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Evaluation of Seismic Assessment Procedures for Existing Reinforced Concrete Structures Damaged in the 2016 Meinong Earthquake

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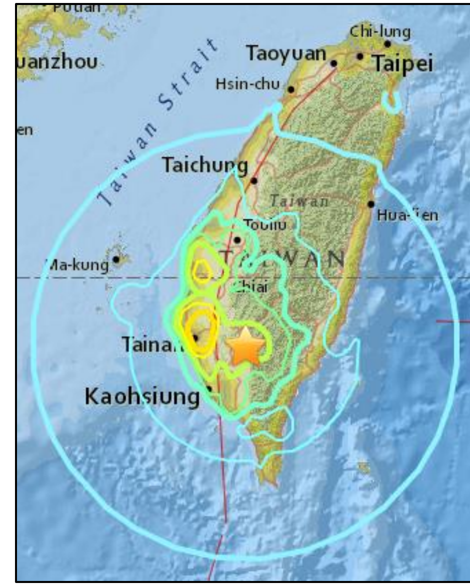
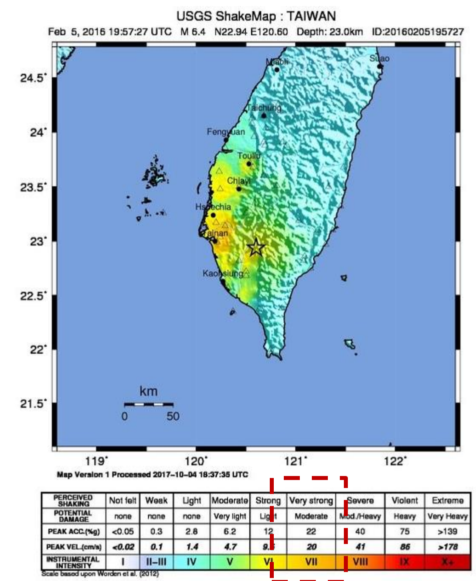
Motivation

- February 2016 Meinong Earthquake, Taiwan
  - Mw = 6.4
  - Focal depth: [16.7-23] km
  - Strike-slip with an oblique thrust component
  - W-NW rupture propagation
  - Damage localized to Tainan City

- NSF-RAPID response initiative
  - Collaborative and multi-team (UW & Purdue)
  - Reconnaissance data
    - Photographs / Sketches
    - Structural drawings
    - Ground motion recordings





Observed Damage

Midrise Residential

Lowrise Residential

Observed Damage

Schools

Government Offices

Observed Damage

Presentation Outline

1. Nanhau district office building selected for use.
2. Observed and “predicted” damage compared
   - ASCE Tier 1
   - ATC 78 procedure
   - **ASCE 41 Tier 3 – Linear Dynamic Analysis**
   - **ASCE 41 Tier 3 – Nonlinear Response History**
3. Observations and conclusions

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Nanhau District Office Building

Nanhau District Office

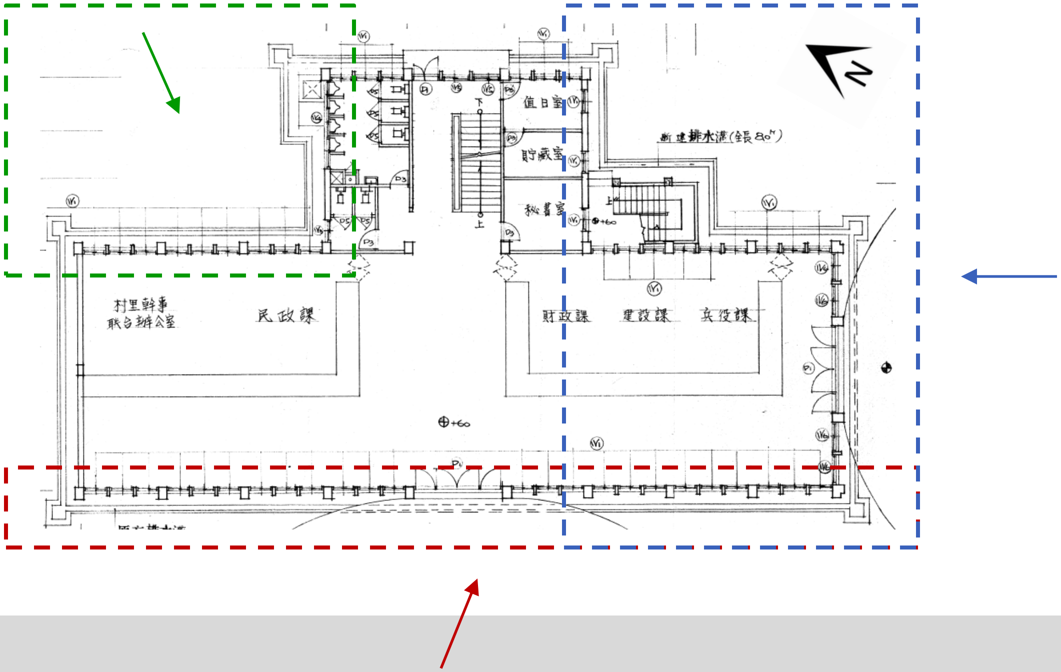
- **Three-story RC Office Building**
  - **Constructed in 1967**
  - Footprint (approx.)
    - 33m in the EW- or “X” direction
    - 18m in the NS- or “Y”-direction
- **Structural Framing**
  - **Moment framing lateral system**
  - **Full- and partial-height (hollow clay tile) infill**
  - **Slab-beam-column gravity system**
    - Slab: 12cm
    - Beam: 24x60cm to 36x85cm and integral with the slab
    - Column: 24x40cm and 36x50cm with strong-axis in the short-building-direction

Building Perspective Views

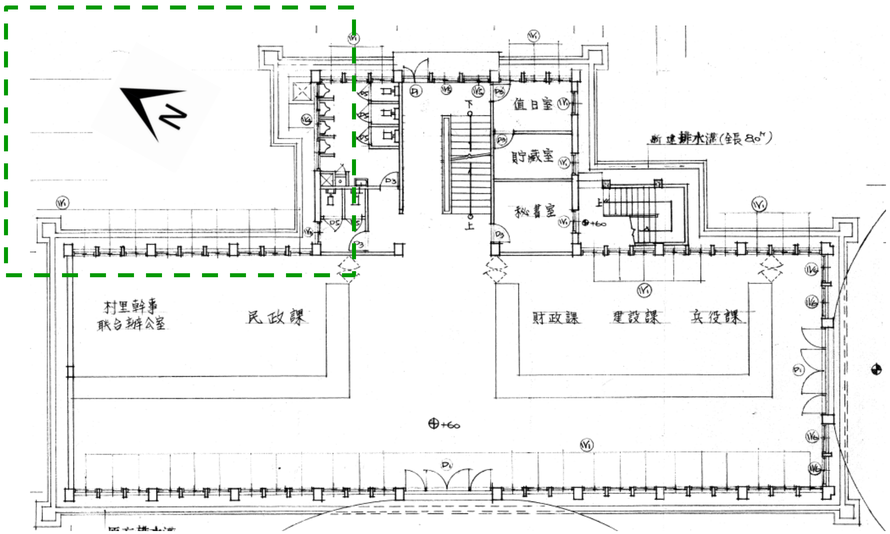
Looking from South

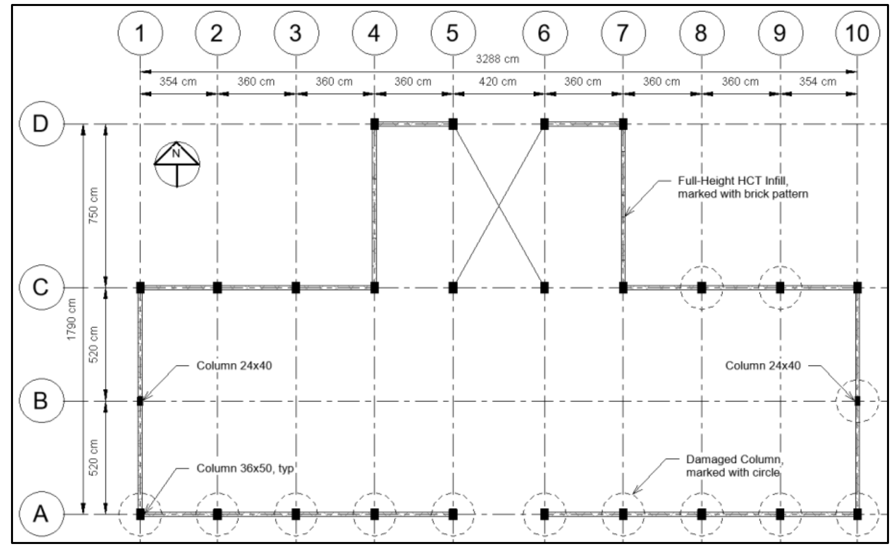
Looking from East

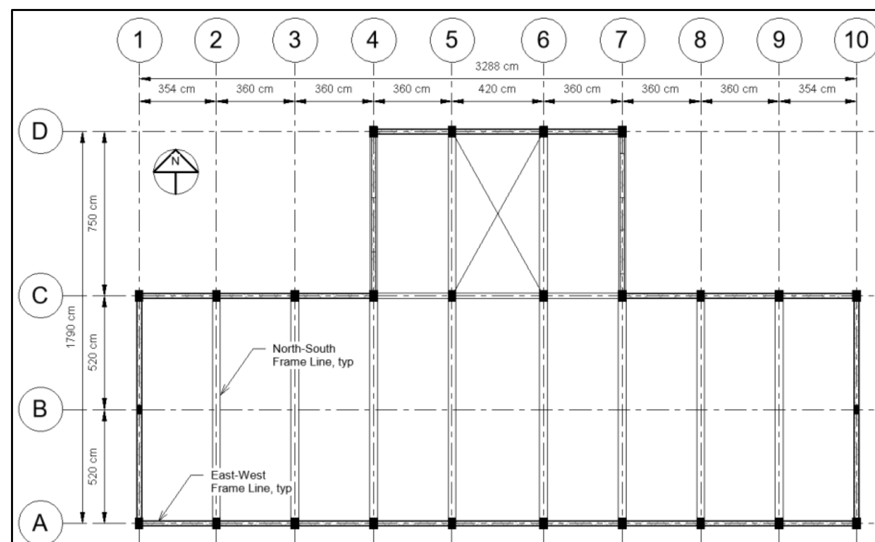
Looking from North



Structural Plans

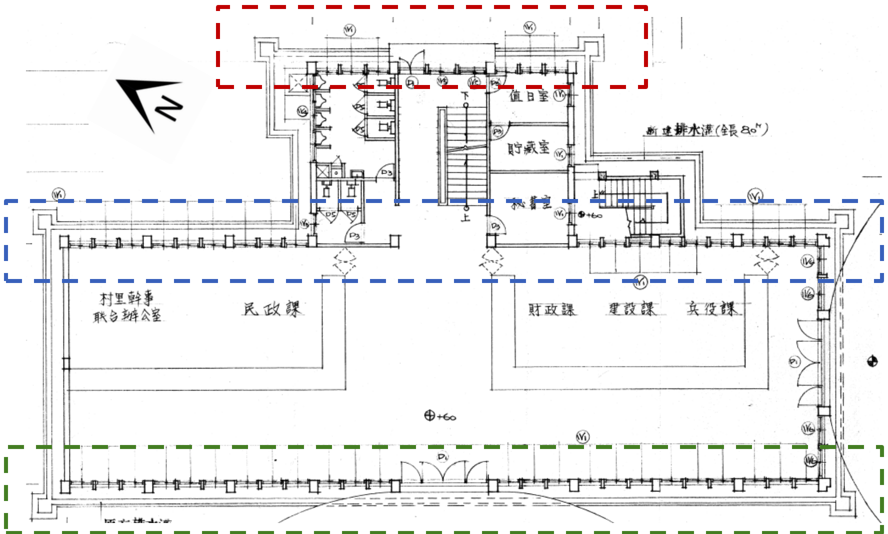


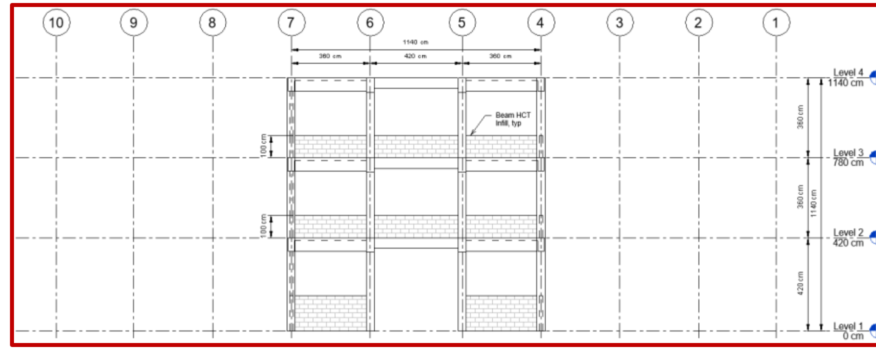


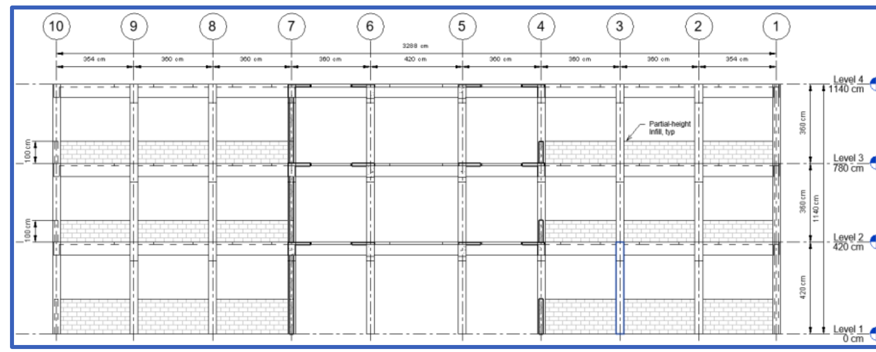


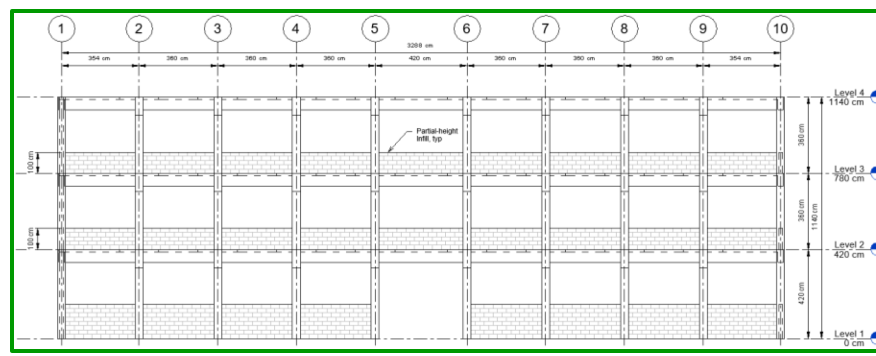
Level 1 and Level 2 Structural Plans, redrawn in Revit

