Procedure of Performance-based Design

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Performance-based Design

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Performance-based design

- More explicit evaluation of the safety and reliability of structures.
- Provides opportunity to clearly define the levels of hazards to be designed against, with the corresponding performance to be achieved.
- Code provisions are intended to provide a minimum level of safety.
- Shortcoming of traditional building codes (for seismic design) is that the performance objectives are considered implicitly.
- Code provisions contain requirements that are not specifically applicable to tall buildings which may results in designs that are less than optimal, both from a cost and safety perspective.
- Verify that code-intended seismic performance objectives are met.

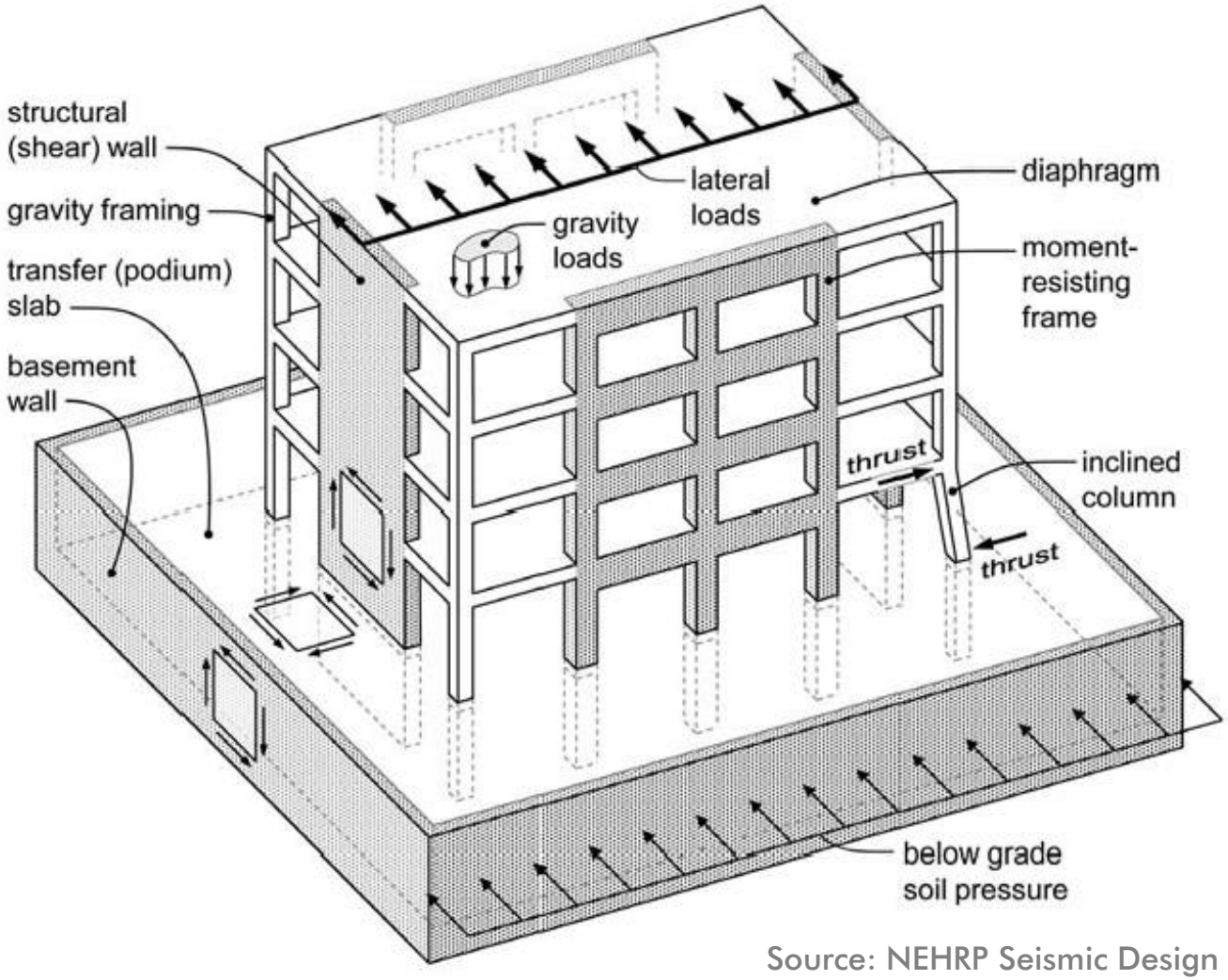
The Building Structural System - Conceptual

