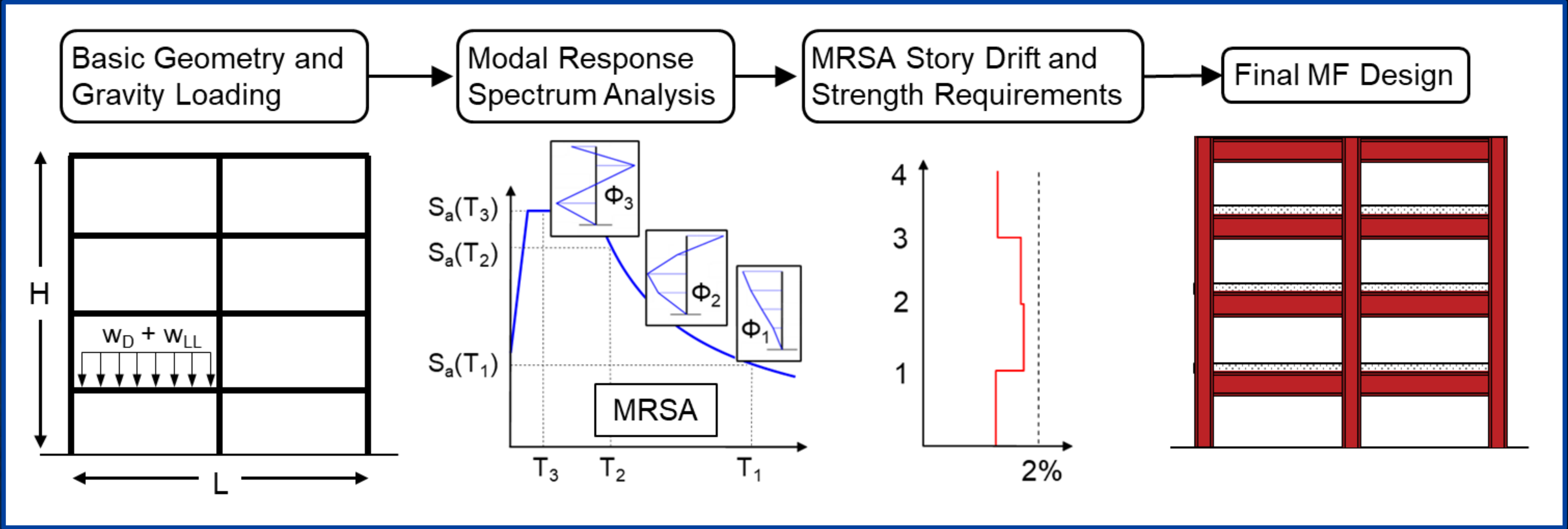
- Loading: ASCE 7 MRSA with the following modifications:
  - Cd = 4.5, ρ = 1.0
  - Reduce base shear by 25% (strength)
  - Section 12.8.7 Stability Coefficient: $\theta_{max} = 0.25$
  - New min base shear equation for checking drifts:
    - $C_{s,d} = 0.35 S_{D1}/(R/I_e) \leq 0.5 S_1/(R/I_e)$



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

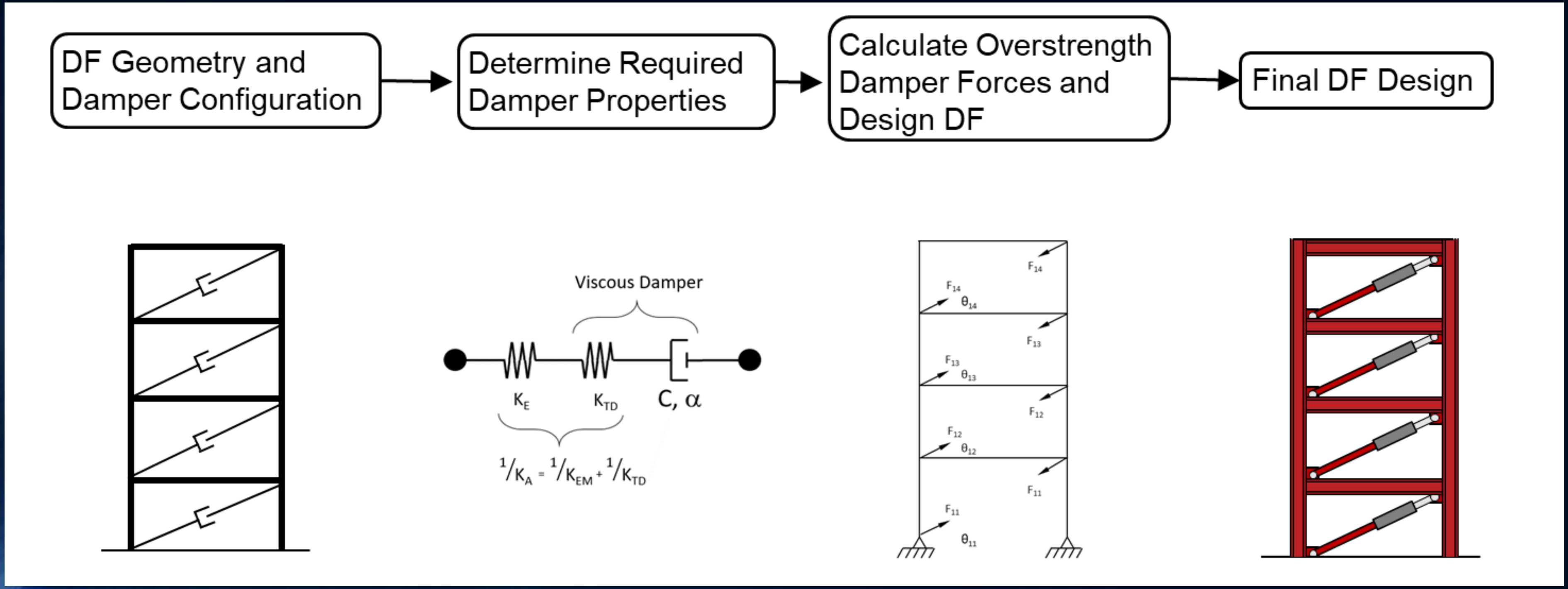
Moment Frame (MF) Design

- Moment Frame (MF) design according to ASCE/SEI 7 Chapter 12
  - Main difference is lower min base shear and Cd = 4.5