Elevation Views

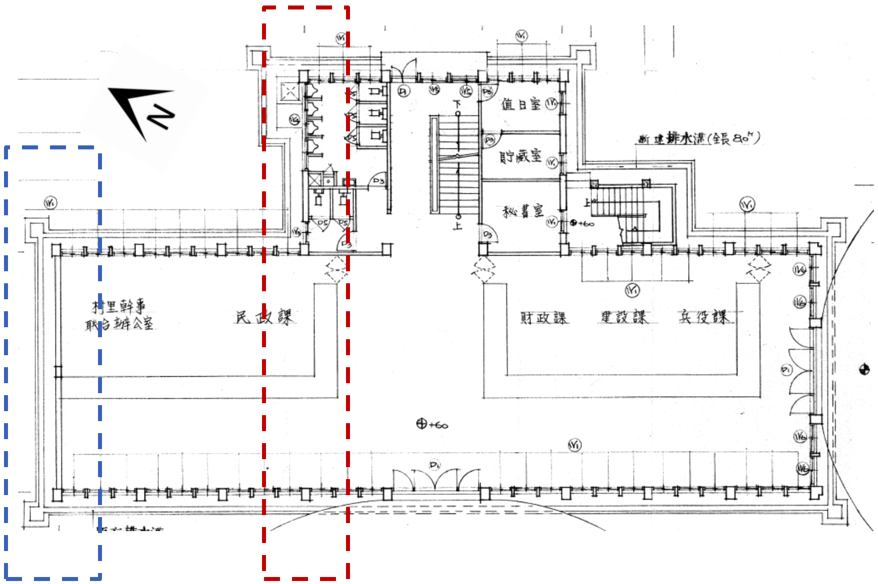


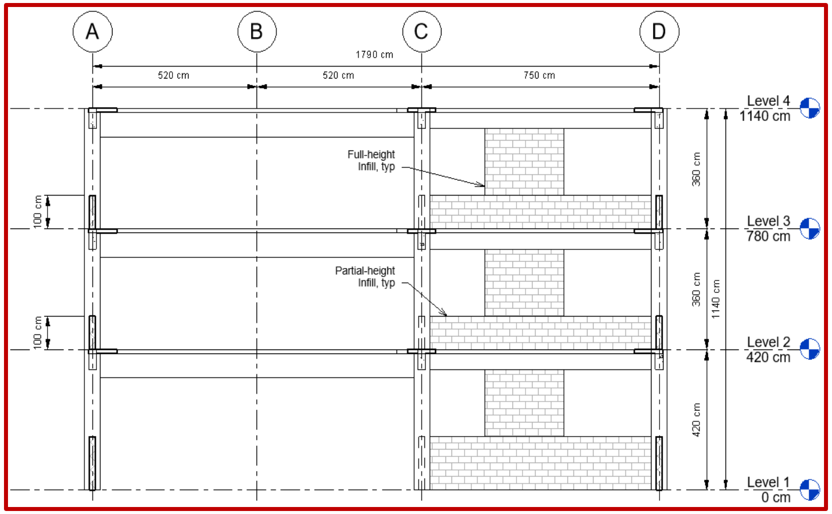


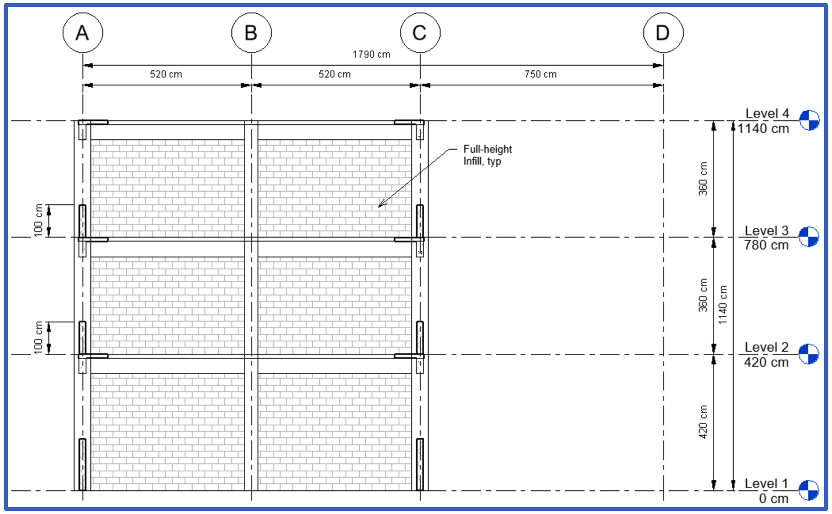




Elevation Views

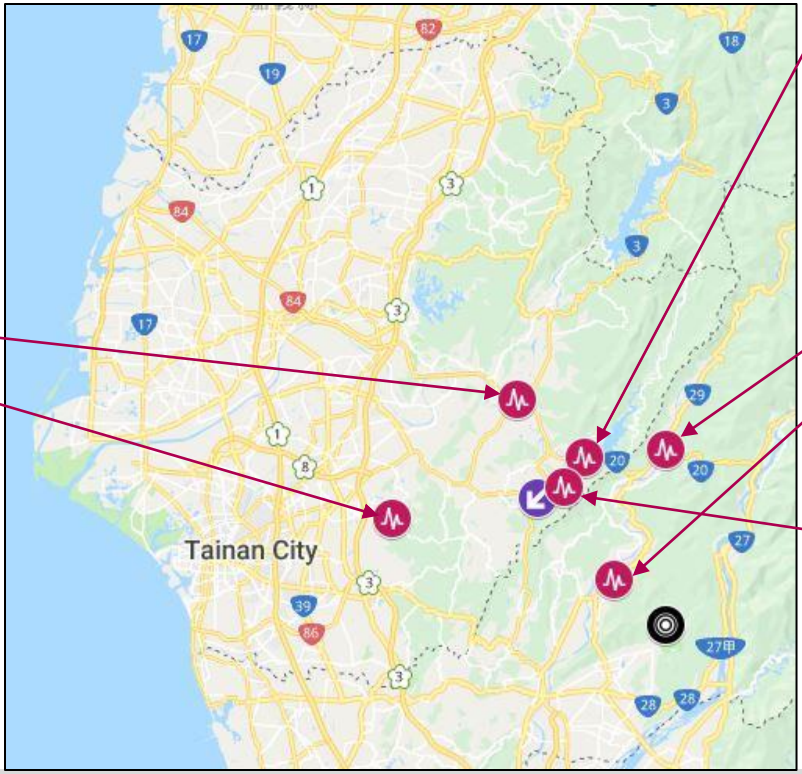






Ground Motion Recordings

- Site Map
  - Epicenter
  - Nanhau District Office (~10mi)
  - Identified recording stations



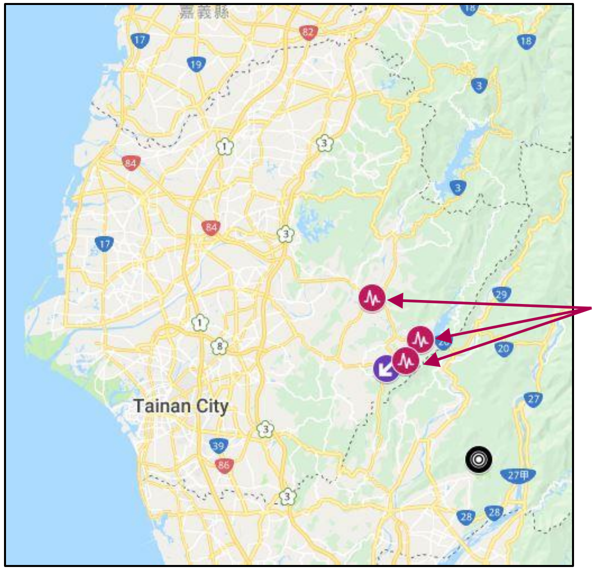
1. CHY061 (3.45mi)
2. CHY062 (5.64mi)
3. CHY063 (8.24mi)
4. KAU047 (7.64mi)
5. KAU068 (6.24mi)
6. A730 (1.55mi)

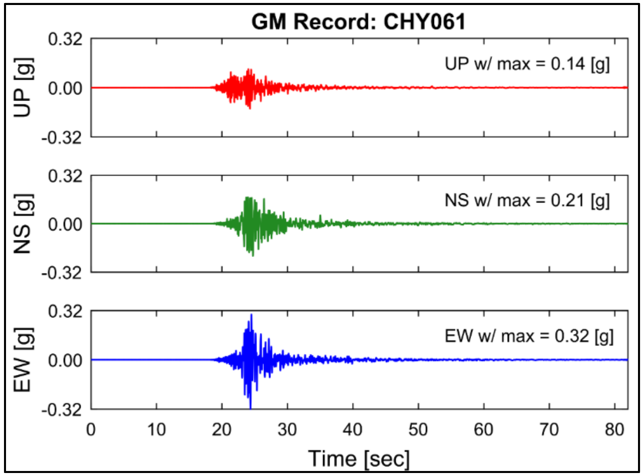
Recording Stations: <*http://www.cwb.gov.tw/V7e/earthquake/station.htm*>

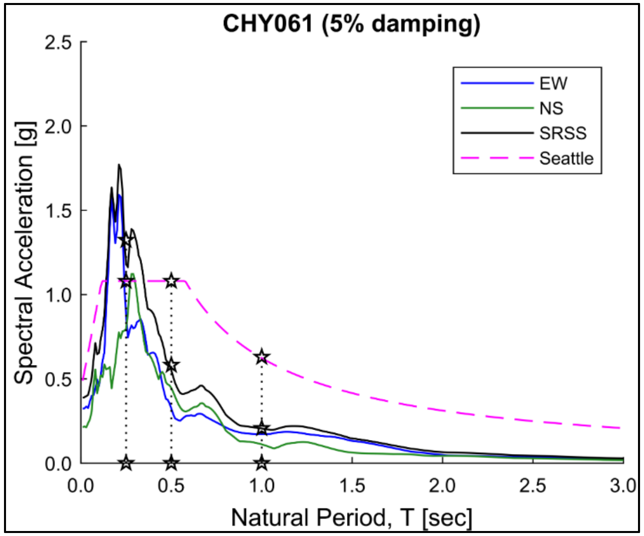
Ground Motion Recordings

- Prioritization based on geotechnical review

  6. A730 (1.55mi)
  2. CHY062 (5.64mi)
  1. CHY061 (3.45mi)



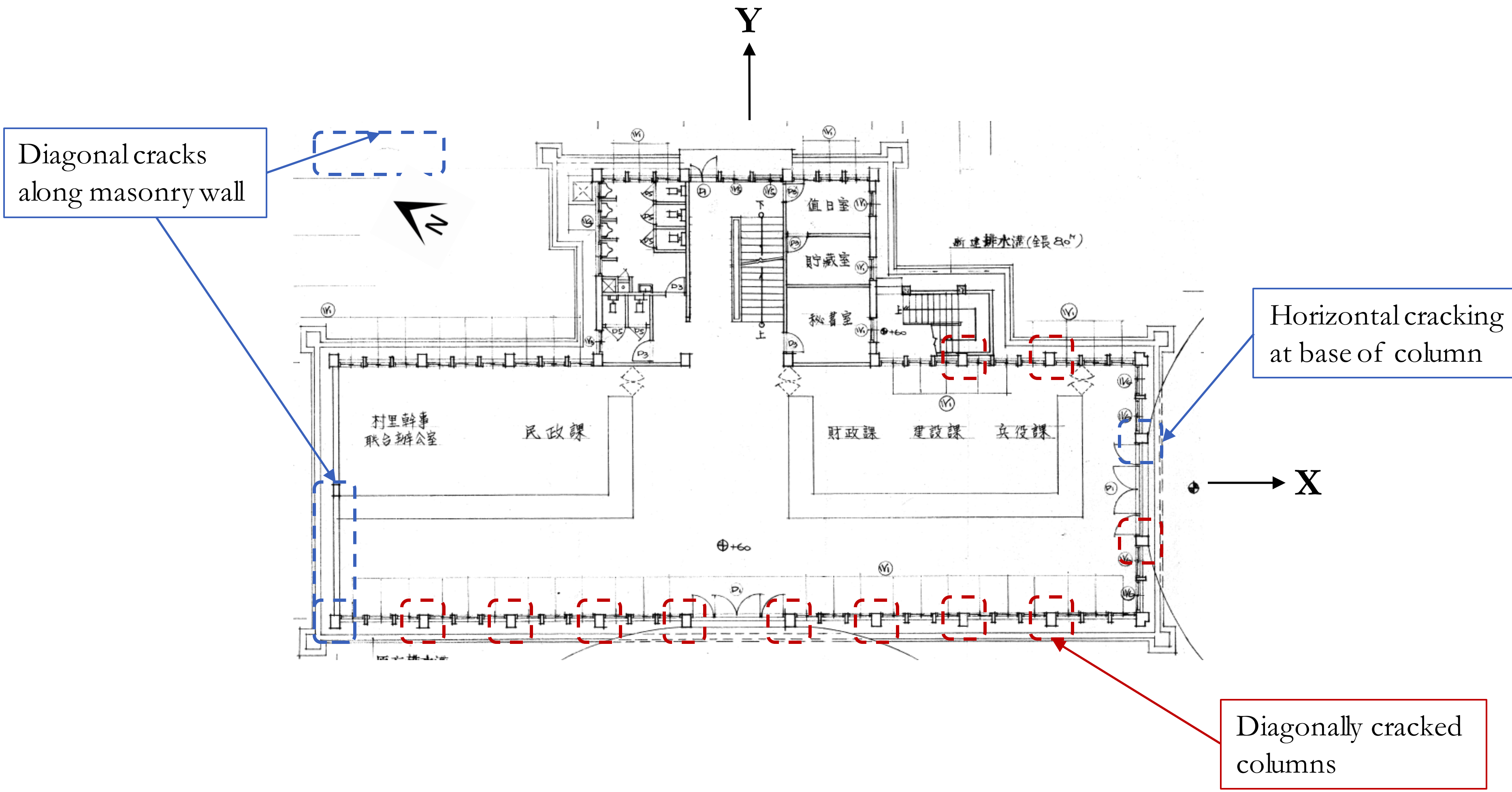




MAX PGA [g]

Station	EW	NS	UP
A730	0.33	0.42	0.14
CHY062	0.43	0.45	0.13
CHY061	0.32	0.21	0.14

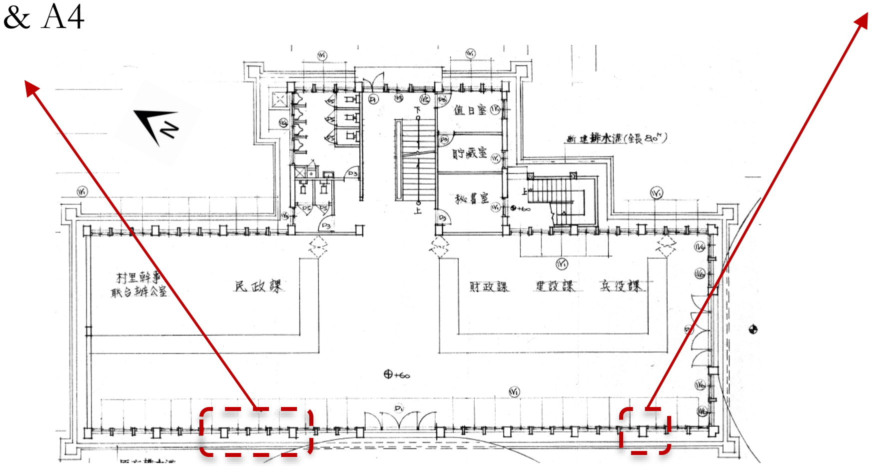
Building Damage



Building Damage

Vertical & Diagonal Cracking at
Columns A3 & A4

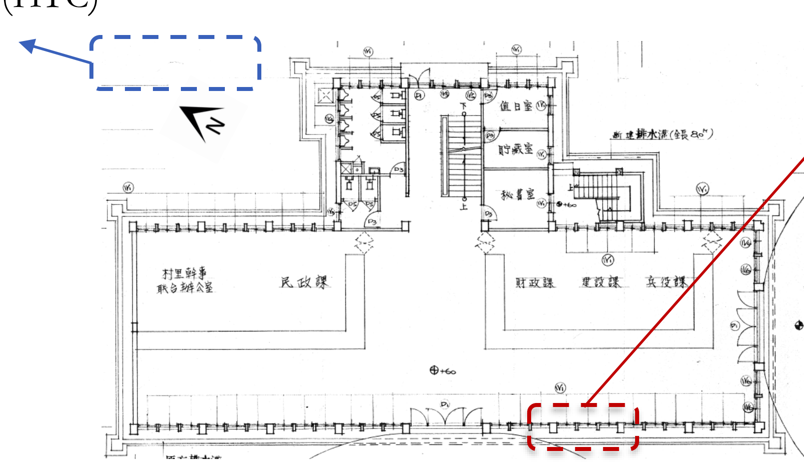
Diagonal Cracking at Column A9



Building Damage

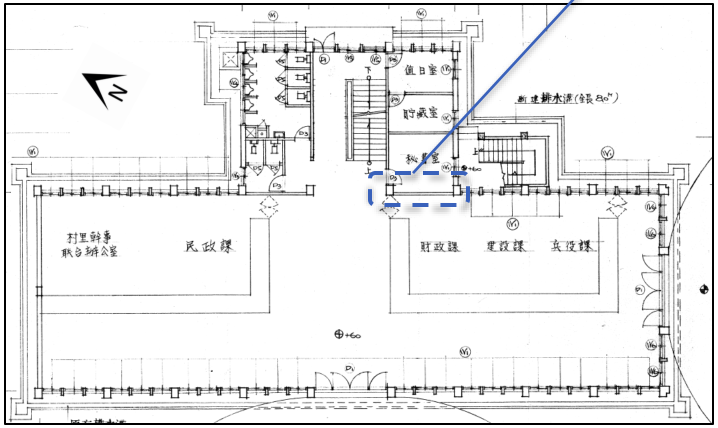
Infill Material Assumed to be Hollow Clay Tile (HTC)

Vertical & Diagonal Cracking at Columns A7 & A8



Building Damage

Kitchen items remained largely in place in spite of damage to the surrounding structural elements.