- **The Gravity Load Resisting System**
  - The structural system (beams, slab, girders, columns, etc.) that acts primarily to support the gravity or vertical loads

- **The Lateral Load Resisting System**
  - The structural system (columns, shear walls, bracing, etc.) that primarily acts to resist the lateral loads

- **The Floor Diaphragm**
  - The structural system that transfers lateral loads to the lateral load resisting system and provides in-plane floor stiffness

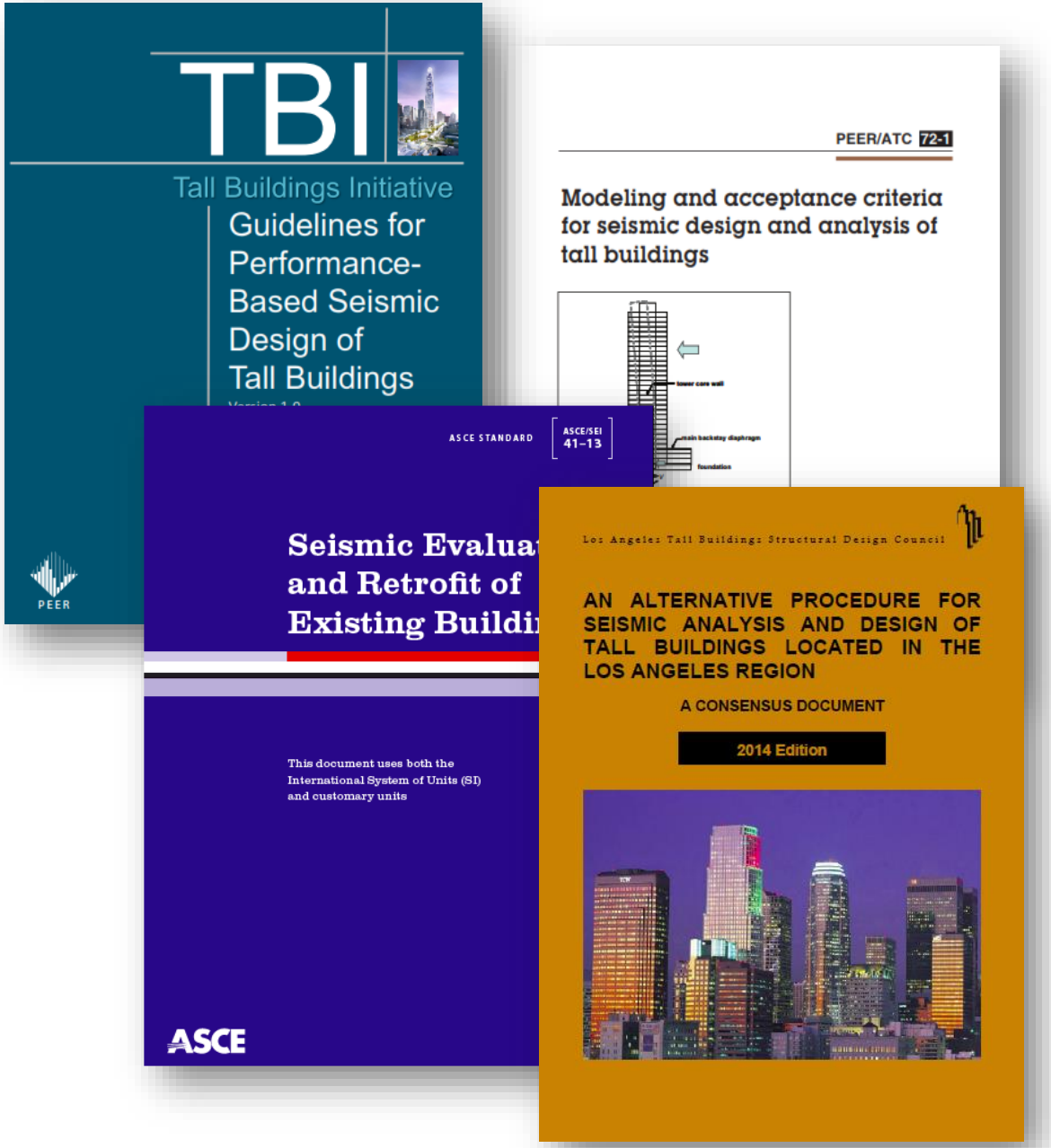
Structural System



Source: NEHRP Seismic Design Technical Brief No. 3

PBD Guidelines

- **PEER 2010/05**, "Tall Building Initiative, Guidelines for Performance Based Seismic Design of Tall Buildings"
- **PEER/ATC 72-1**, "Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings"
- **ASCE/SEI 41-13**, "Seismic Evaluation and Retrofit of Existing Buildings"
- **LATBSDC 2014**, "An Alternative Procedure for Seismic Analysis and Design of Tall Buildings Located in the Los Angeles Region"



Required Information

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Required Information

- Basis of design
- Geotechnical investigation report
- Site-specific probabilistic seismic hazard assessment report
- Wind tunnel test report

Basis of Design

- Description of building
- Structural system
- Codes, standards, and references
- Loading criteria
  - Gravity load, seismic load, wind load
- Materials
- Modeling, analysis, and design procedures
- Acceptance criteria