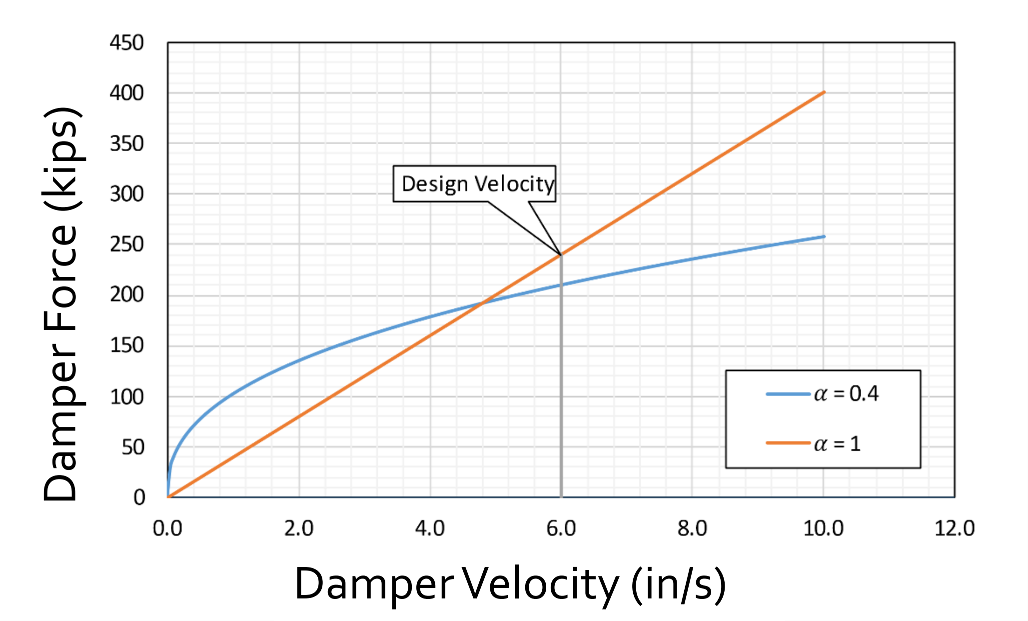
Damper Frame (DF) Design

- Damper Frame (DF) is designed based on Moment Frame (MF) response (MRSA drift profile, story stiffness from ELF loading)
- Highly prescriptive and typically no iteration



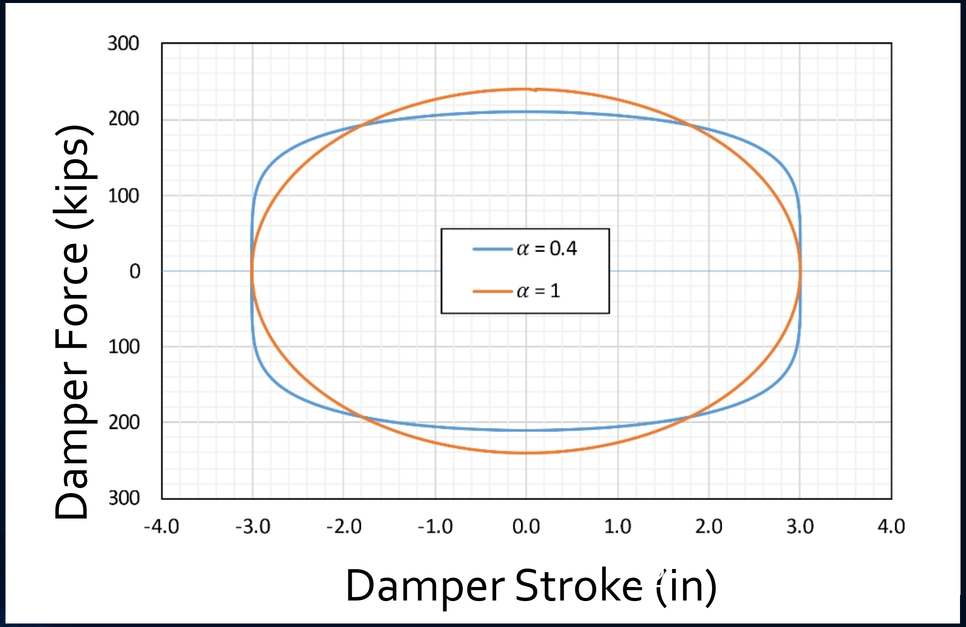
Damper Behavior

- Basic Damper force equation: $F = CV^{\alpha}$
- Damper properties calibrated to provide **<u>25% first mode damping at DE</u>** utilizing stiffness proportional distribution. Two-stage calculation:
  1. Compute a linear damping constant "$C_{(L)}$"
  2. Compute "$C_{(NL)}$" for α = 0.4 and damper velocity at DE



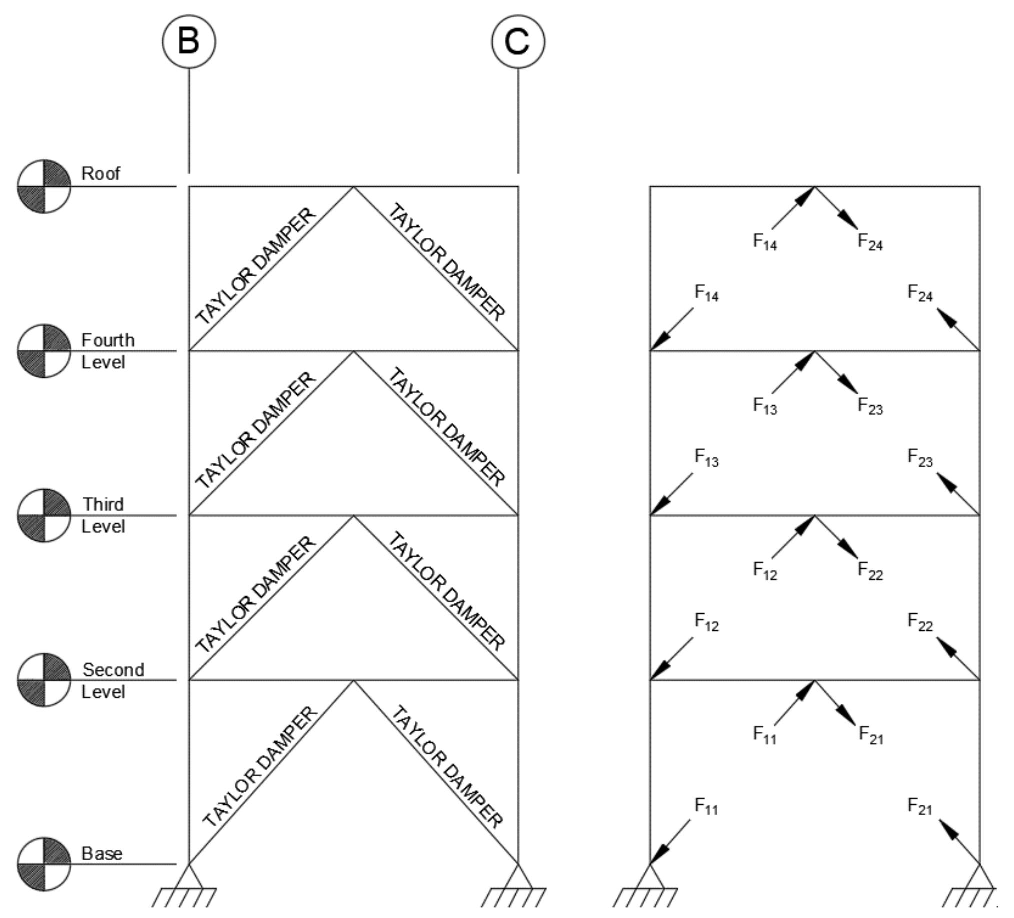
Equivalent Energy Dissipation

At DE Velocity



Damper Frame (DF) Design

- Use Overstrength damper forces for capacity-based design of beams, columns, connections, etc.
- Design process nearly identical to BRB frame
  - Added: Column axial force reduction
- Can be done in minutes with an excel spreadsheet