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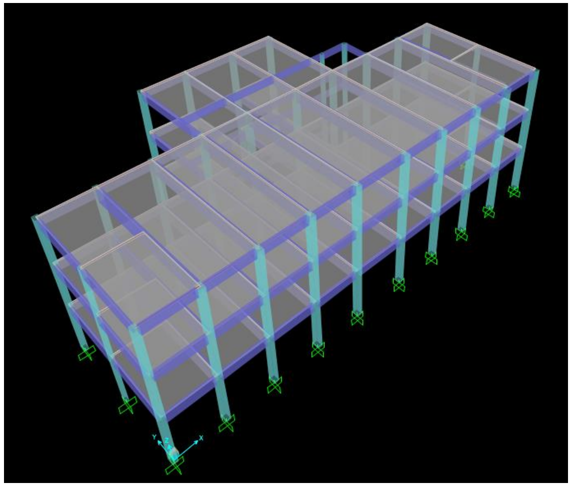
ASCE 41 Tier 3

Linear Analysis

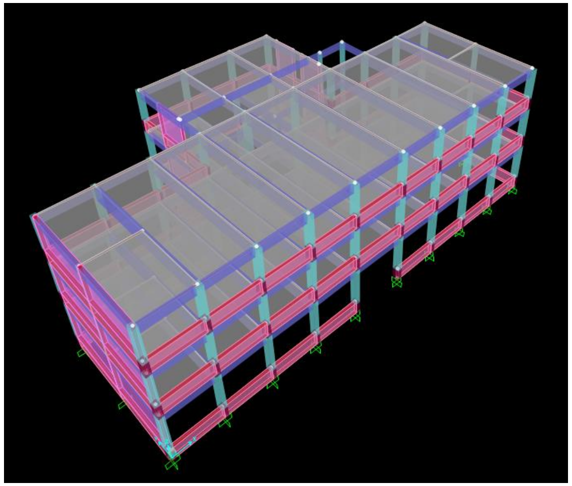
Model Variations of Masonry Infill

Model #2	Model #3	Model #5	Model #6
Bare Frame	ASCE Compliant	ASCE 41 (+)	ASCE 41 (+)

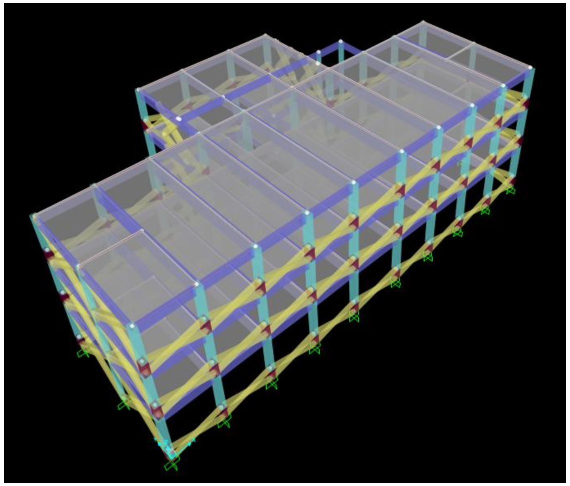
Bare Frame



Shell Elements



Diagonal Struts

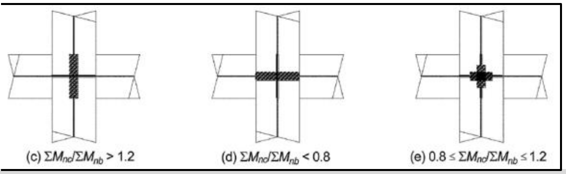


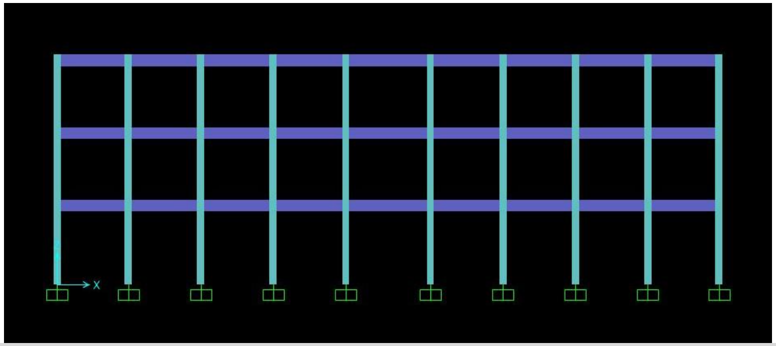
No Infill

Model #2	Model #3	Model #5	Model #6
Bare Frame	ASCE Compliant	ASCE 41 (+)	ASCE 41 (+)

- Element Types
  - Column → Rectangular, FRAME — $0.30EI_g$ where $E = 57000\sqrt{f'_{cE}}$
  - Beam → Rectangular, FRAME — $0.35EI_g$
  - Slab → Area, SHELL — $0.35m_{11,22}$ & Thin-plate formulation

- Joint Flexibility
  - Implicitly modeled
  - Based on ΣM_c / ΣM_b





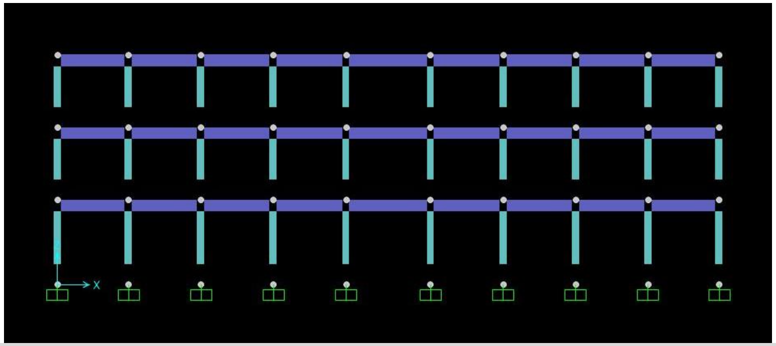
Joint flexibility based on: Section 10.4.2.2 (ASCE 41-17)

Rigid Column Offsets

Model #2	Model #3	Model #5	Model #6
Bare Frame	**ASCE Compliant**	ASCE 41 (+)	ASCE 41 (+)

Baseline of Model #2, plus…

- Modeled Infill
  - Infill → Rigid end-zone offset
  - Bottom of column up to height of infill (100cm)
  - Considered to be ASCE Compliant ("induce short-column effect")

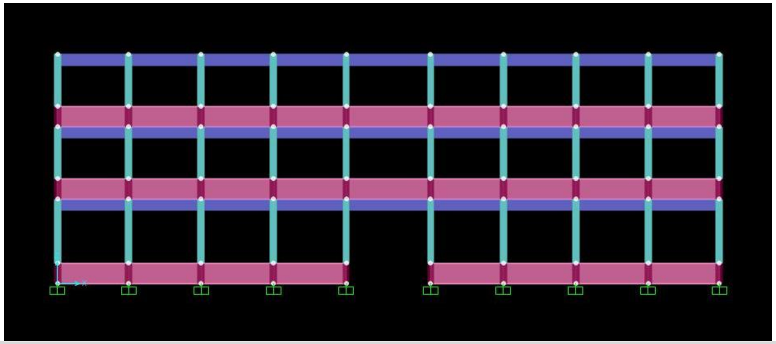


Shell Elements

Model #2	Model #3	Model #5	Model #6
Bare Frame	ASCE Compliant	**ASCE 41 (+)**	ASCE 41 (+)

Baseline of Model #2, plus…

- Modeled Infill
  - Infill → Area, SHELL $0.15f_{11}$ & $0.15f_{22}$ & $0.29f_{12}$
  - Thin-plate formulation
  - Not addressed in ASCE 41, but visually representative
- Joint Flexibility
  - Rigid column
  - Flexible beam



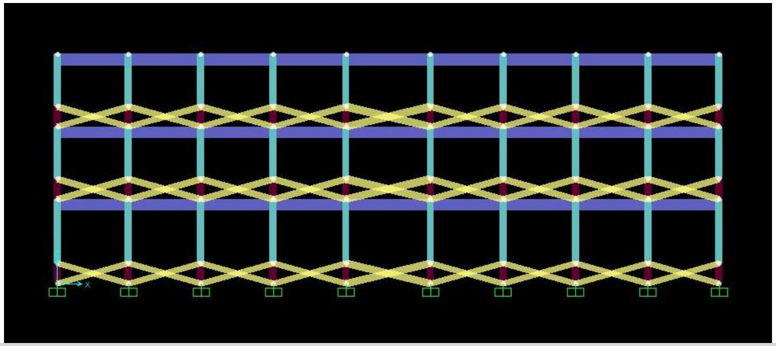
Diagonal Struts

Model #2	Model #3	Model #5	Model #6
Bare Frame	ASCE Compliant	ASCE 41 (+)	**ASCE 41 (+)**

Baseline of Model #2, plus…

- Modeled Infill
  - Infill → Rectangular, TRUSS — Compression-only
  - Approach cited in ASCE 41 — Reference required → FEMA 356
  - Depth = Infill thickness (24cm)
  - Effective width, a:

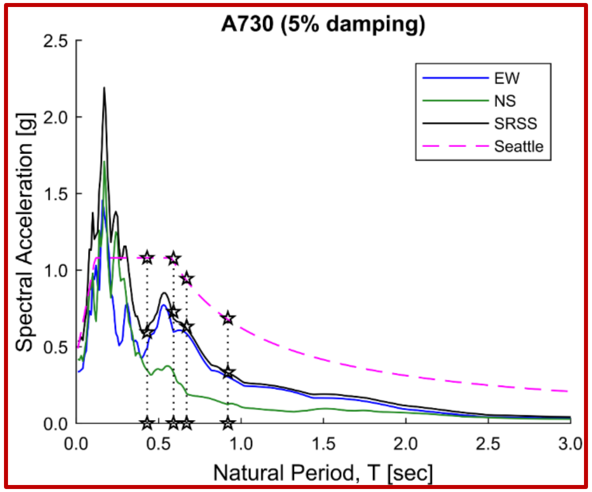
- $\lambda_1 = \left[\frac{E_{me} t_{inf} \sin 2\theta}{4 E_{fe} I_{col} h_{inf}}\right]^{1/4}$
- $a = 0.175(\lambda_1 h_{col})^{-0.4} * r_{inf}$



FEMA 356: *Prestandard and Commentary for the Seismic Rehabilitation of Buildings. (Section 7.5.2.1 & Eq. 7-14)*

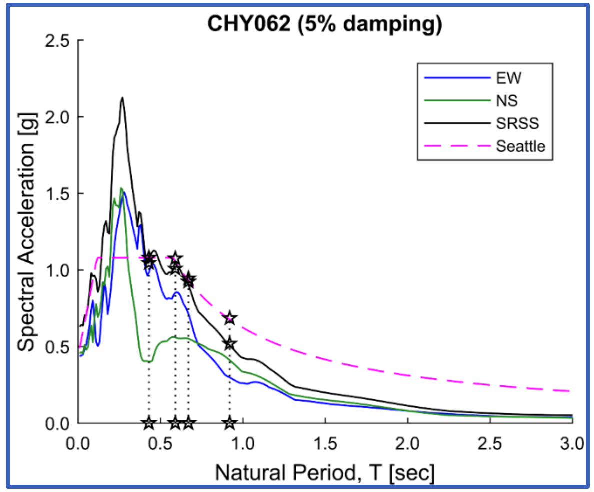
Fundamental Periods and Spectral Acceleration

GM: A730



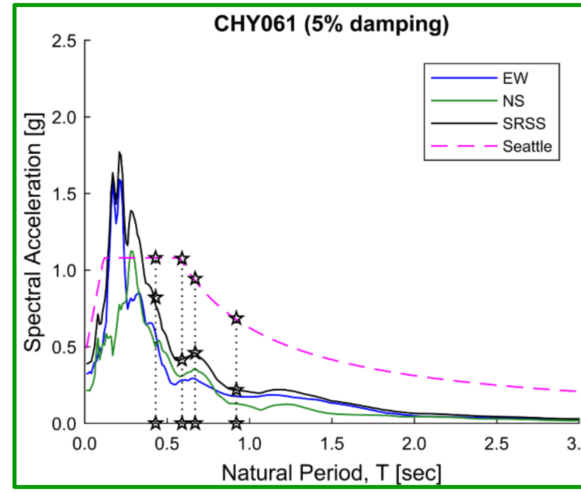
Model	Type	T_1	S_a
#2	BF	0.92	0.33
#3	C	0.59	0.73
#5	SH	0.67	0.63
#6	DS	0.43	0.59

GM: CHY062



Model	Type	T_1	S_a
#2	BF	0.92	0.52
#3	C	0.59	1.01
#5	SH	0.67	0.92
#6	DS	0.43	1.05

GM: CHY061



Model	Type	T_1	S_a
#2	BF	0.92	0.22
#3	C	0.59	0.41
#5	SH	0.67	0.46
#6	DS	0.43	0.82

Applied Loading

- Gravity
  - Q_{G1} = 1.1(DL+0.25LL) — Equation 7-1 (ASCE 41-17)
  - Q_{G2} = 0.9DL — Equation 7-2 (ASCE 41-17)

- Lateral
  - Explicit use of acceleration records — Section 7.4.2.2.2 (ASCE 41-17)
  - Not scaled — **Not** Section 2.4.3 (ASCE 41-17)
  - Q_E = E_{EW} & E_{NS}
  - Newmark time-integration
  - 5% Rayleigh damping — Mass and stiffness proportional

- Load Combinations
  - Q_{UD} = $Q_G \pm Q_E$ — Deformation-controlled action
  - Q_{UF} = $Q_G \pm {}^{(XQ_E)}/_{(C_1 C_2 J)}$ — Force-controlled action

Acceptance Criteria

Deformation-controlled actions

- Moment, M2 and M3
- Expected material strength
  - f_{cE} = $1.50 * f'_c$
  - f_{yE} = $1.25 * f_y$

  - Limit = $\dfrac{M_{max}/M_{n,CE}}{m_{Table}}$

  - M_{Max} → $Q_{UD} = Q_G \pm Q_E$
  - $M_{n,CE}$ → $f\ (\ fiber\ section\ geometry\ )$ Mφ analysis
  - m_{Table} → $f\ (\ structural\ parameters\ )$ Table 10-10 (ASCE 41-17)

Table C7-1. Examples of Possible Deformation-Controlled and Force-Controlled Actions

Component	Deformation-Controlled Action	Force-Controlled Action
Moment frames		
• Beams	Moment (*M*)	Shear (*V*)
• Columns	—	Axial load (*P*), *V*
• Joints	—	V^a

Acceptance Criteria

Force-controlled actions

- Shear, V2 and V3
- Specified material strength
  - $f_{cL} = f'_c$
  - $f_{yL} = f_y$

  - Limit $= \dfrac{V_{max}}{V_{n,CL}}$

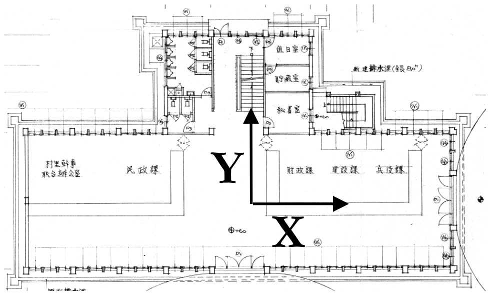
  - J $\rightarrow min\left(1.0, {}^{M_{max}}/_{M_{n,CE}}\right)$ Section 7.5.2.1.2 (ASCE 41-17)
  - $V_{Max} \rightarrow Q_G \pm {}^{(XQ_E)}/_{(C_1 C_2 J)}$
  - $V_{n,CL} = k_{nl} * V_{Col0L}$ Eq. 10-3 (ASCE 41-17)

$$= k_{nl}\left[\alpha_{Col}\left(\frac{A_v f_{ytL} d}{a}\right) + \lambda\left(\frac{6\sqrt{f'_{cL}}}{M_{UD}/V_{UD}d} * \sqrt{1+\frac{N_{UD}}{6\sqrt{f'_{cL}}A_g}}\right)0.8A_g\right]$$