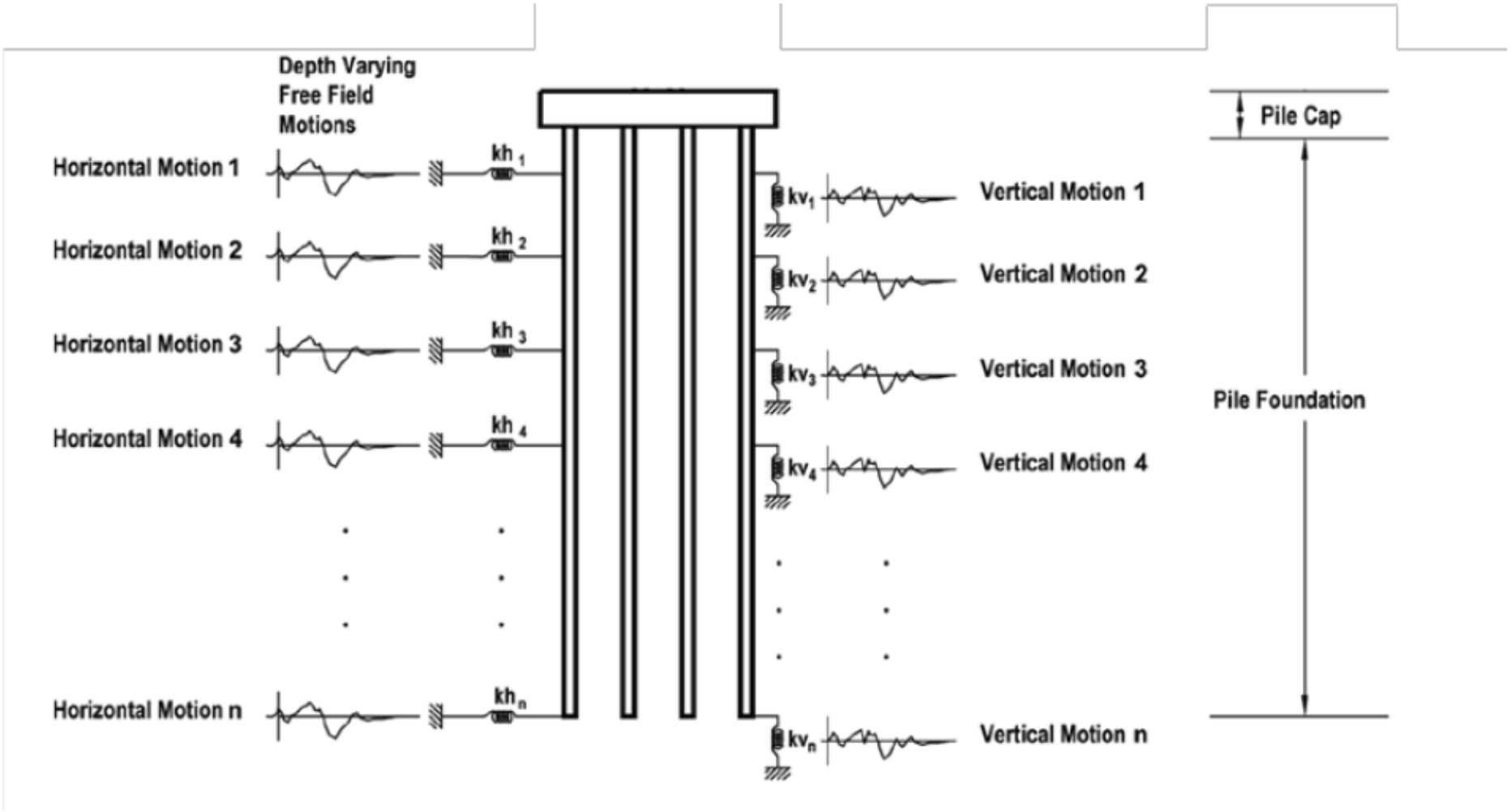
Geotechnical Investigation Report

- SPT values
- Soil stratification and properties
- Soil type for seismic loading
- Ground water level
- Allowable bearing capacity (Factors to increase in capacity for transient loads and stress peaks)
- Sub-grade modulus (Vertical and lateral)
- Liquefaction potential
- Pile foundation
  - Ultimate end bearing pressure vs. pile length
  - Ultimate skin friction pressure vs. pile length
  - Allowable bearing capacity
  - Allowable pullout capacity
- Basement wall pressure