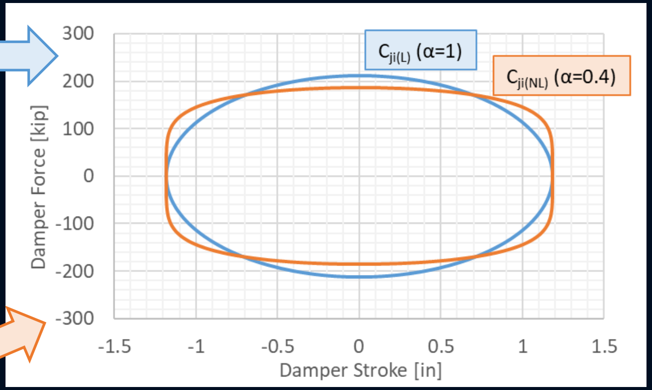
Details of the DF Design Procedure

- Maximum Velocity Stage:
  - $C_{ji(L)} = 0.25\left(\frac{k_i}{N_i}\right)\left(\frac{T_1}{\pi}\right)\left(\frac{1}{\cos^2\theta_{ji}}\right)$ (linear damper constant)
  - $v_{ji} = \omega_1 \cdot d_{ji} \cdot \min\left[1.0, V_t/\left(C_{s,d}W\right)\right]$ (DE velocity for $C_{ji(NL)}$, no V_{min})

    d_{ji} = DE level damper stroke from MRSA of MF
  - $C_{ji(NL)} = C_{ji(L)}\frac{\pi}{\lambda}\left(v_{ji}\right)^{(1-\alpha)}$ (equivalent nonlinear damper constant)

    λ = 3.582 (MCEER-00-0010), α = 0.4
  - Specified nonlinear damping constants allow for smoothing in elevation:

    $0.9\, C_{ji(NL)} \le C_{ji(NL)\text{spec}} \le 1.3\, C_{ji(NL)}$



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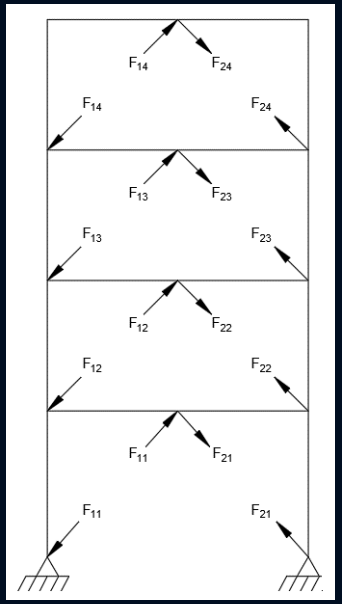
Details of the DF Design Procedure

- <u>Maximum Velocity Stage</u> (Cont'd):
  - $v_{ji}^{*} = A_v \omega_1 d_{ji}$ (DE velocity for damper forces)

    $A_v = 1 + 0.1(n_s - 1)$ (higher mode amplification)
  - $f_{ji} = C_{ji(NL)spec} \left(v_{ji}^{*}\right)^{\alpha}$ (DE damper force)
  - $f_{MCE,ji} = C_{ji(NL)spec} \left(1.5 v_{ji}^{*}\right)^{\alpha}$ (MCE damper force, nominal specified force)
  - $F_{ji} = R_v C_{ji(NL)spec} \left(\Omega_v v_{ji}^{*}\right)^{\alpha}$ (Overstrength damper force, used for DF design)

    $R_v = 1.15$ (accounts for environmental and manufacturing factors)

    $\Omega_v = 2.5$ (overstrength factor on DE velocity)



Details of the DF Design Procedure

- <u>Maximum Displacement Stage</u>:
  - $s_{req} = I_e \Omega_d d_{ji}$ (Required damper stroke in typical stories)

    $d_{ji} = \Delta_{ji}\cos(\theta_{ji})$ (DE level damper stroke from MRSA of MF)

    For SDC D and lower:

$$\Omega_d = \begin{cases} 3.5 & n_s \le 4 \\ 4.0 - (0.125 n_s) \quad \textit{for} & 5 < n_s < 12 \\ 2.5 & n_s \ge 12 \end{cases}$$

("Overstrength" factor for damper strokes)

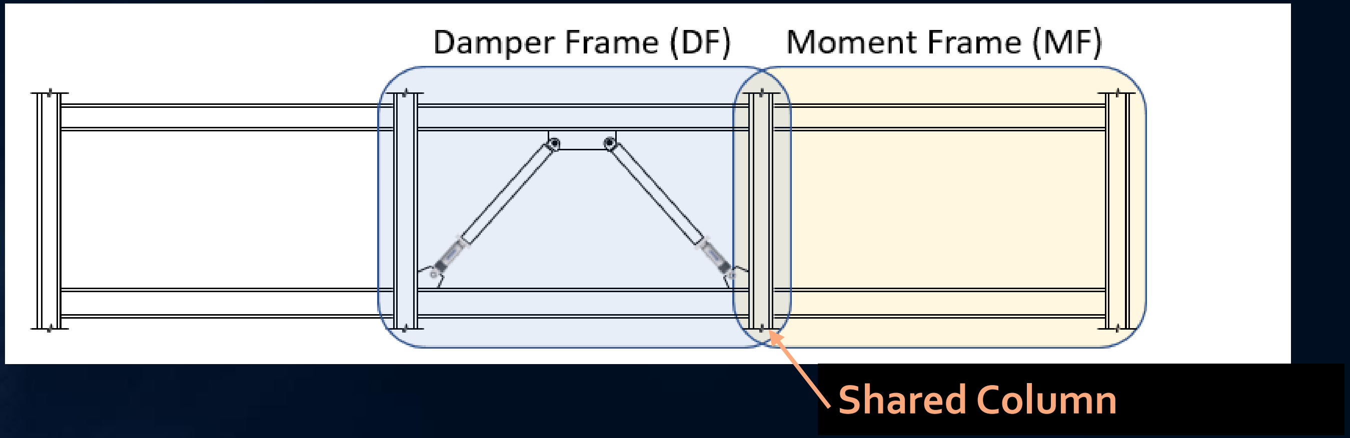
    For SDC E:

$$\Omega_d = \begin{cases} 3.5 & n_s \le 8 \\ 4.0 - (0.125 n_s) \quad \textit{for} & 8 < n_s < 14 \\ 2.75 & n_s \ge 14 \end{cases}$$