Table C7-1. Examples of Possible Deformation-Controlled and Force-Controlled Actions

Component	Deformation-Controlled Action	Force-Controlled Action
Moment frames		
• Beams	Moment (M)	Shear (V)
• Columns	—	Axial load (P), V
• Joints	—	V^a

Analysis Results – GM A730

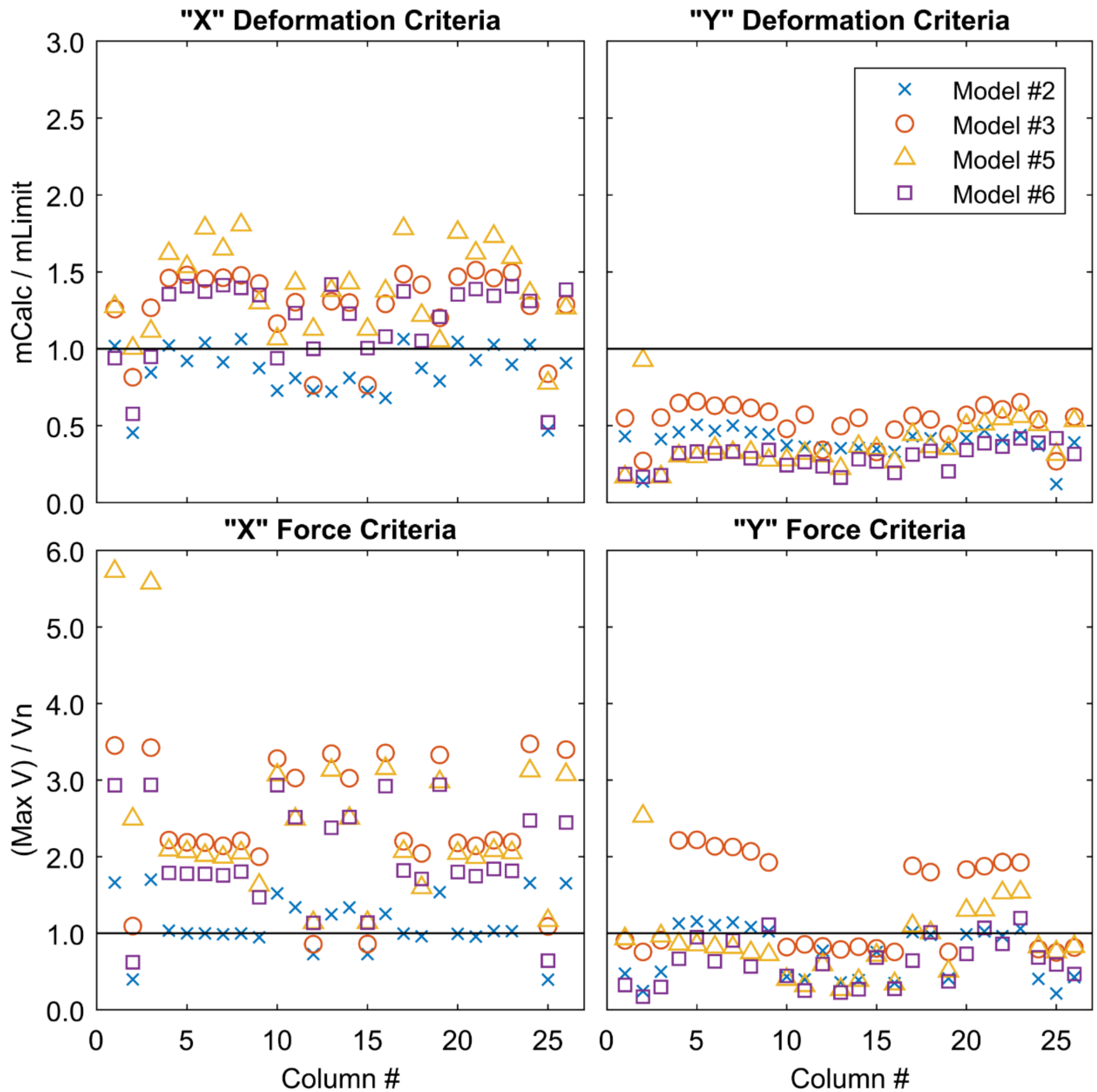


Deformation Controlled

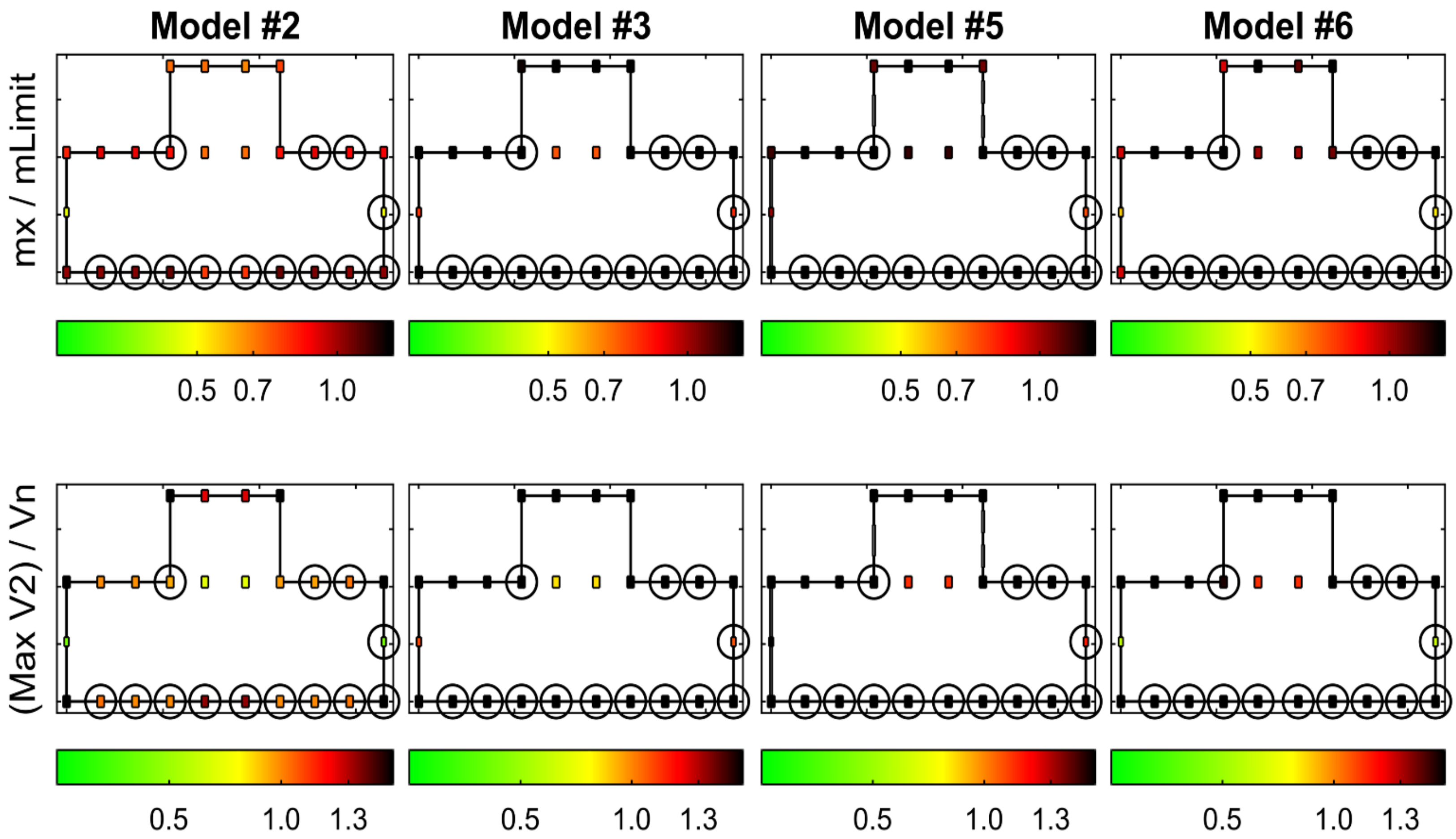
$$\frac{m_{calc}}{m_{Table}} = \frac{M_{max}/M_{n,CE}}{m_{Table}}$$

Force Controlled

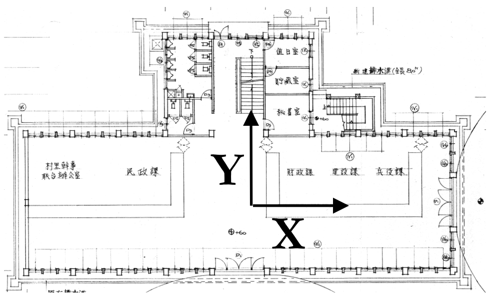
$$V_{max}/V_{n,CL}$$



Analysis Results



Analysis Results – GM A730

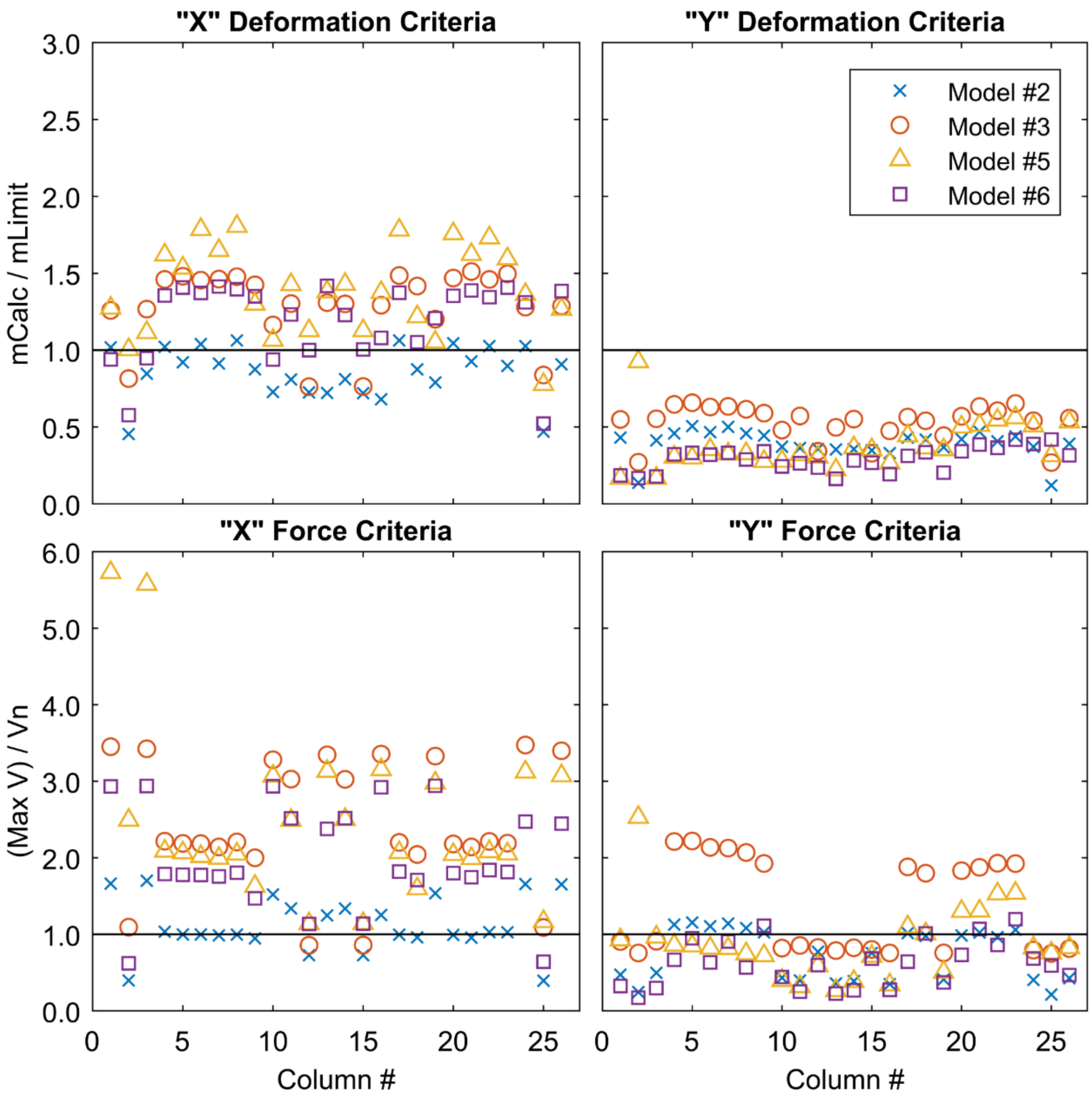


Deformation Controlled

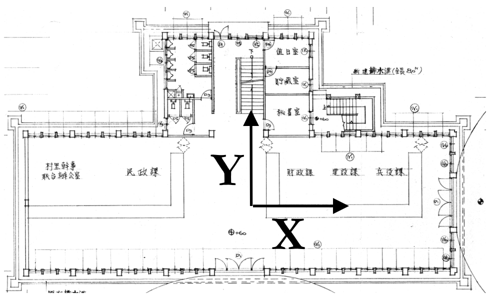
$$\frac{m_{calc}}{m_{Table}} = \frac{M_{max}/M_{n,CE}}{m_{Table}}$$

Force Controlled

$$V_{max}/V_{n,CL}$$



Analysis Results – CHY-062

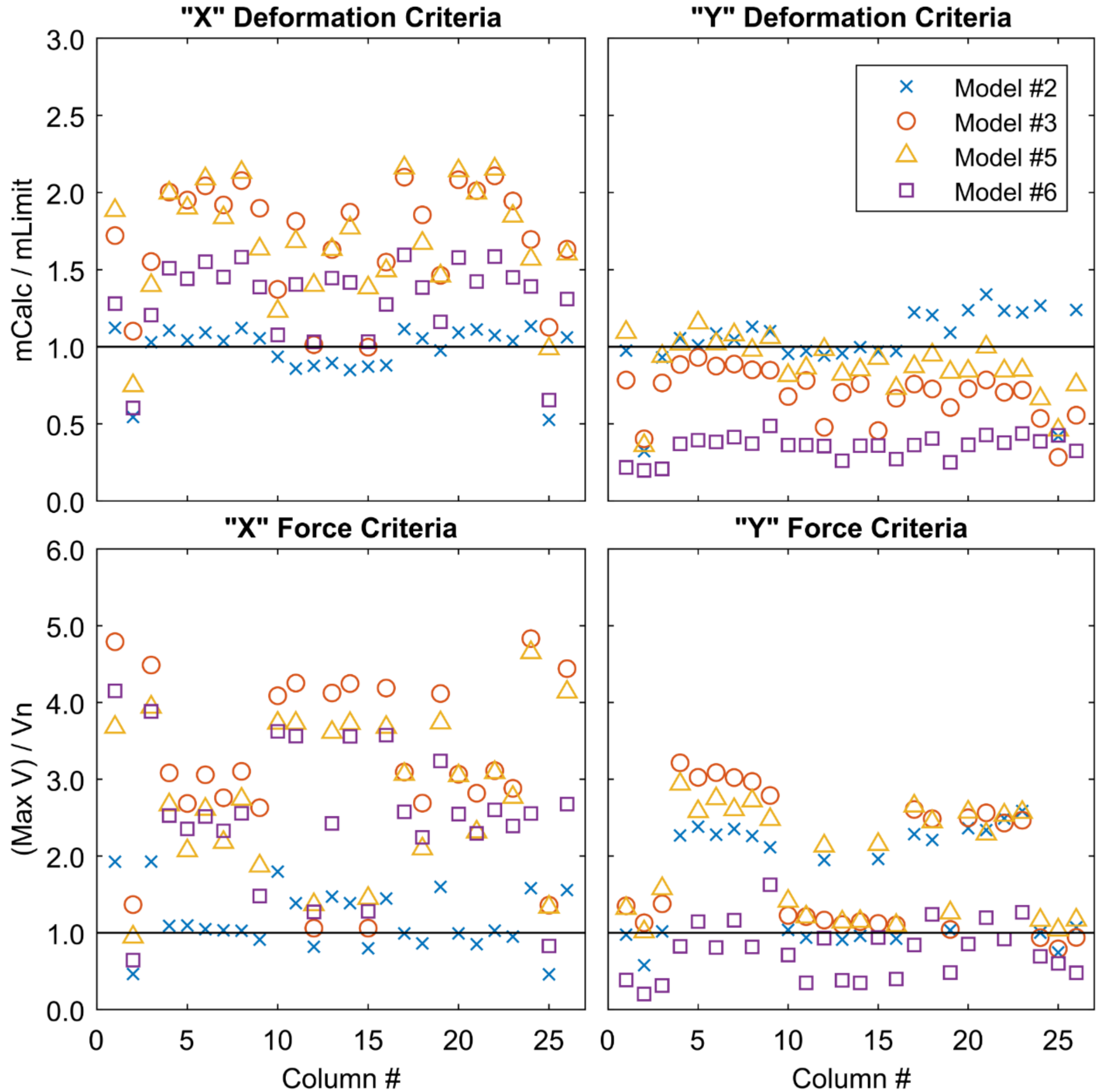


Deformation Controlled

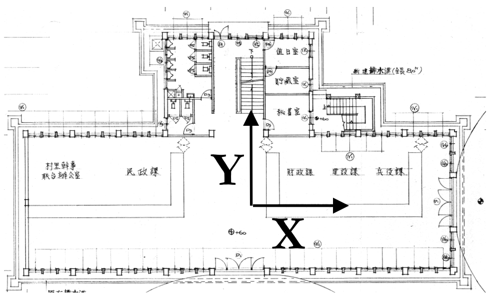
$$\frac{m_{calc}}{m_{Table}} = \frac{M_{max}/M_{n,CE}}{m_{Table}}$$