Site-specific Probabilistic Seismic Hazard Assessment Report

- Recommend response spectra (SLE, DBE, MCE)
- Ground motions scaled for MCE spectra
- If piles are modeled in nonlinear model,
  - Depth-varying ground motions along the pile length
  - Springs and dashpots
- If vertical members are restrained at pile cap level,
  - Amplified ground motions at surface level

Depth-varying Ground Motions along Pile Length



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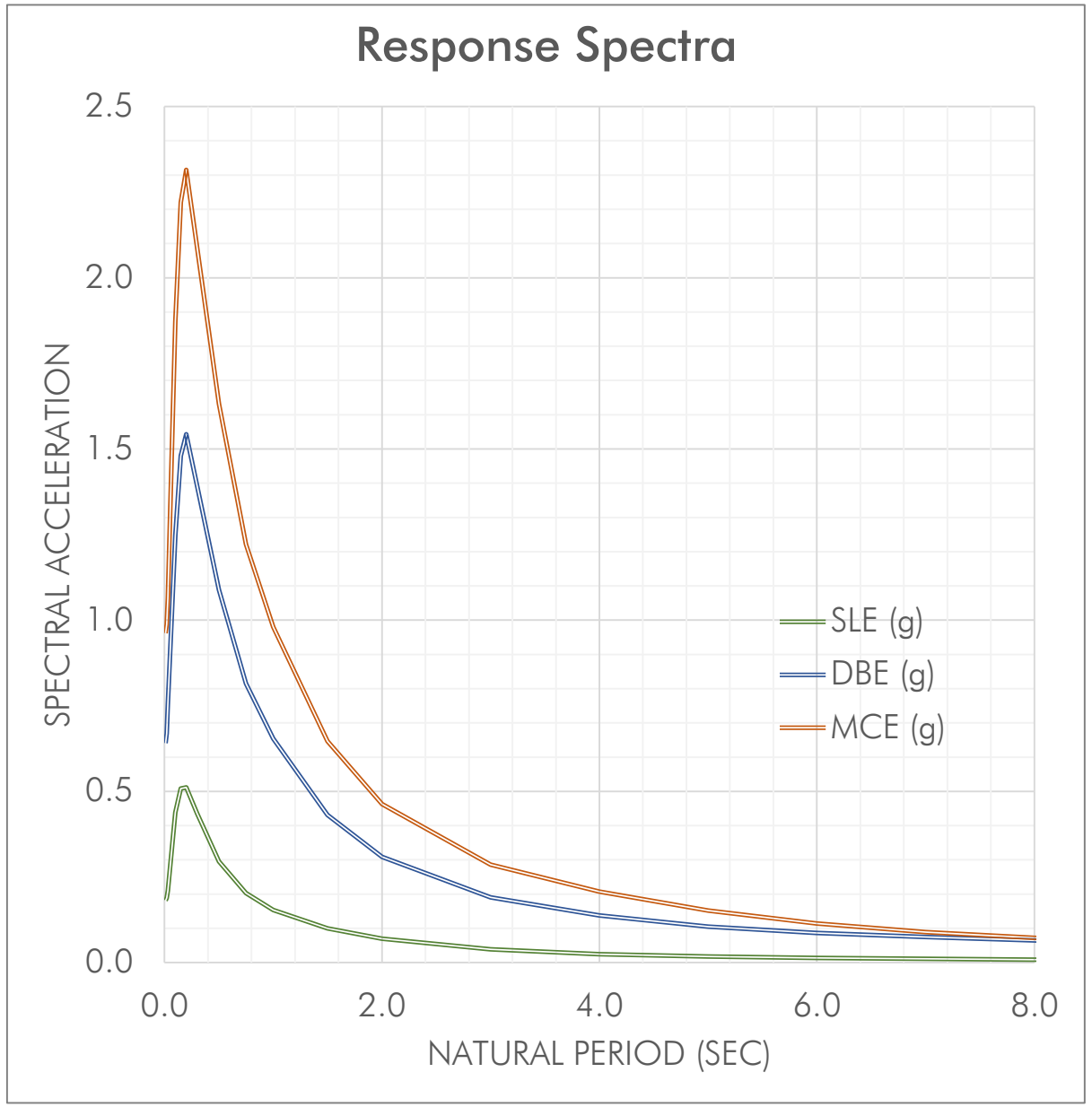
Response Spectra