  - $s_{req,1} = 0.85 I_e \Omega_d d_{j1} \left(\dfrac{\Delta_2 / h_{s,2}}{\Delta_1 / h_{s,1}} \right)$ (Required damper stroke at first story)

Seismic Load Effect: Explained

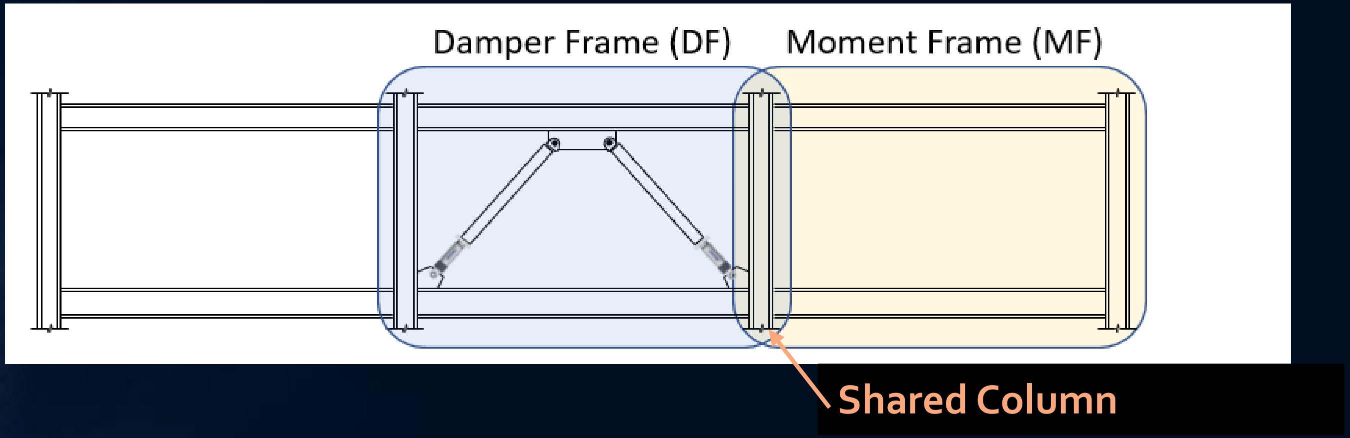
- Foundation and Elements that do not transfer forces between MF and DF:
  - $E_h = max(E, E_{TD}, E \pm 0.7E_{TD})$
- Shared elements and transfer elements:
  - $E_h = max(E, \boldsymbol{\Omega_F} E_{TD}, E \pm 0.7\boldsymbol{\Omega_F} E_{TD})$



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

Seismic Load Effect: Actual Notation

- Foundation and Elements that do not transfer forces between MF and DF:
  - $E_h = max(Q_{MD}, Q_{TD}, Q_{MD} \pm 0.7 Q_{TD})$
- Shared elements and transfer elements:
  - $E_h = max(Q_{MD}, \Omega_F Q_{TD}, Q_{MD} \pm 0.7 \Omega_F Q_{TD})$



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

3D Effects

- **Orthogonal load combination** (e.g. biaxial columns)
  - Damper forces use **100%** in primary direction and **60%** in secondary direction

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

System Validation and Codification: FEMA P-695 Methodology via ICC-ES AC 494

- 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”

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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

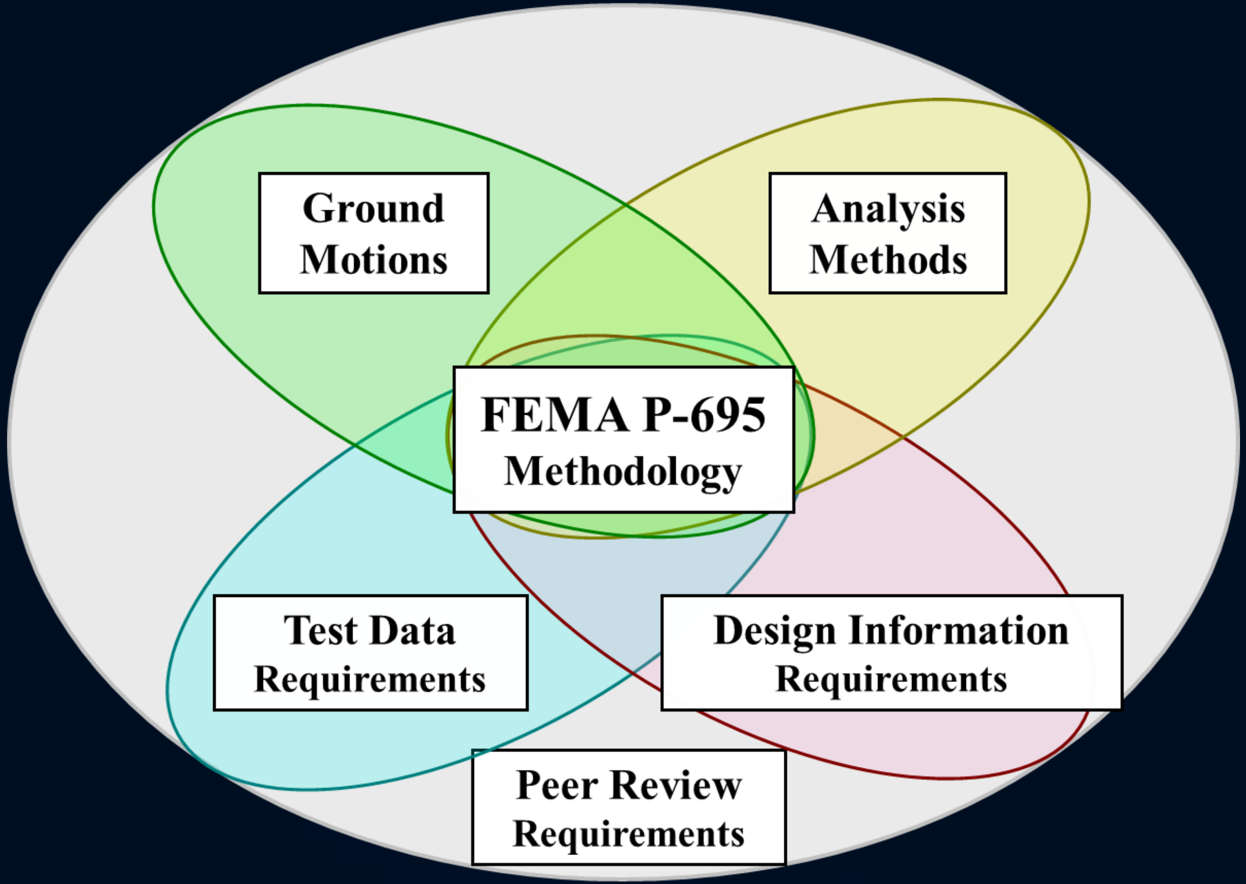
(Editorially revised February 2021)