Force Controlled

$$V_{max}/V_{n,CL}$$



Analysis Results – CHY-061

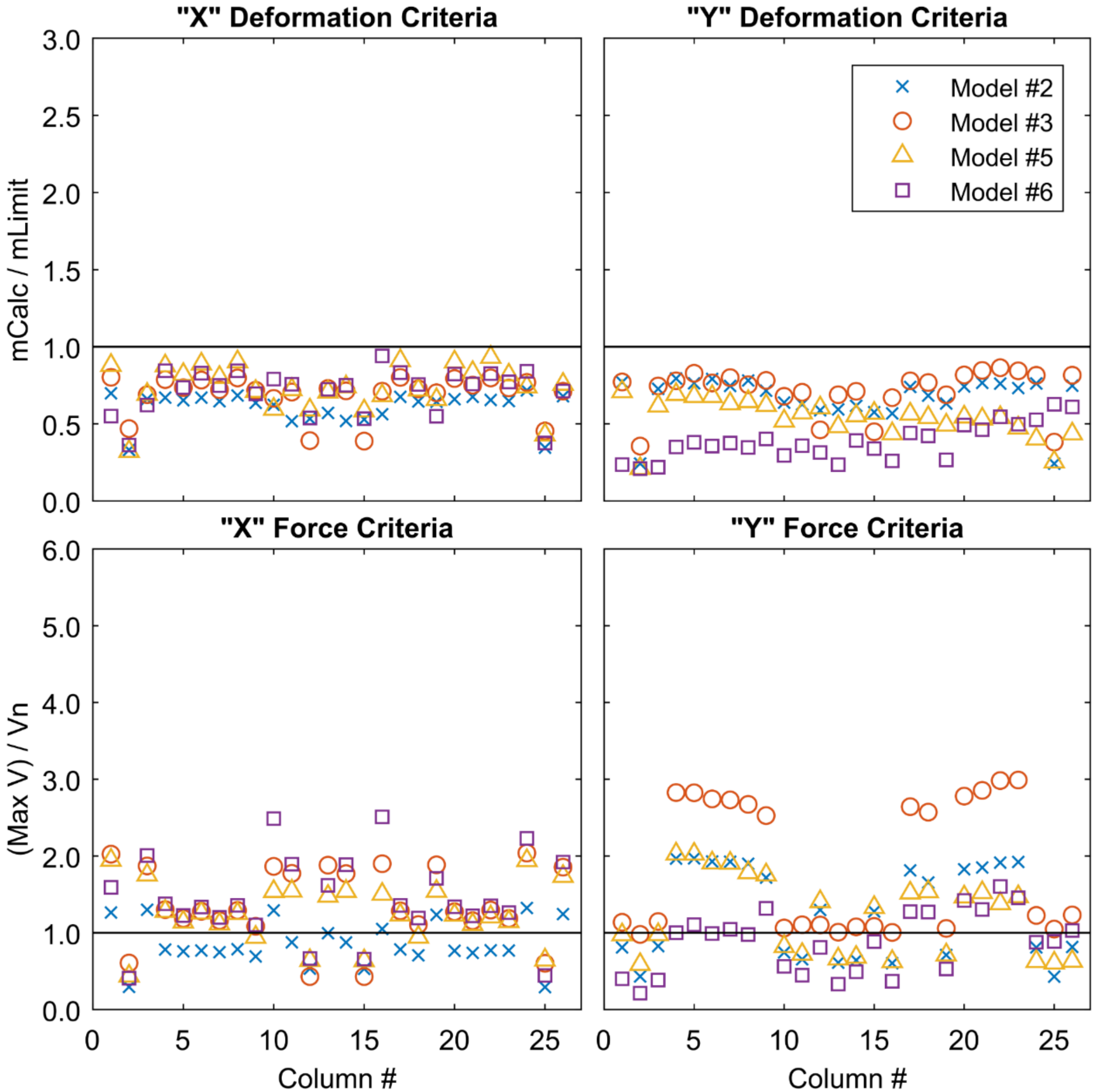


Deformation Controlled

$$\frac{m_{calc}}{m_{Table}} = \frac{M_{max}/M_{n,CE}}{m_{Table}}$$

Force Controlled

$$V_{max}/V_{n,CL}$$



Summary

1. Bare frame model is too flexible to provide a reliable characterization of structural response

2. All models predict (> 1) shear failure violation to acceptance criteria, though cases of shear failure identified for columns not damaged

3. No significant improvement between the ASCE 41 Compliant model and the variations that exceed code provisions

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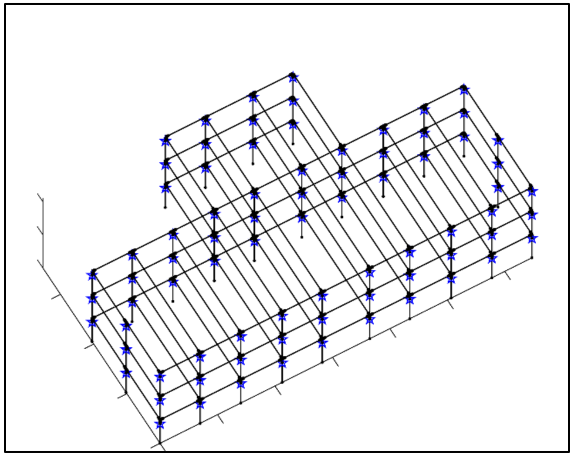
ASCE 41 Tier 3

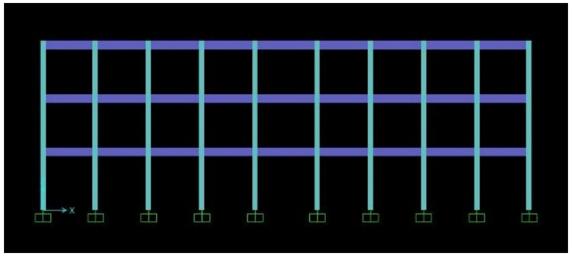
Nonlinear Analysis

Model Variations of Masonry Infill

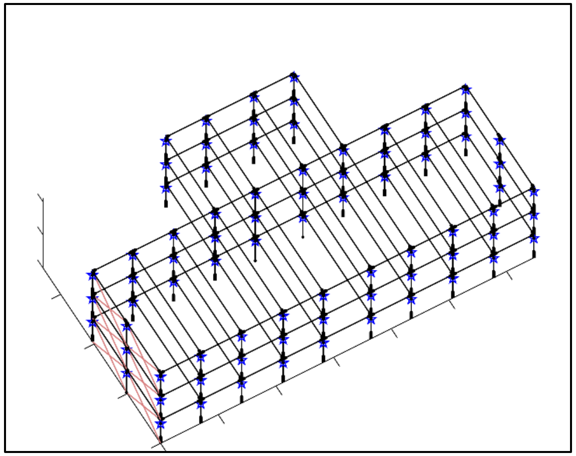
Model: CM	Model: NM	Model: FM	Model: CM1EI
Bare Frame	ASCE Compliant	ASCE (+)	ASCE (+)

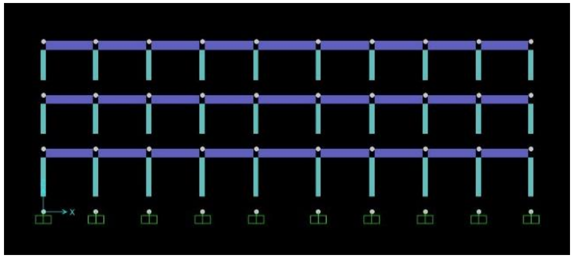
Bare Frame



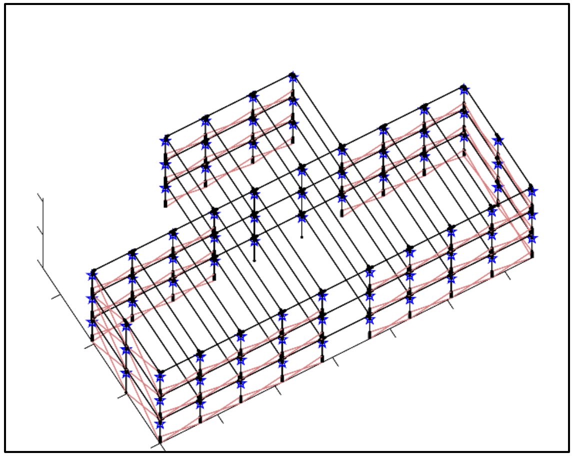


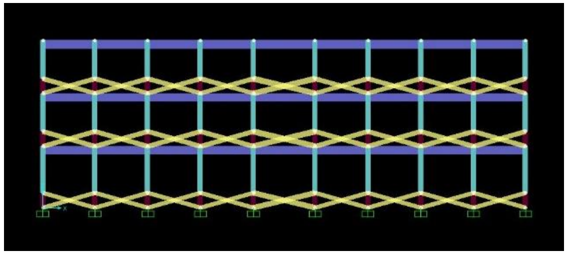
ASCE Compliant





Diagonal Struts



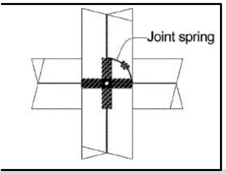


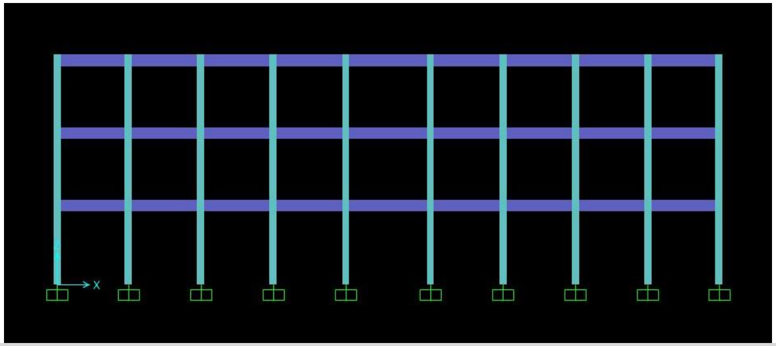
Bare Frame

Model: CM	Model: NM	Model: FM	Model: CM1EI
Bare Frame	ASCE Compliant	ASCE (+)	ASCE (+)

- Element Types
  - Column → beamWithHinges $0.30EI_g$ where $E = 57000\sqrt{f'_{cE}}$
  - Beam → elasticBeamColumn $0.35EI_g$
  - Slab → rigidDiaphragm Nodal constraint

- Joint Flexibility
  - Rigid joint assumption





Infill Variations

Model: CM	Model: NM	Model: FM	Model: CM1EI
Bare Frame	**ASCE Compliant**	**ASCE (+)**	**ASCE (+)**

Baseline of Bare Frame, but…

- Modeled Infill
  - FH → truss
  - PH → elasticBeamColumn

ASCE Compliant

NL hysteretic response, TBD
$5.00EI_g$

  - FH infill → truss
  - PH infill → truss

Diagonal Struts

NL hysteretic response, TBD
NL hysteretic response, TBD

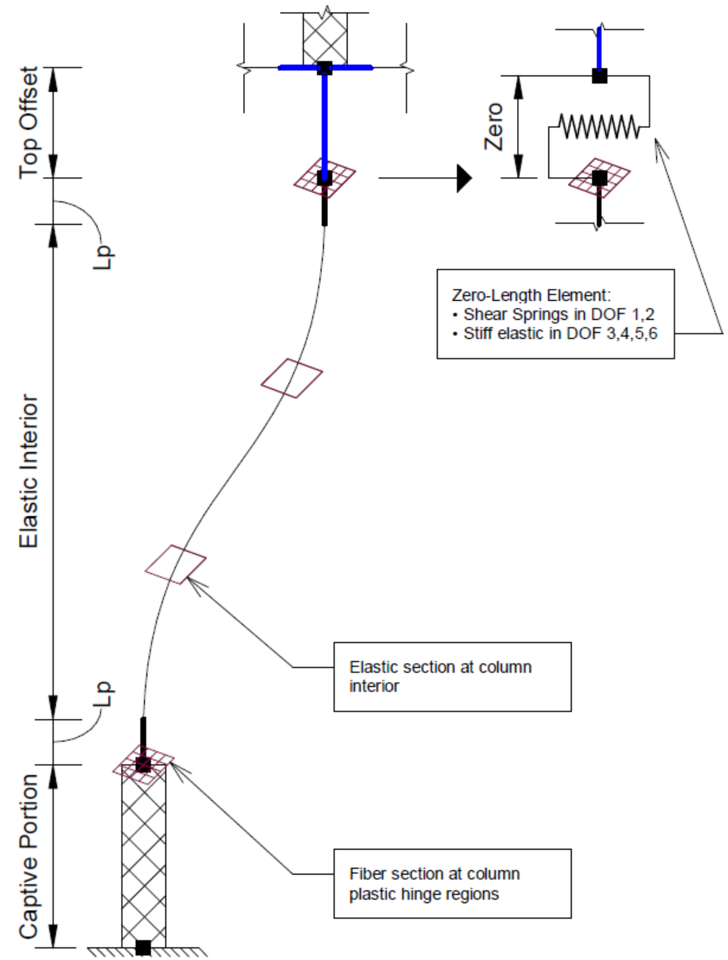
- Element Modification
  - Column → $1.00EI_g$

Stiffened Compliant

Differs Table 10-5 (ASCE 41-17)

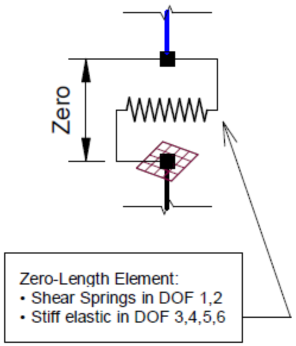
Model Details

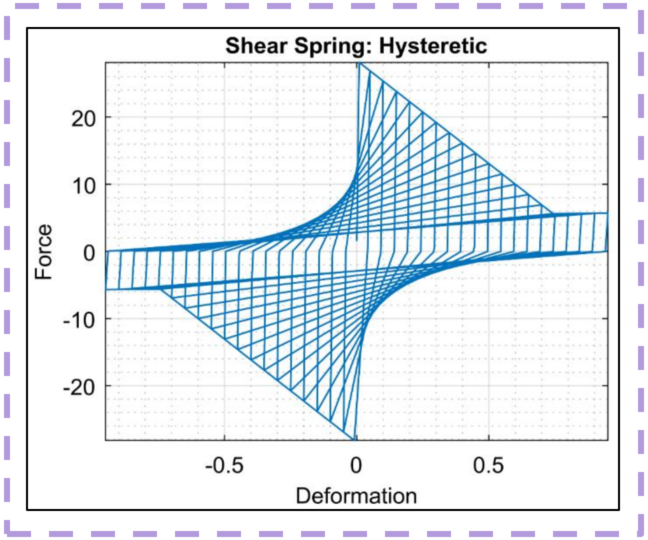
- NL Column
  - Force-based (*beamWithHinges*)
  - Defined plastic hinge regions at ends
  - (4) integration points
    - (1) each end with assigned fiber section
    - (2) interior with assigned elastic section
- Captive portion
  - Varies with treatment of partial-height infill
- Elastic beam
- Frame joint offsets
- Hysteretic shear spring