- **Service Level Earthquake (SLE)**
  - 50% of probability of exceedance in 30 years (43-year return period)
- **Design Basis Earthquake (DBE)**
  - 10% of probability of exceedance in 50 years (475-year return period)
- **Maximum Considered Earthquake (MCE)**
  - 2% of probability of exceedance in 50 years (2475-year return period)



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Wind Tunnel Test Report

- Wind-induced structural loads and building motion study
  - **10-year** return period wind load
  - **50-year** or **700-year** return period wind load
  - Comparison of wind tunnel test results with various wind codes
  - Floor accelerations (1-year, 5-year return periods)
  - Rotational velocity (1-year return period)
  - Natural frequency sensitivity study

Performance-based Design Procedure

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- Geotechnical investigation
- Probabilistic seismic hazard assessment

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Preliminary design

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Wind tunnel test

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Detailed code-based design

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SLE Evaluation

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MCE Evaluation

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Peer review

Performance-based Design Procedure

Preliminary design

Structural system development

- Bearing wall system
- Dual system
- Special moment resisting frame
- Intermediate moment resisting frame

Finite element modeling

- Linear analysis models
- Different stiffness assumptions for seismic and wind loadings

Check overall response

- **Modal analysis**
  - Natural period, mode shapes, modal participating mass ratios
- **Gravity load response**
  - Building weight per floor area
  - Deflections
- **Lateral load response (DBE, Wind)**
  - Base shear, story drift, displacement

Preliminary member sizing

- Structural density ratios
- Slab thickness
- Shear wall thickness
- Coupling beam sizes
- Column sizes