Previously approved June 2018

PREFACE

System Validation and Codification: FEMA P-695 Methodology via ICC-ES AC 494

- 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”



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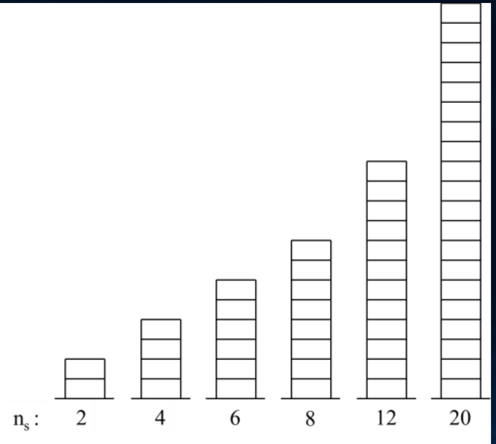
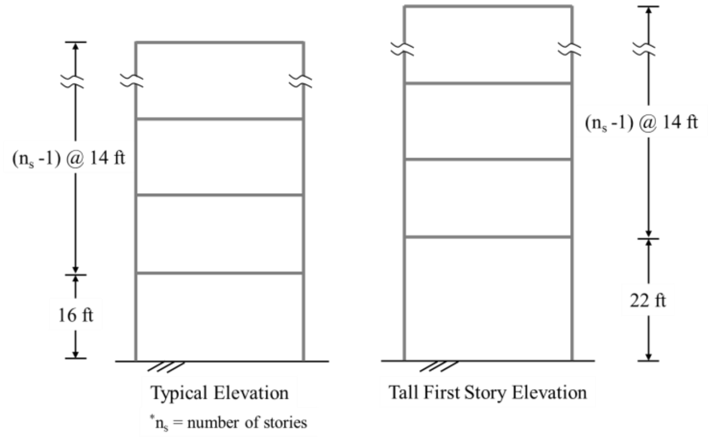
Archetype Design Space

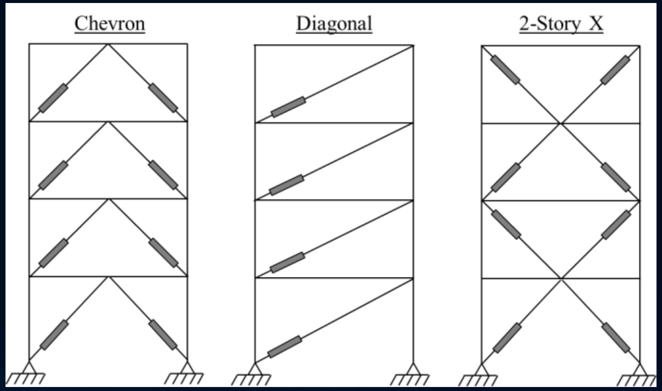
- Approximately 100 designs
- Typically 180 ft by 120 ft
- 2- to 20-story
- Typical story heights are 14 ft with 1st story heights of 16 ft or 22 ft
- Mostly perimeter frames, some space frames





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

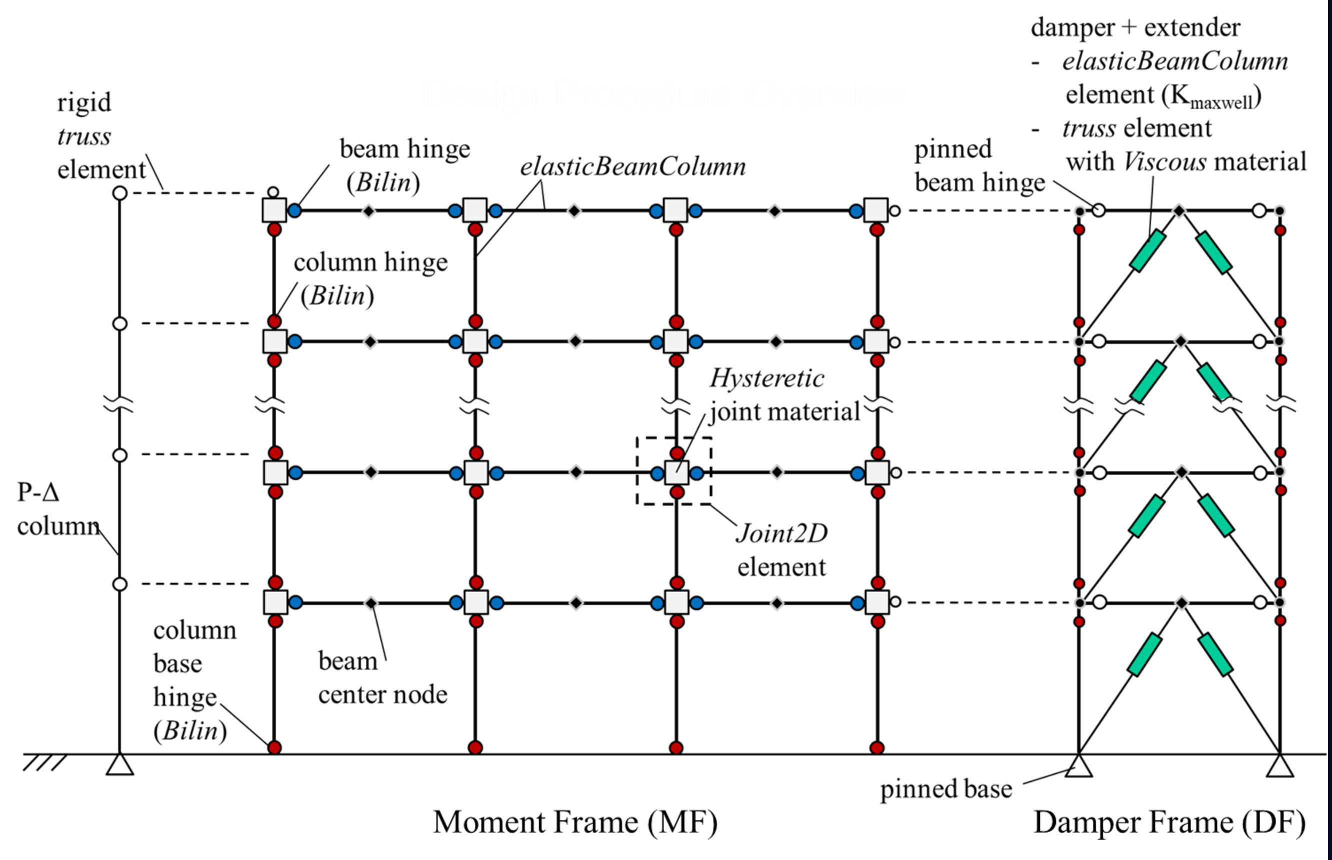


Archetype Design Space

- 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)