Constitutive Modeling: Shear Springs

- Zero-length elements
  - Top of all columns
  - Effective in both lateral translation DOFs
  - Defined, hysteretic material response w/ trilinear backbone
    - Elastic slope to $V_{n,CL}$
    - 1% degrading slope to $0.2V_n$

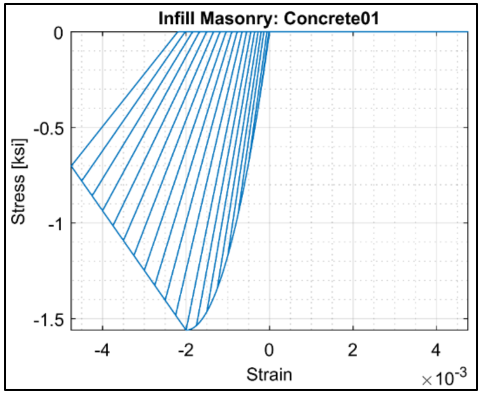




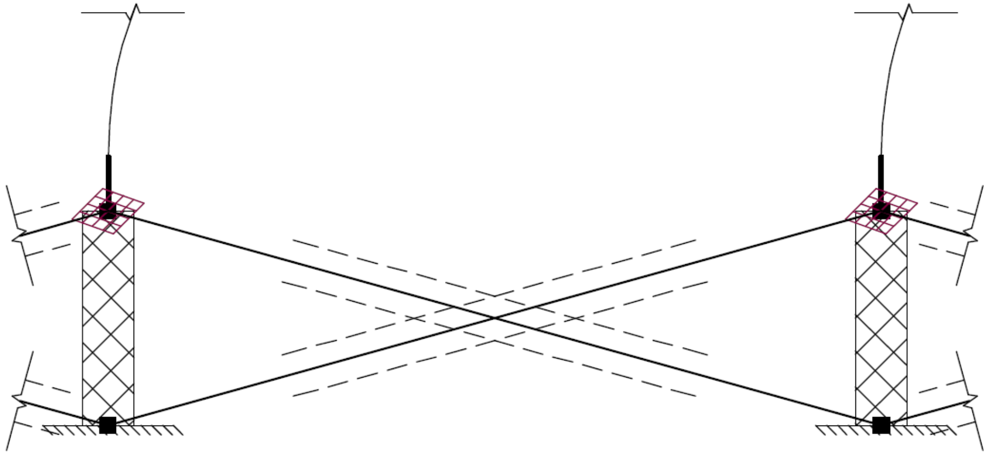
Constitutive Modeling: Masonry Struts

- Dual diagonal struts
  - Depth = Infill thickness (24cm)
  - Width → FEMA effective width

- Assigned Concrete01 uniaxial material
  - Kent-Park compression region
  - No tensile capacity
  - Masonry inputs as "weak concrete"



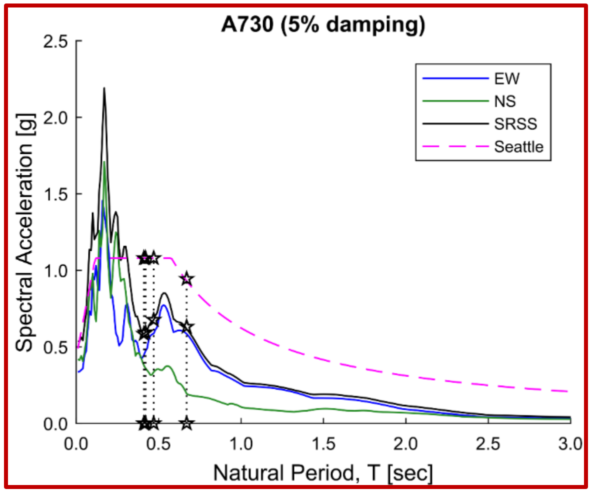
Captive region modeled with $5.00EI_g$ elasticBeamColumn



Noh, et al (2017): *Modeling of Masonry Infilled RC Frames Subjected to Cyclic Loads: State of the Art Review and Modeling with OpenSees*

Fundamental Periods and Spectral Acceleration

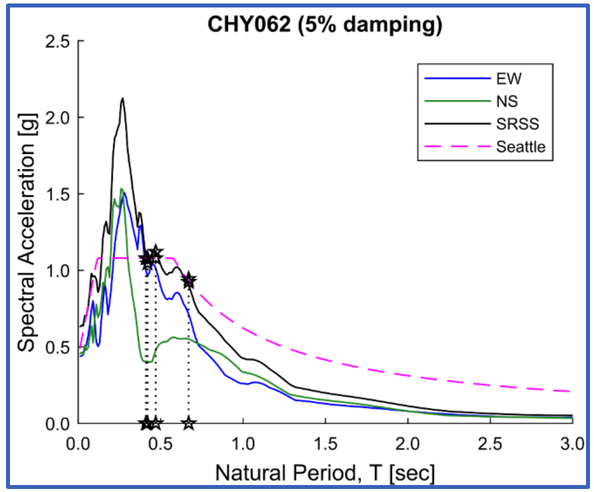
GM: A730



Model	Type	T_1	S_a
#2	BF	0.67	0.63
#3	C	0.47	0.68
#5	DS	0.41	0.59
#6	C+	0.42	0.59

Linear S_a ~ [0.22, 0.46]

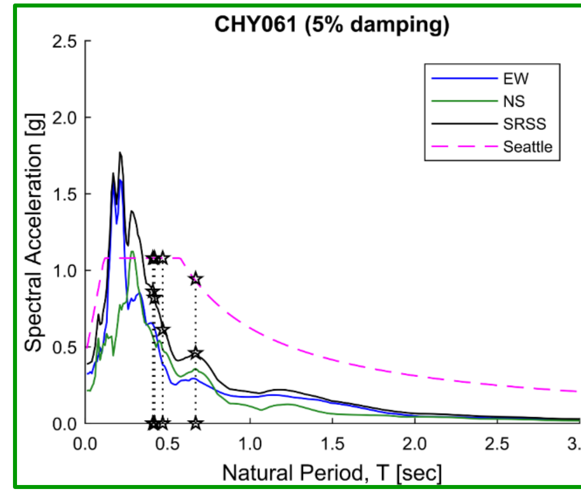
GM: CHY062



Model	Type	T_1	S_a
#2	BF	0.67	0.92
#3	C	0.47	1.12
#5	DS	0.41	1.08
#6	C+	0.42	1.05

Linear S_a ~ [0.52, 1.01]

GM: CHY061



Model	Type	T_1	S_a
#2	BF	0.67	0.46
#3	C	0.47	0.61
#5	DS	0.41	0.86
#6	C+	0.42	0.82

Linear S_a ~ [0.33, 0.73]

Linear T_1 ~ [0.43, 0.92]

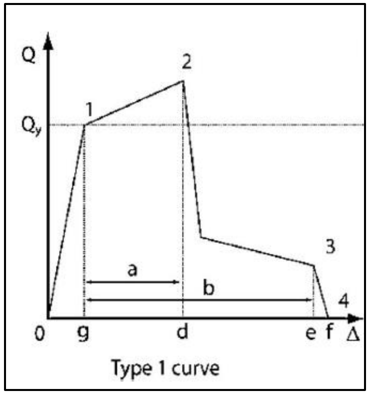
Applied Loading

- Gravity
  - $Q_{G1} = 1.1(DL+0.25LL)$ — Equation 7-1 (ASCE 41-17)
  - $Q_{G2} \rightarrow$ Not considered — Equation 7-2 (ASCE 41-17)

- Lateral
  - Explicit use of acceleration records — Section 7.4.2.2.2 (ASCE 41-17)
  - Not scaled — **Not** Section 2.4.3 (ASCE 41-17)
  - $Q_E = E_{EW}$ & E_{NS}
  - Newmark time-integration
  - 2.7% Modal damping† — Modes 1, 2, & 3
  - 0.3% Rayleigh damping† — Mass and stiffness proportional

† (90% | 10%) proportioning of modal damping to Rayleigh damping per recommendation from ATC project lead.

Acceptance Criteria



Deformation-controlled actions

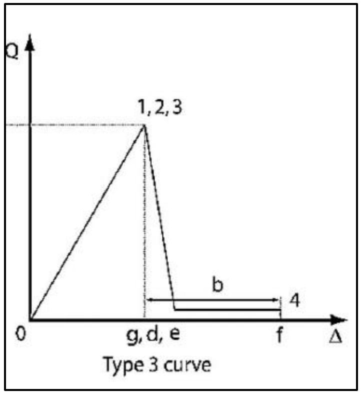
- Based on column rotation†
- Expected material strength
  - $f_{cE} = 1.50*f'_c$
  - $f_{yE} = 1.25*f_y$

  - Limit $= \dfrac{\varphi_{max} * L_p}{b}$ Limited to 0.7b, for CP

  - a $= \left[0.42 - 0.043\left(\dfrac{N_{UD}}{A_g f'_{cE}}\right) + 0.63\rho_t - 0.23\left(\dfrac{V_{yE}}{V_{Col0E}}\right)\right] \geq 0.0$
  - b $= \left[\dfrac{0.5}{5 + \left(\dfrac{N_{UD}}{A_g f'_{cE}}\right)\left(\dfrac{1}{\rho_t}\right)\left(\dfrac{f'_{cE}}{f_{ytE}}\right)} - 0.01\right] \geq a$ ASCE 41-17, Table 10-8

† Elastic curvature, intrinsic to output rotation deformation, was assumed negligible and thus not calculated or removed when compared to plastic rotation limit "b"

Acceptance Criteria



Force-controlled actions

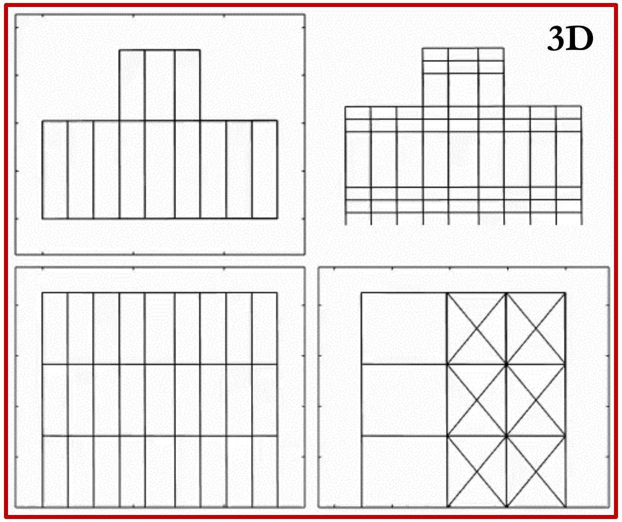
- Based on shear force
- Specified material strength
  - $f_{cL} = f'_c$
  - $f_{yL} = f_y$

- Limit $= \dfrac{V_{max}}{V_{n,CL}}$

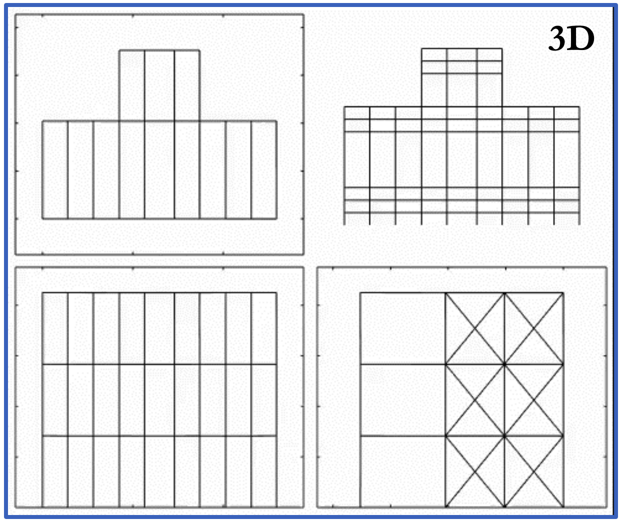
- $V_{n,CL} = k_{nl} * V_{Col0L}$ Eq. 10-3 (ASCE 41-17)

$$= k_{nl}\left[\alpha_{Col}\left(\frac{A_v f_{ytL} d}{a}\right) + \lambda\left(\frac{6\sqrt{f'_{cL}}}{M_{UD}/V_{UD}d} * \sqrt{1+\frac{N_{UD}}{6\sqrt{f'_{cL}}A_g}}\right)0.8A_g\right]$$