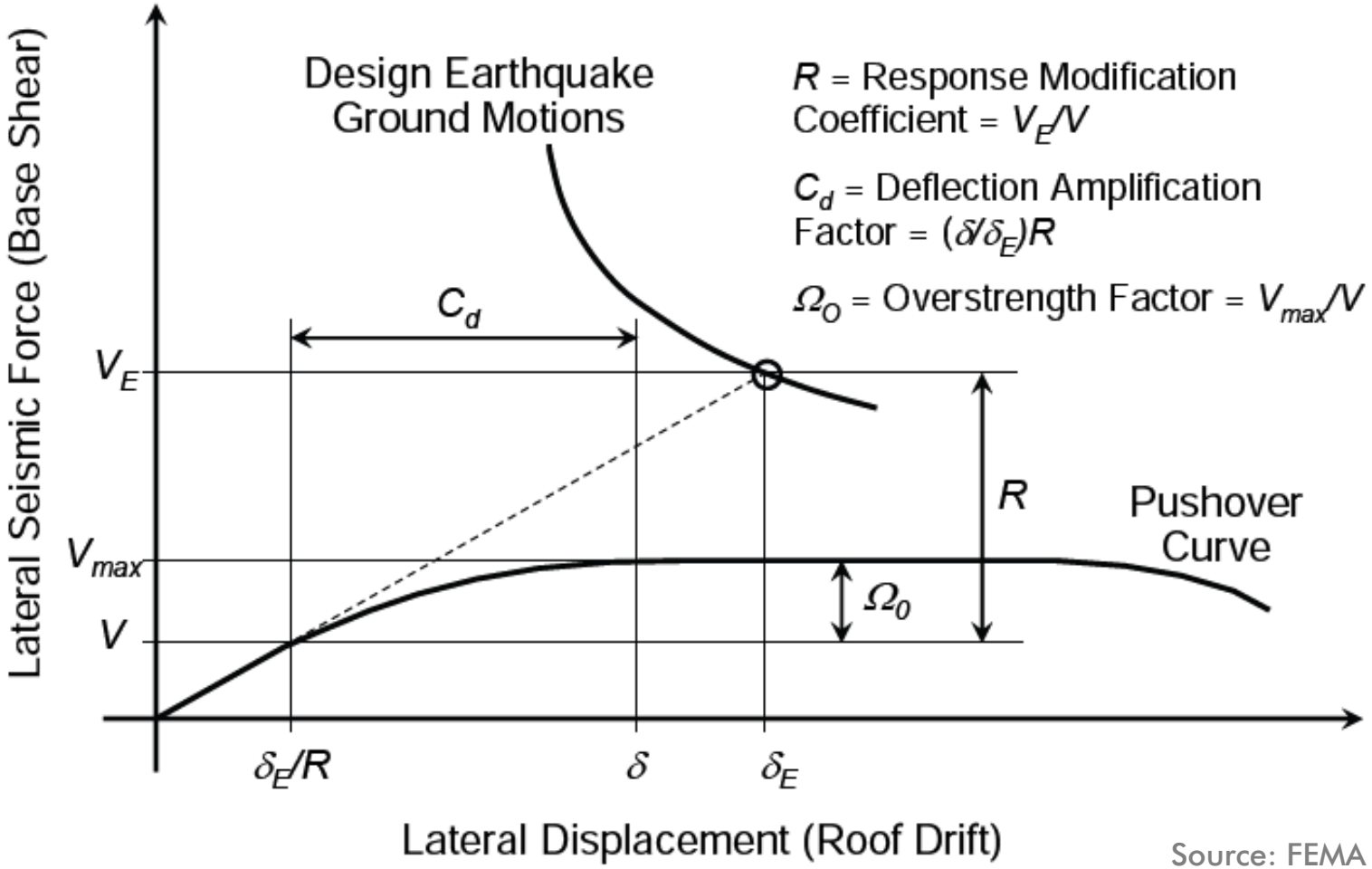
Detailed Code-based Design

- **Modeling**
  - Nominal material properties are used.
  - Different cracked section properties for wind and seismic models
  - Springs representing the effects of soil on the foundation system and basement walls
- **Gravity load design**
  - Slab
  - Secondary beams
- **Wind design**
  - Apply wind loads from wind tunnel test in mathematical model
  - Ultimate strength design
    - 50-year return period wind load x Load factor
    - 700-year return period wind load
  - Serviceability check
    - Story drift ≤ 0.4%, Lateral displacement ≤ H/400 (10-year return period wind load)
    - Floor acceleration (1-year and 5-year return period wind load)

Detailed code-based design

- **Seismic design (DBE)**
  - Use recommended design spectra of DBE from PSHA
  - Apply seismic load in principal directions of the building
  - Scaling of base shear from response spectrum analysis
  - Consider accidental torsion, directional and orthogonal effects
  - 5% of critical damping is used for un-modeled energy dissipation
  - Define load combinations with load factors
  - Design and detail reinforcement

Scaling of Response Spectrum Analysis Results



Source: FEMA P695 | June 2009

SLE Evaluation

- Linear model is used.
- Site-specific service level response spectrum is used without reduction by scale factors.
  - 2.5% of critical damping is used for un-modeled energy dissipation.
  - $1.0D + 0.25\ L \pm 1.0\ E_{SLE}$
- Seismic orthogonal effects are considered.
- Accidental eccentricities are not considered in serviceability evaluation.
- Response modification coefficient, overstrength factor, redundancy factor and deflection amplification factor are not used in serviceability evaluation.