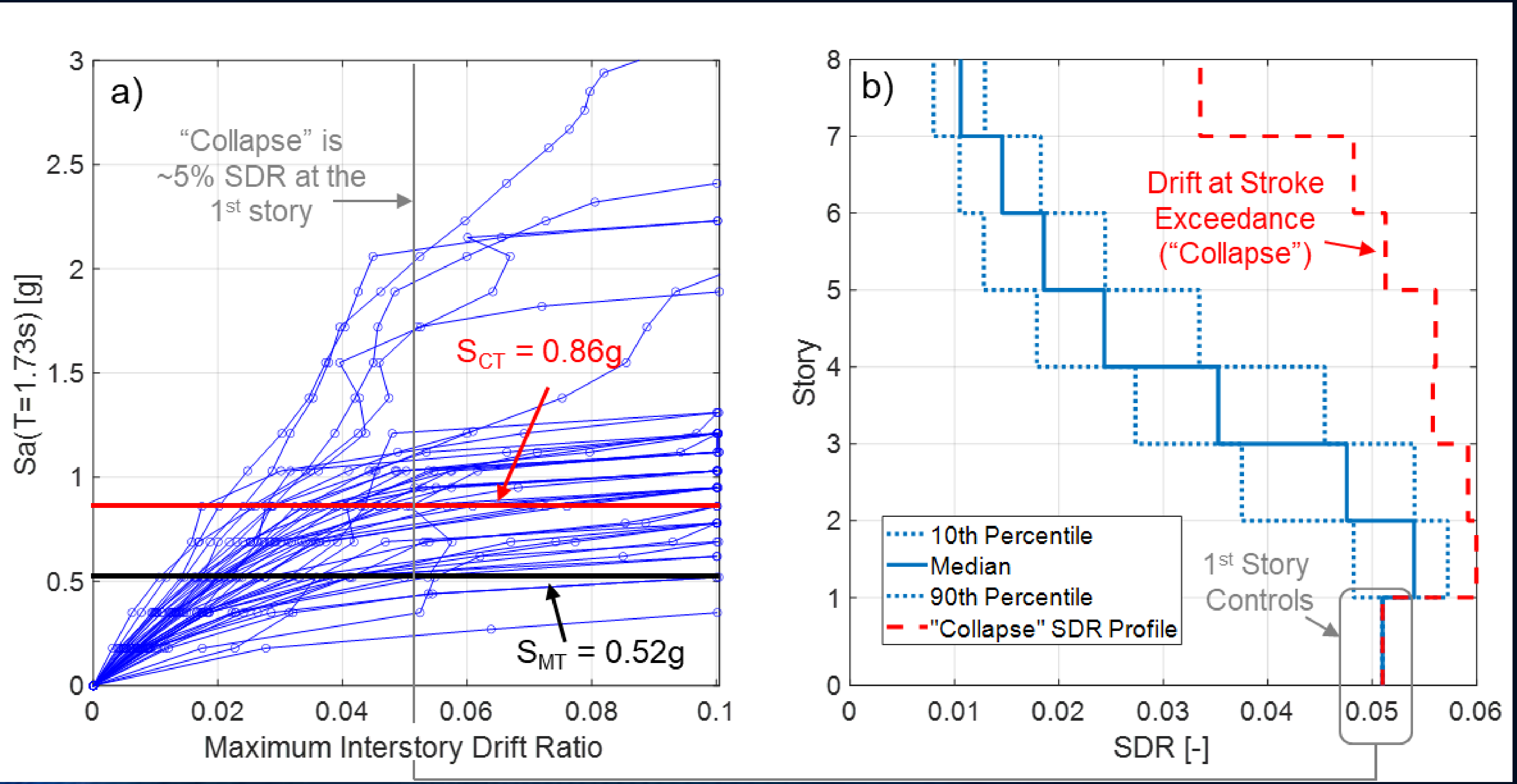
Nonlinear Modeling

- 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)



Example Application of the FEMA P-695 Methodology

- Incremental Dynamic Analysis (IDA)