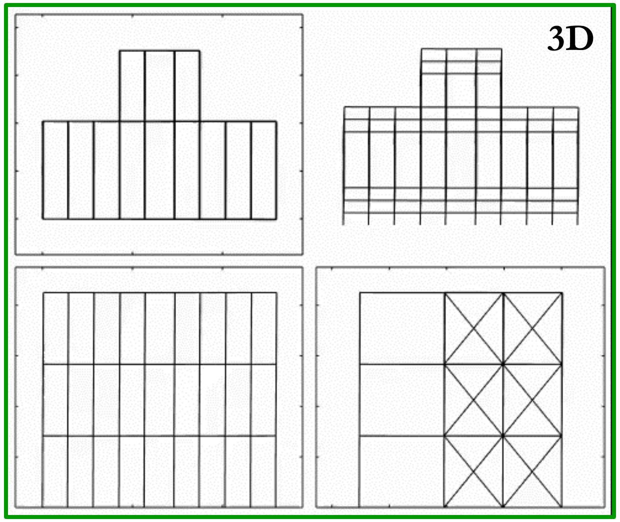
Analysis Results



ASCE Compliant
GM: A730



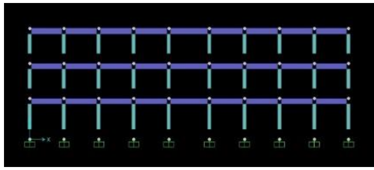
ASCE Compliant
GM: CHY062

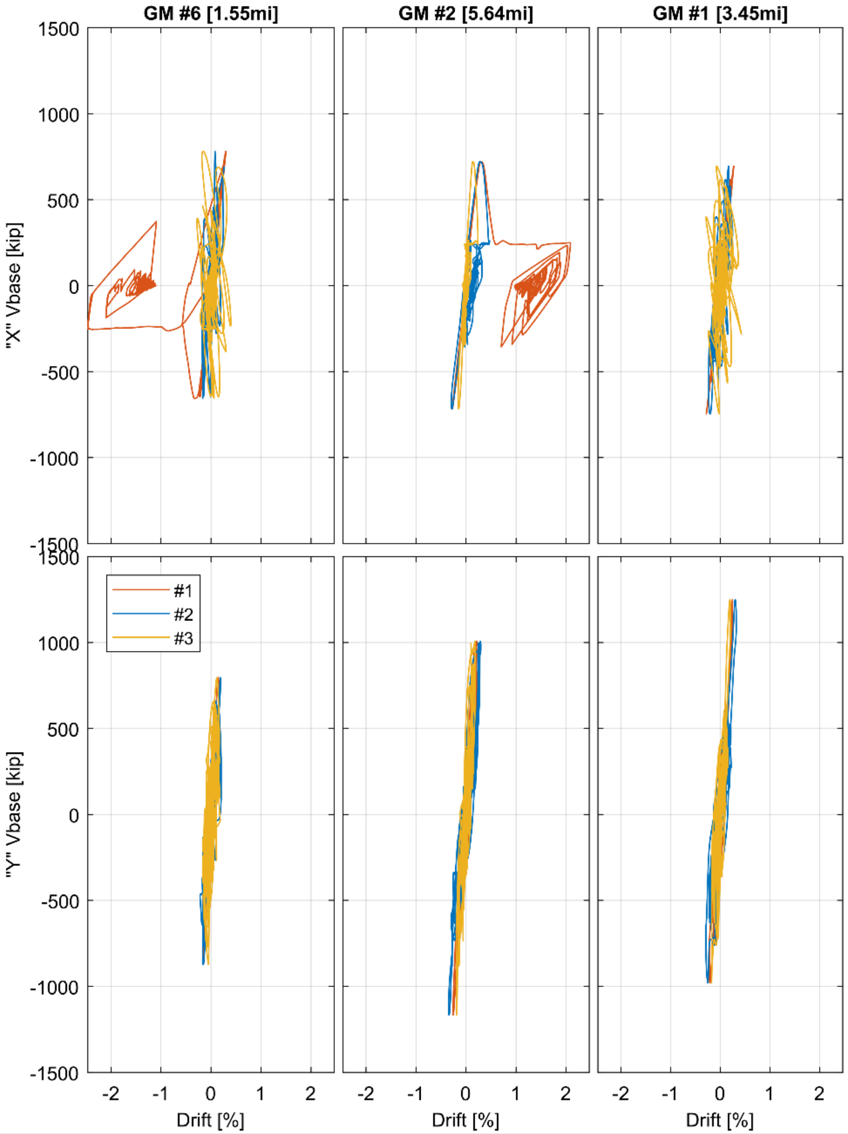


ASCE Compliant
GM: CHY061

Analysis Results: V_{base} vs Story Drift

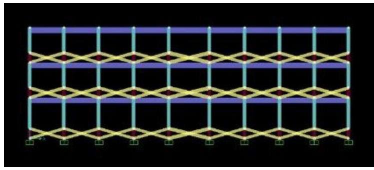
ASCE Compliant

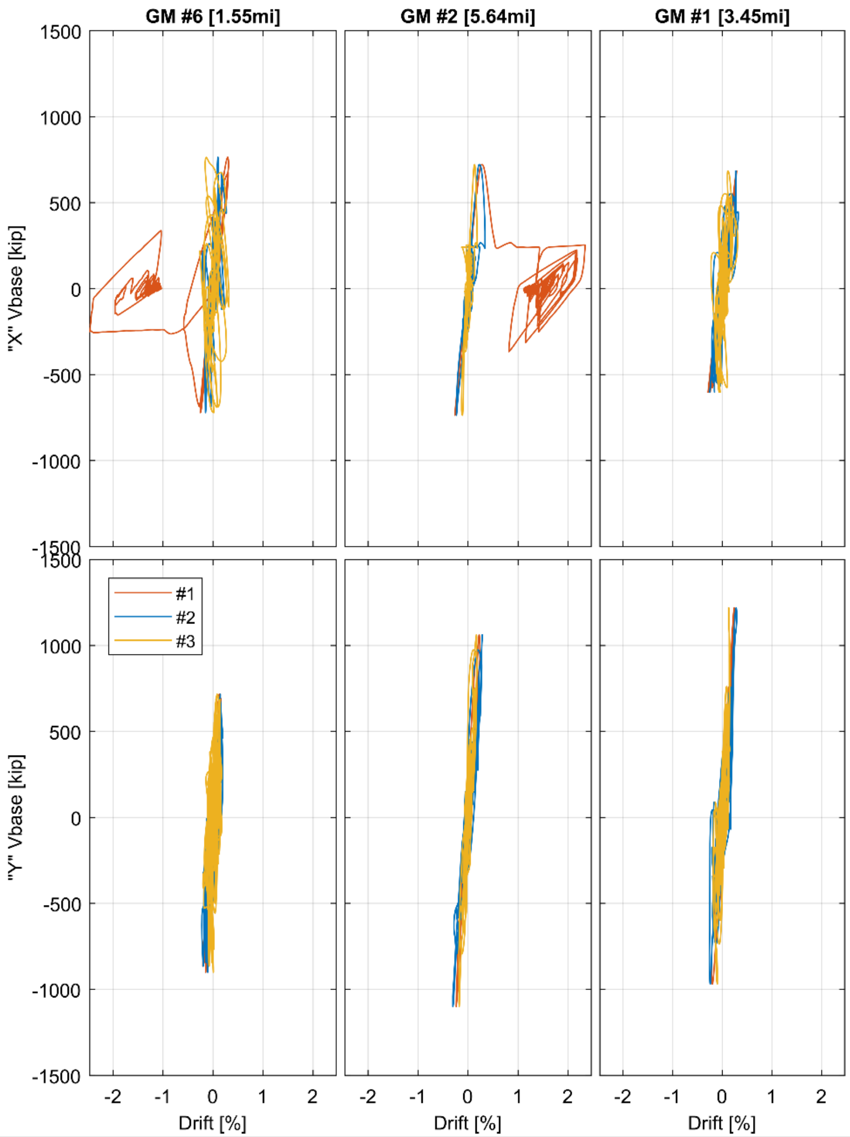




Analysis Results: V_{base} vs Story Drift

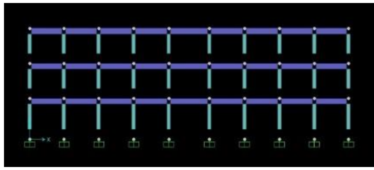
Diagonal Struts

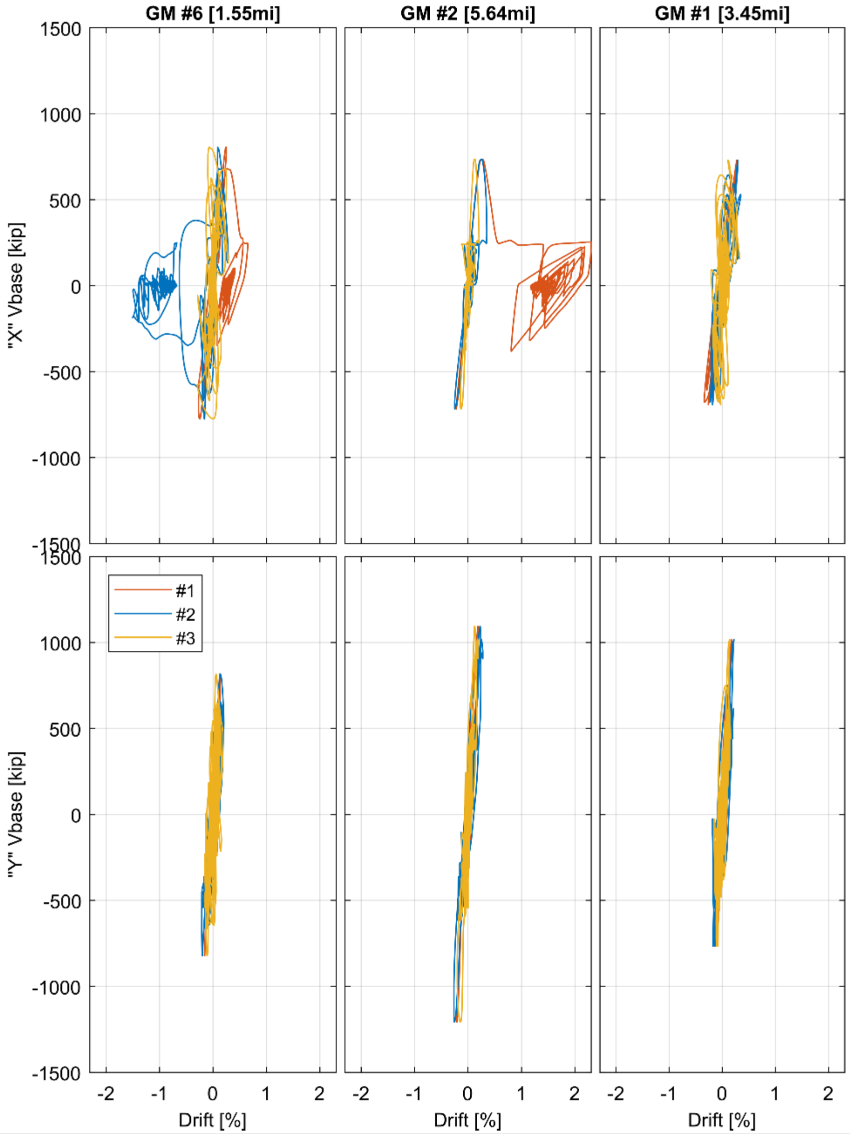


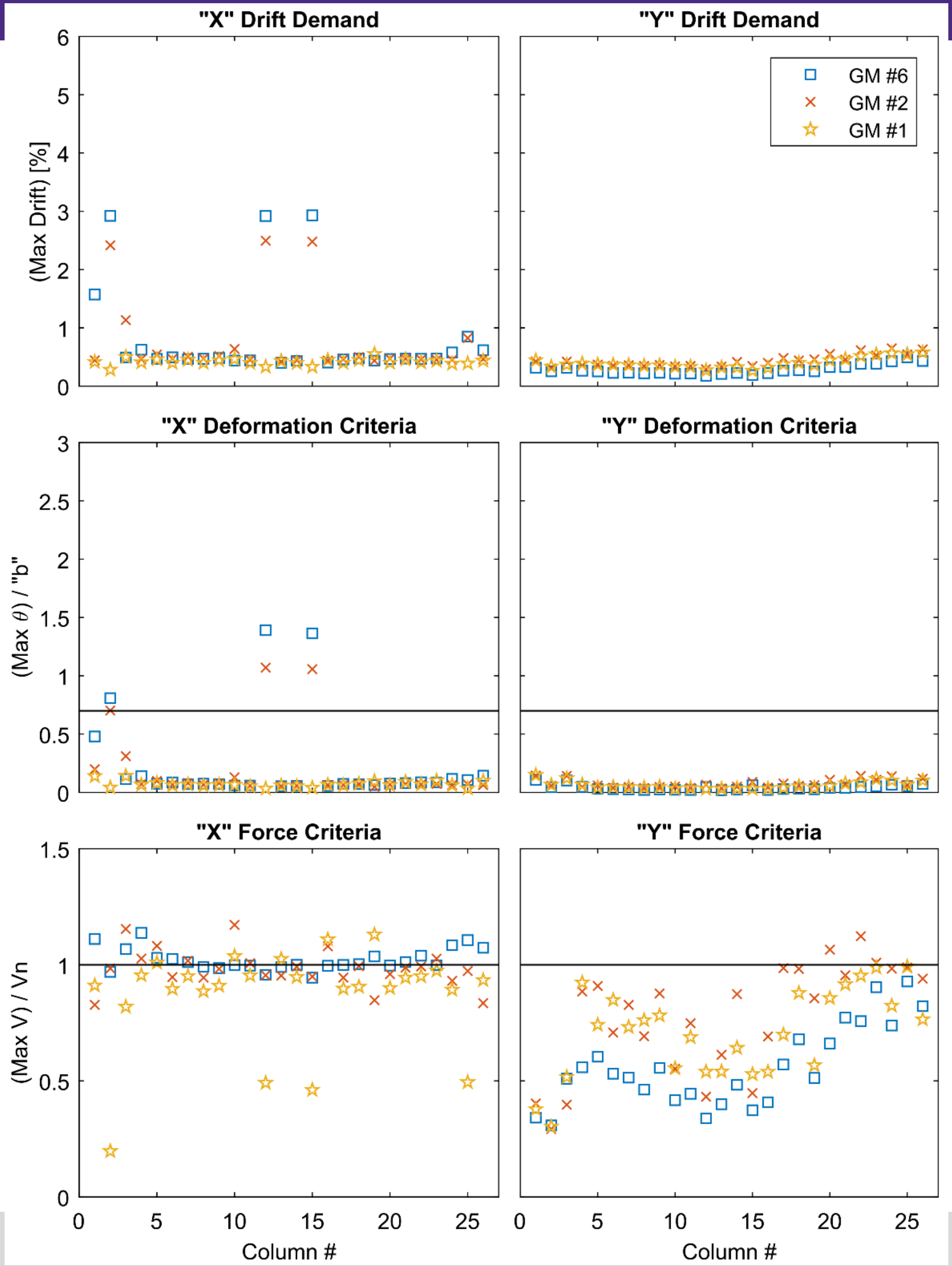


Analysis Results: V_{base} vs Story Drift

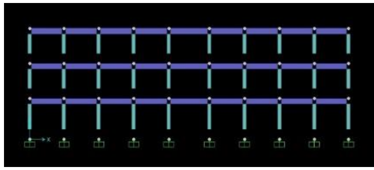
Stiffened Compliant





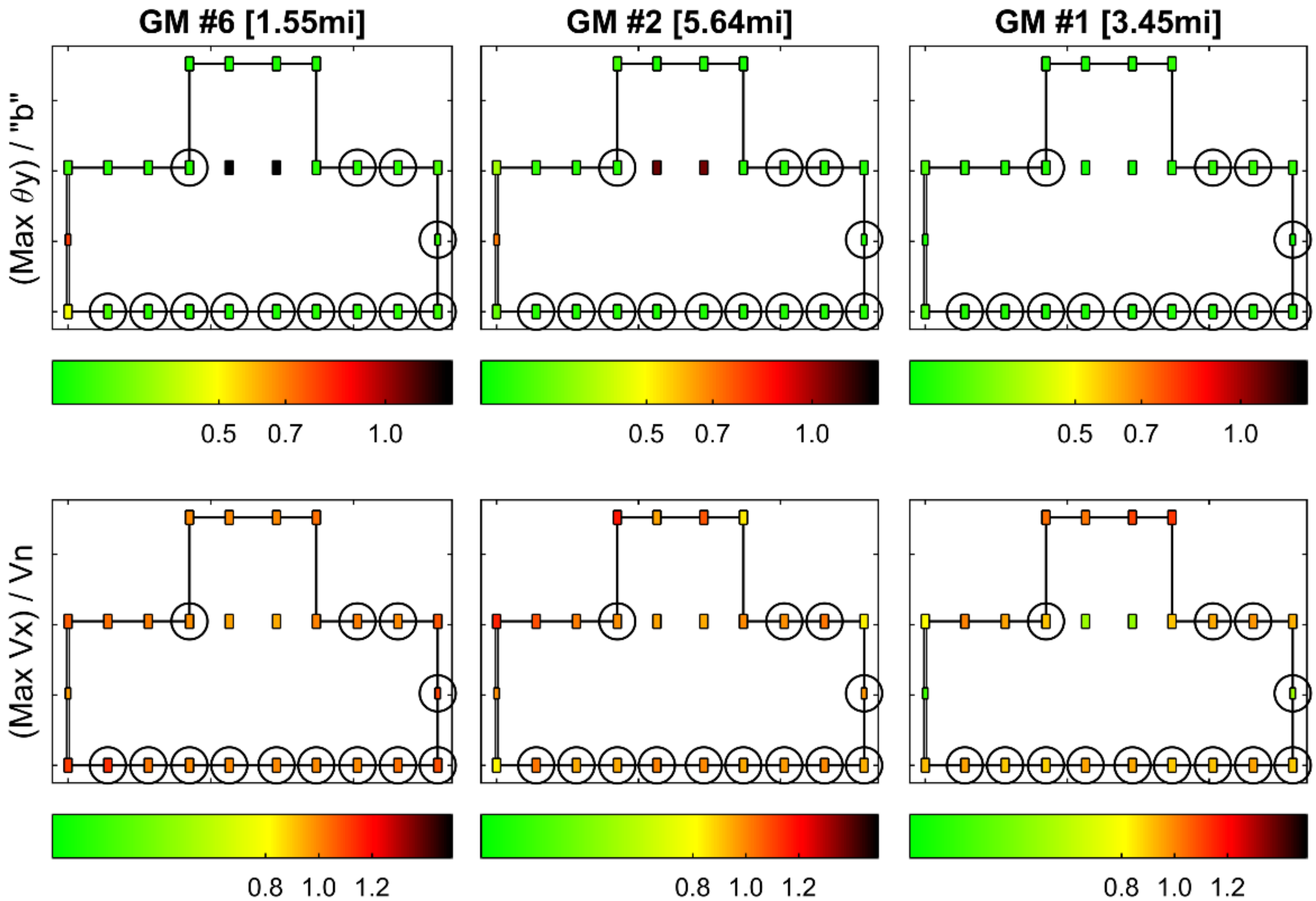


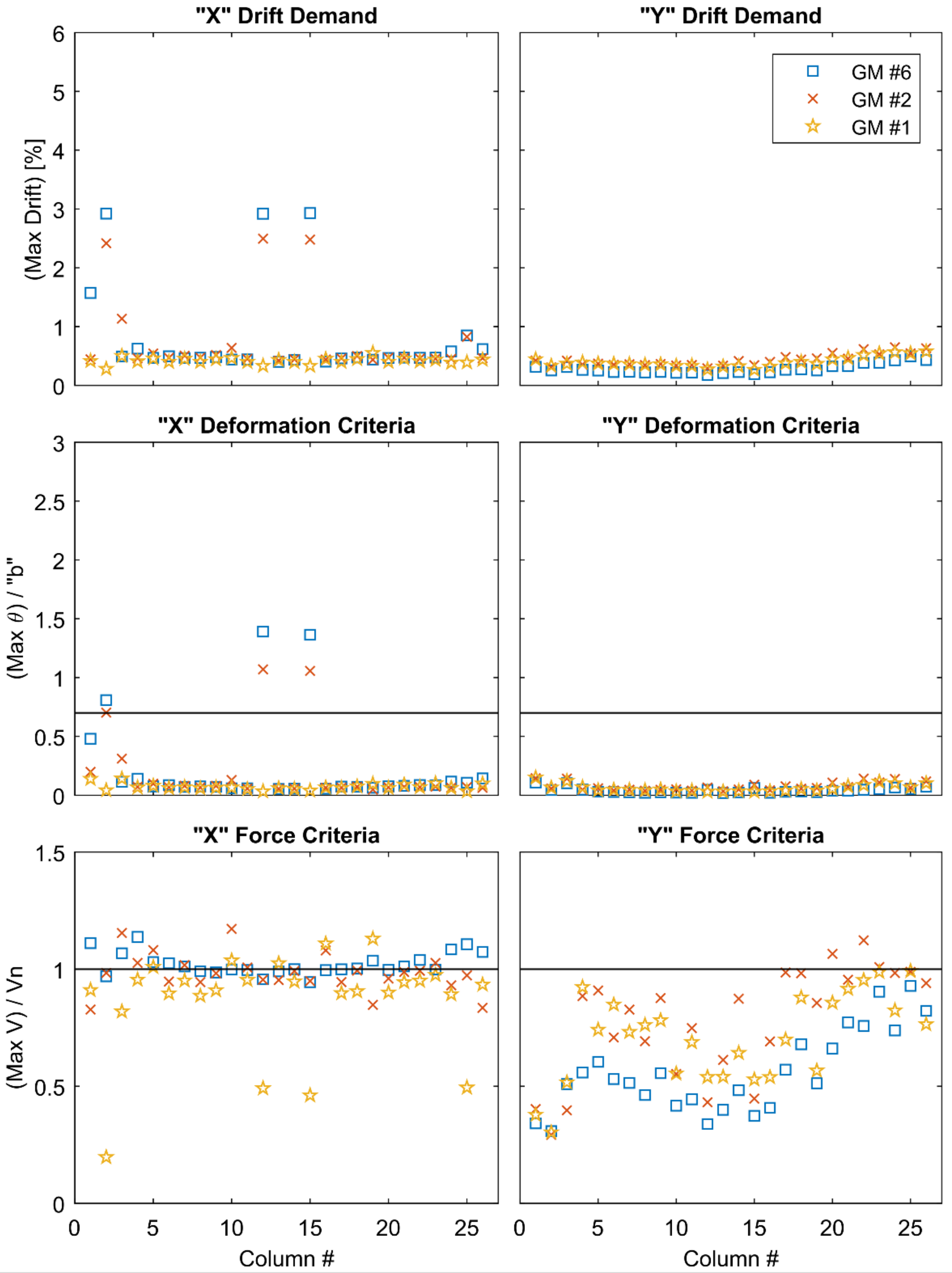
ASCE Compliant



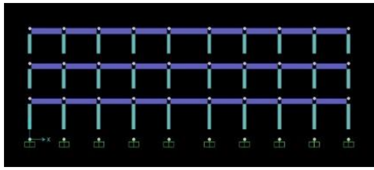
Analysis Results

ASCE Compliant

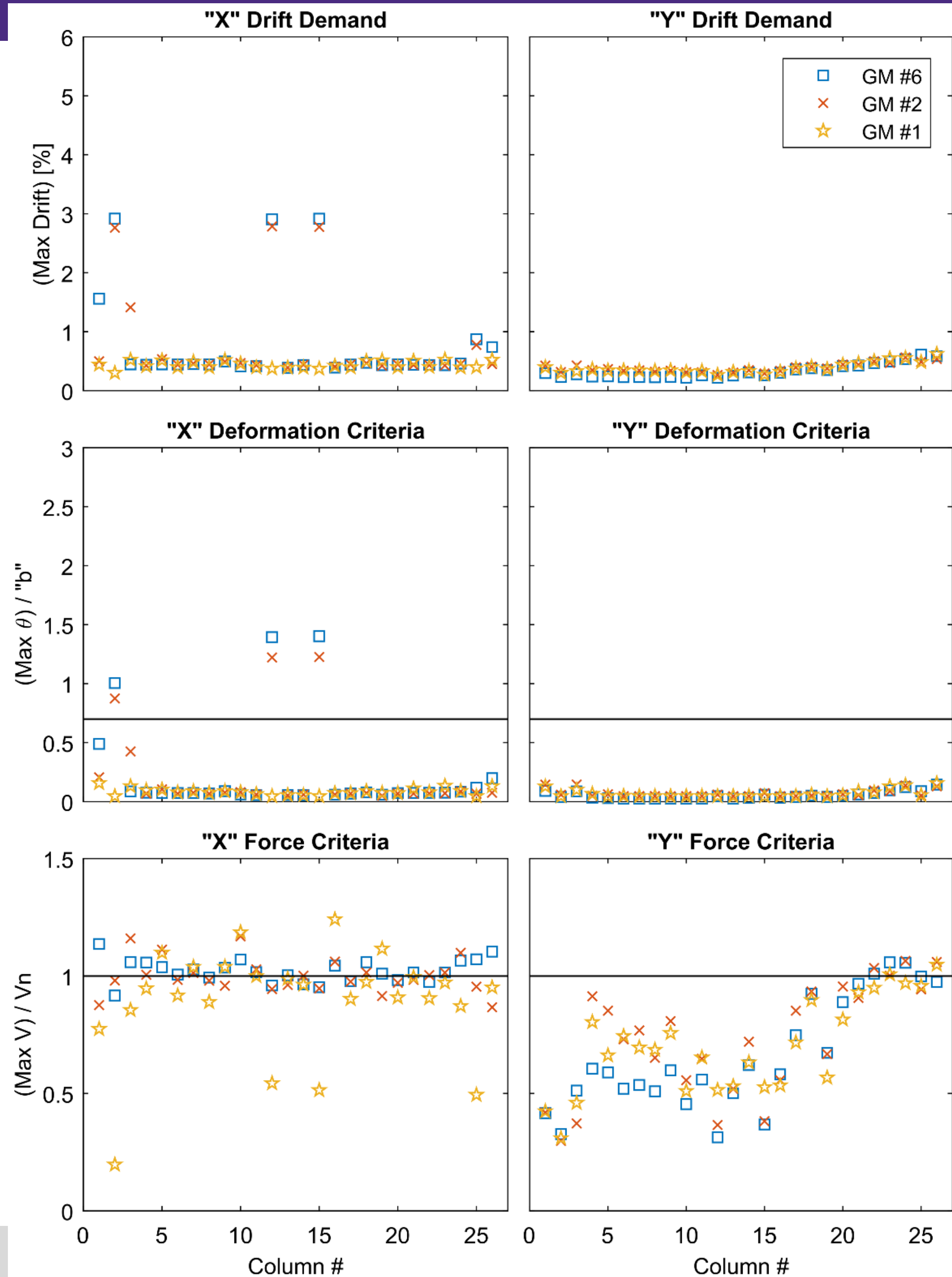




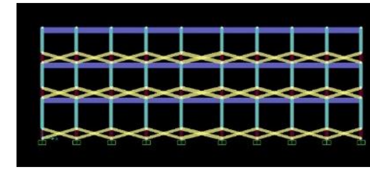
ASCE Compliant



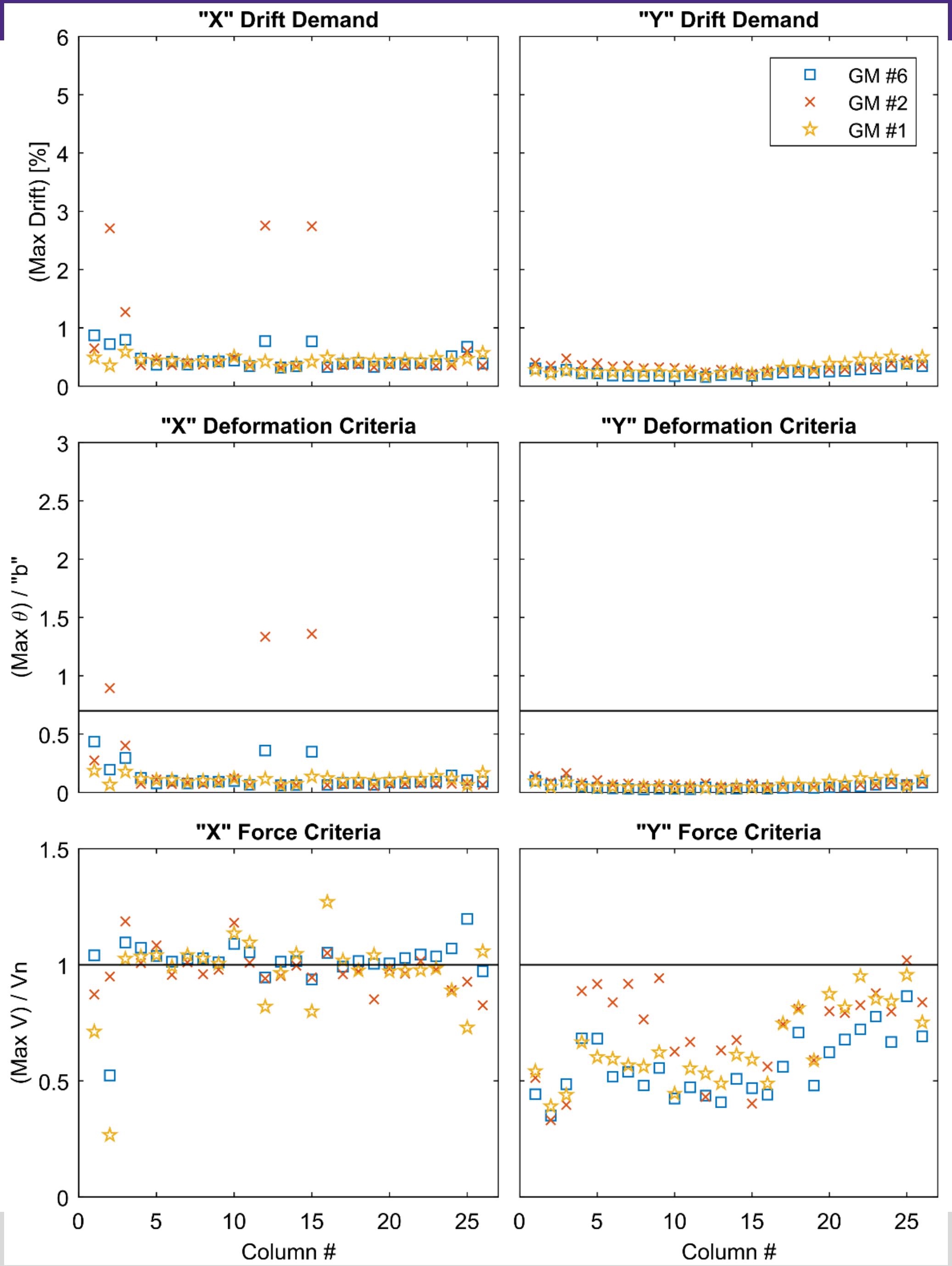
Many shear "failures": $V_{max} \approx V_n$



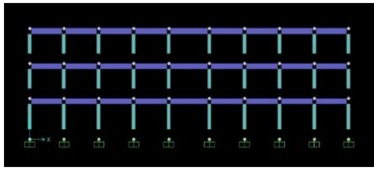
Diagonal Struts



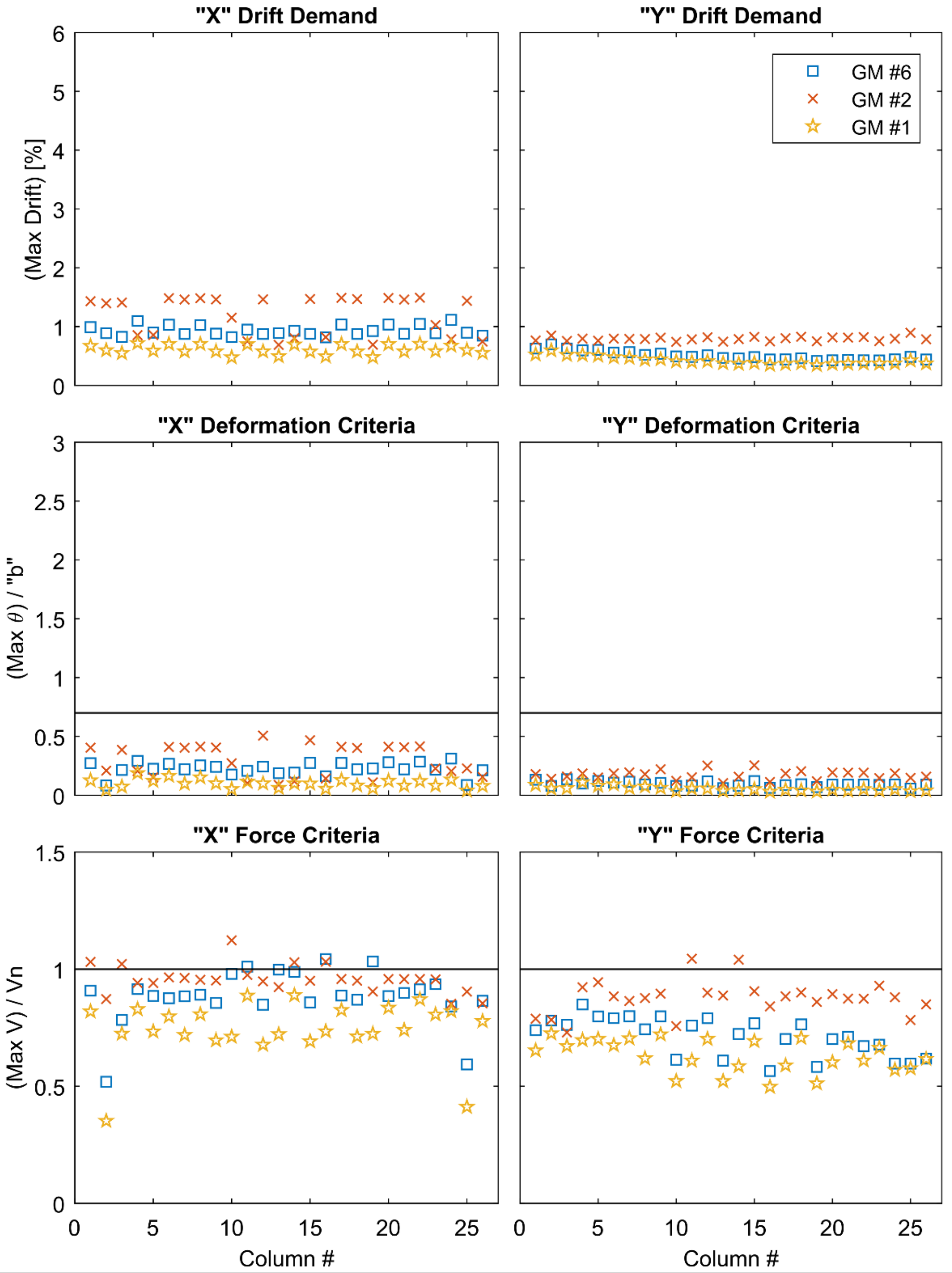
Many shear "failures": $V_{max} \approx V_n$



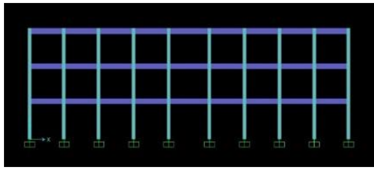
Stiffened Compliant



Many shear "failures": $V_{max} \approx V_n$



Bare Frame



Few shear "failures"

Summary

1. "Failure" pattern is not consistent with the observed damage. Damage suggests limited deformations on the N&NW. One rationale is that the un-modeled "addition" that would have otherwise restrained motion

2. No significant improvement between the ASCE 41 Compliant model and the variations that exceed code provisions

3. Limitations intrinsic to the hysteretic shear model (no consideration of axial load amplification on shear capacity) pre-maturely govern response

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Conclusion

Overarching Conclusions

1. **Partial-height infill**
   - Need to model partial-height infill.
   - Neglecting partial-height infill results in model that is too soft (large T) and under-prediction of demands (small S_a (T).
   - ASCE 41 recommendations for modeling infill should be improved; current recommendations are difficult to understand.
   - Different methods for modeling infill produce approximately the same results.

2. **Modeling column shear failure**
   - Need to model column shear failure; shear failure determines system response
   - Likely need improved nonlinear response models that include axial load in calculation of shear capacity, V_n