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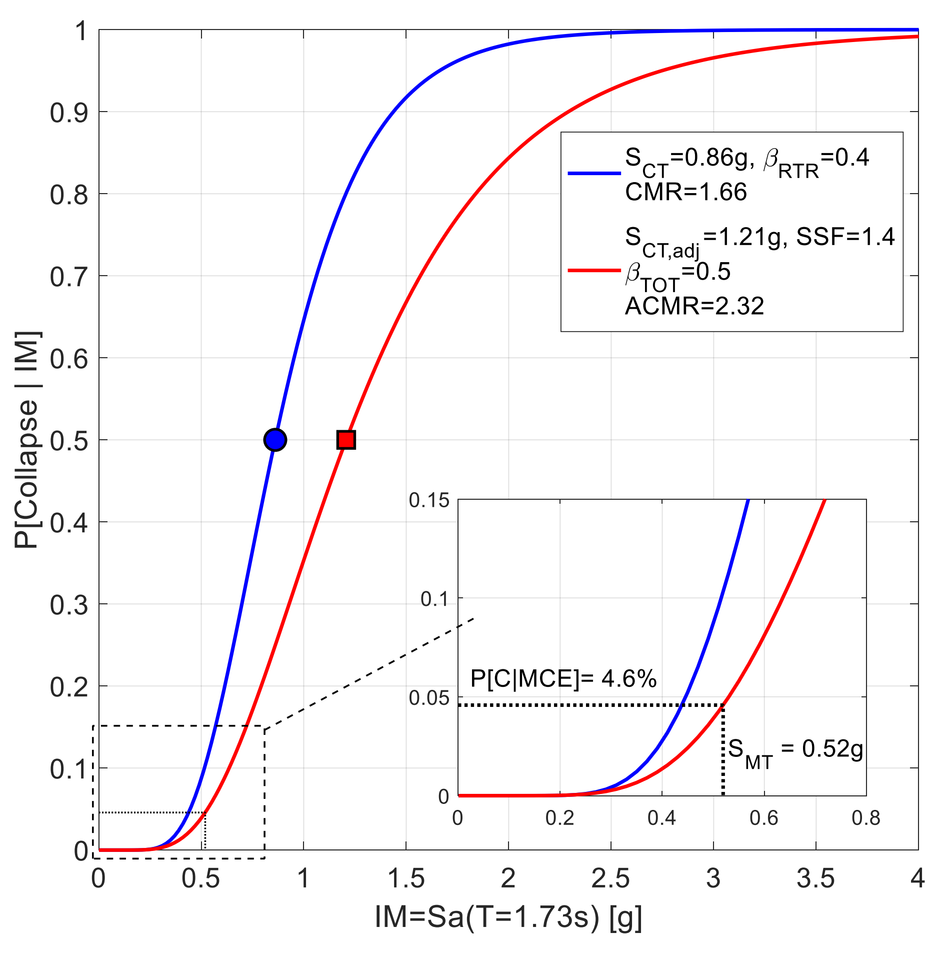
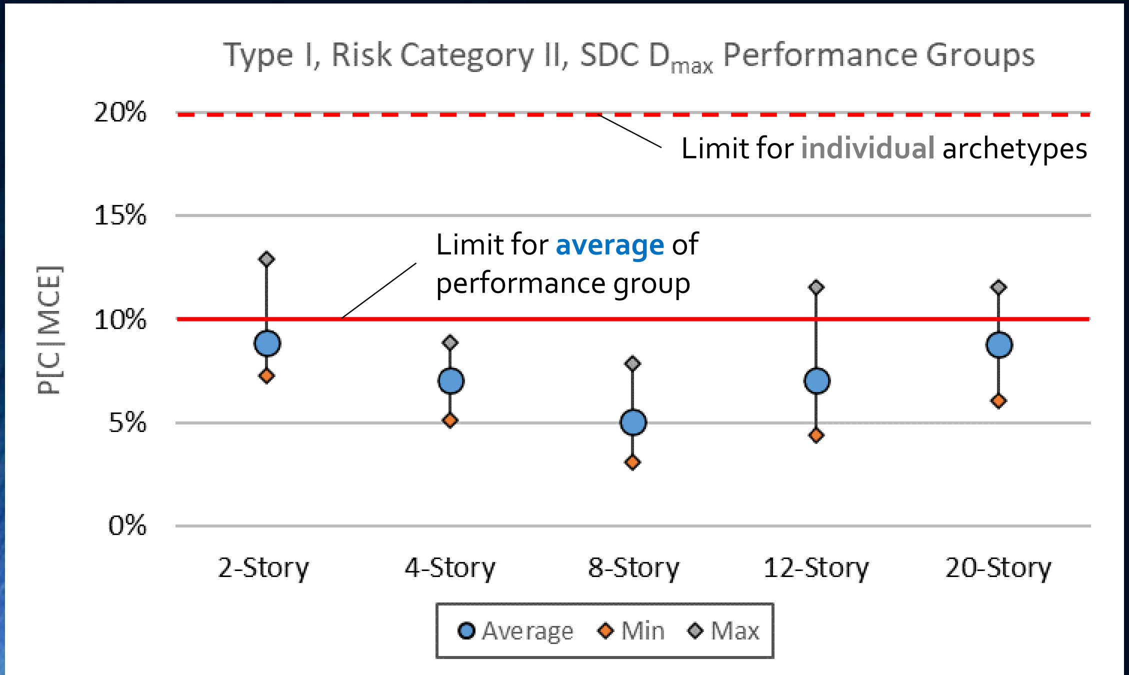
Example Application of the FEMA P-695 Methodology

- P(Collapse|MCE)

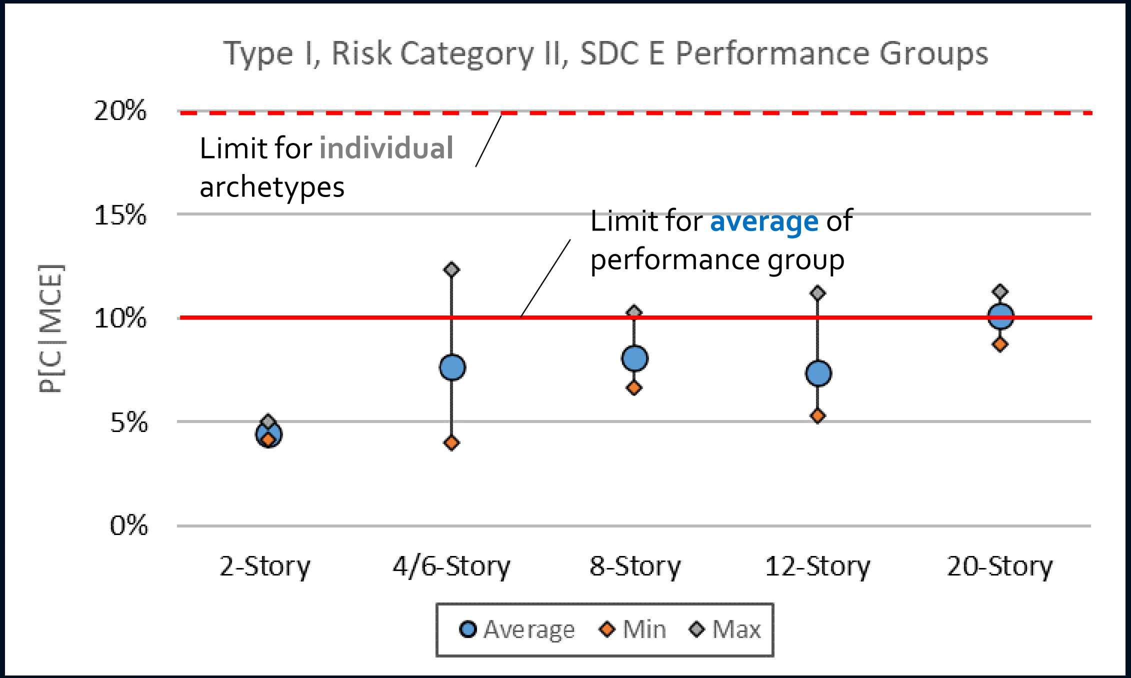


Summary: Collapse Performance

- TDMF designs meet the AC 494 / FEMA P-695 collapse performance requirements



SDC D_{max} (S_{DS} = 1.0, S_{D1} = 0.6)
(required by AC494)
50 archetypes



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

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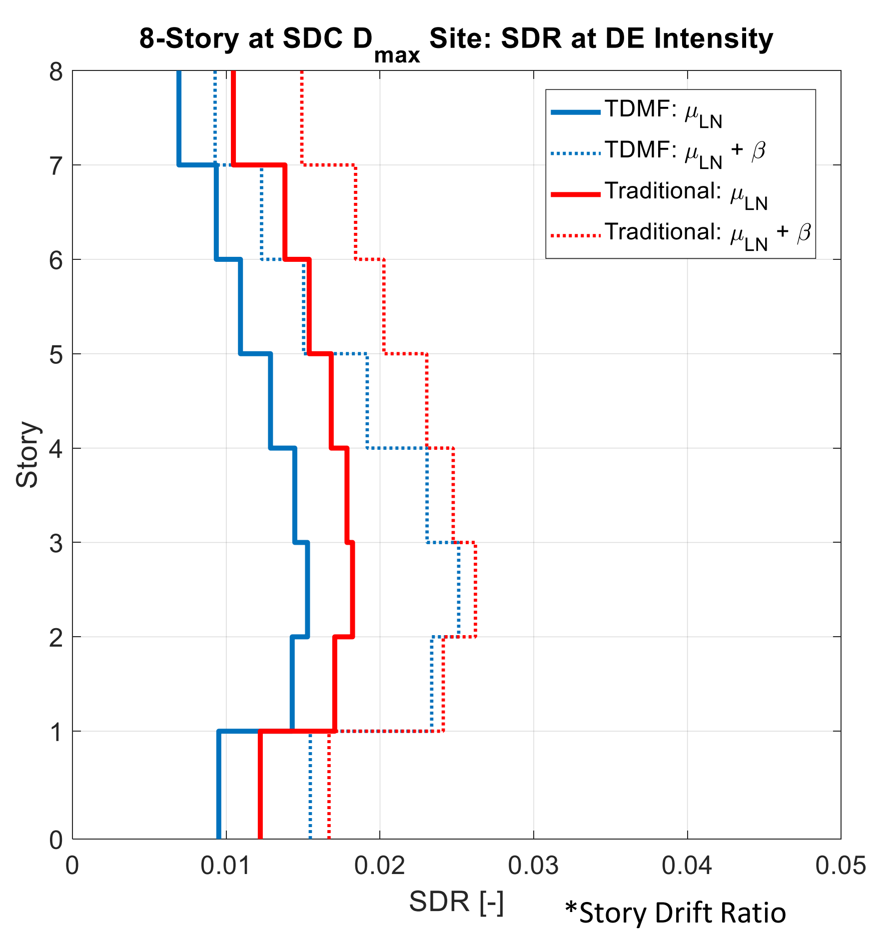
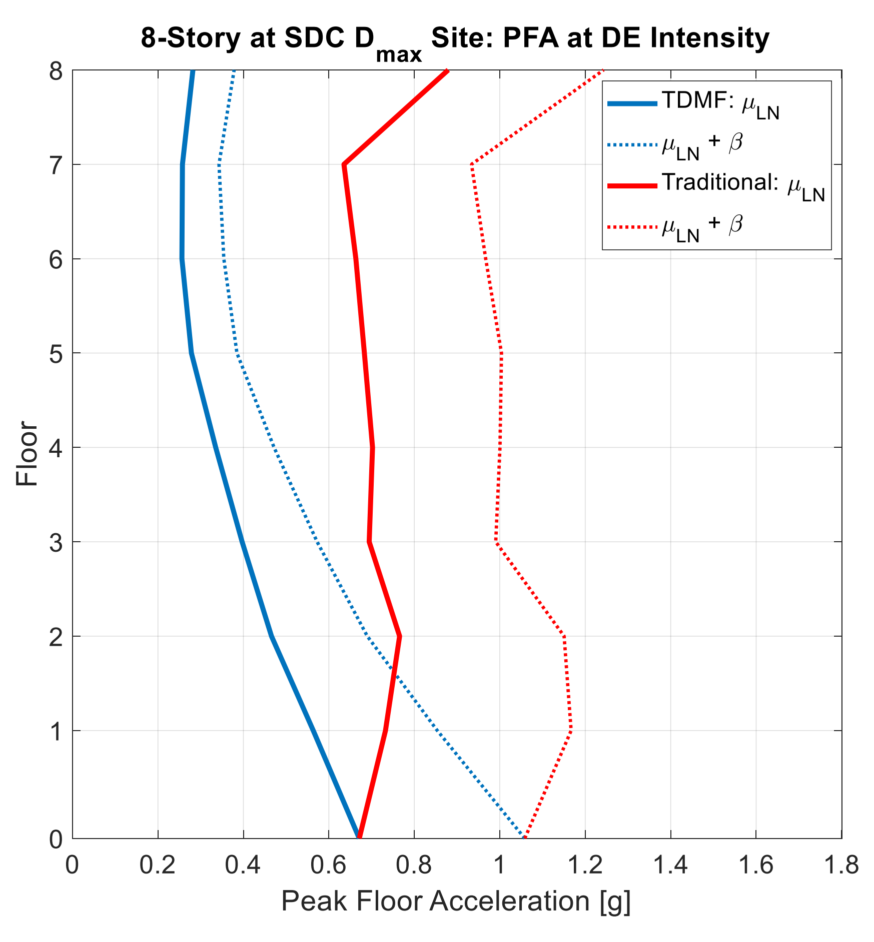
Comparison to Traditional Steel MRF

- Performance at DE intensity



*Story Drift Ratio



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Comparison to Traditional Steel MRF

- Steel tonnage comparison

	Total Weight* w_{total} [psf]			Moment Frame Weight** w_{MF} [psf]		
	Traditional	TDMF	**%diff**	Traditional	TDMF	**%diff**
8-Story RBS with Doubler Plates	13.51	11.02	**-18%**	9.09	6.28	**-31%**
8-Story RBS without Doubler Plates	16.00	11.97	**-25%**	11.58	7.24	**-37%**
8-Story WUF-W without Doubler Plates	18.12	13.89	**-23%**	13.70	9.09	**-34%**

* Total weight includes gravity framing and damping system framing (does not include secondary beams or doubler plates)

** Moment frame weight is for entire building (2 frames per direction)

NOTE: Values presented correspond to the entire 8-story 180 ft X 120 ft building (Area = 172800 ft^2)

Conclusions

1. A new linear design procedure for steel moment frames with viscous dampers is developed
   - Follows ASCE 7 ch. 12, with slight modifications
   - No nonlinear modeling
   - No peer review
2. ICC-ES AC 494 makes new lateral systems feasible within a reasonable time-frame (~2 years in this case)
3. The new design method provides a good option for resilient design
   - Supplemental damping reduces both drift and acceleration

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