Acceptance Criteria (SLE)

- Demand to capacity ratios
  - ≤ 1.5 for deformation-controlled actions
  - ≤ 0.7 for force-controlled actions
- Capacity is computed based on nominal material properties with the strength reduction factor of 1.
- Story drift shall not exceed 0.5% of story height in any story with the intention of providing some protection of nonstructural components and also to assure that permanent lateral displacement of the structure will be negligible.

MCE Evaluation

- Nonlinear model is used.
- Nonlinear response history analysis is conducted.
- Seven pairs of site-specific ground motions are used.
- 2.5% of constant modal damping is used with small fraction of Rayleigh damping for un-modeled energy dissipation.
- Average of demands from seven ground motions approach is used.
- Capacities are calculated using expected material properties and strength reduction factor of 1.0.

Expected Material Strengths

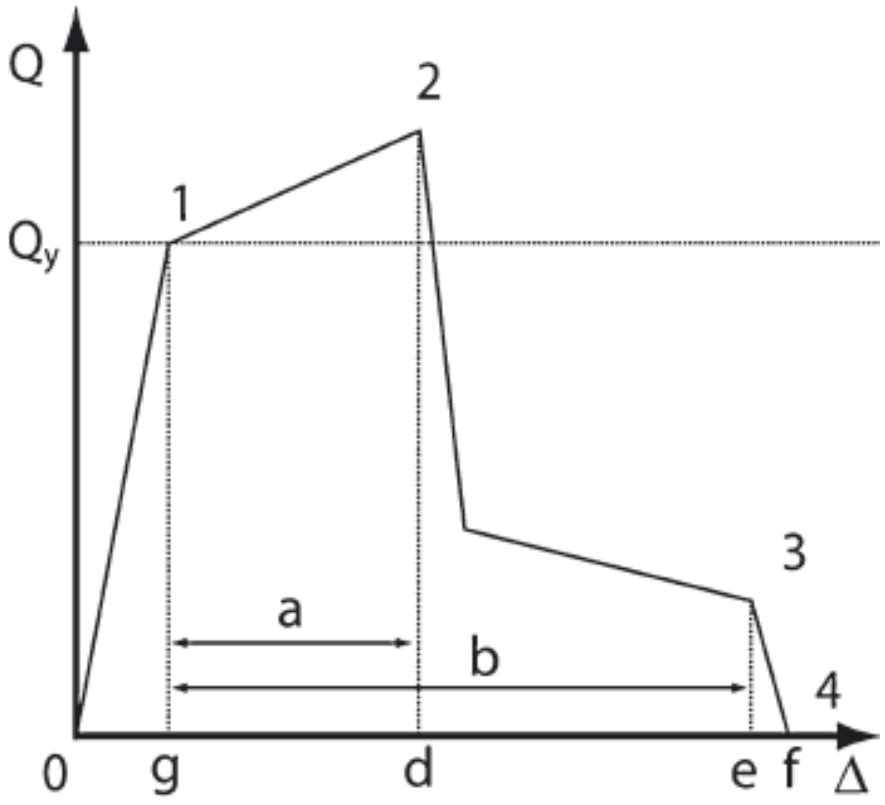
Table 2. Expected Material Strengths

Material		Expected Strength
		Strength (ksi)
Yield Strength for Structural steel		
	Hot-rolled structural shapes and bars	
	ASTM A36/A36M	$1.5F_y$
	ASTM A572/A572M Grade 42 (290)	$1.3F_y$
	ASTM A992/A992M	$1.1F_y$
	All other grades	$1.1F_y$
	Hollow Structural Sections	
	ASTM A500, A501, A618 and A847	$1.3F_y$
	Steel Pipe	
	ASTM A53/A53M	$1.4F_y$
	Plates	$1.1F_y$
	All other products	$1.1F_y$
Yield Strength for Reinforcing steel		1.17 times specified f_y
Ultimate Strength for Concrete		1.3 times specified f'_c

Source: LATBSDC 2014

Deformation-controlled Actions

- Behavior is ductile and reliable inelastic deformations can be reached with no substantial strength loss.
- Results are checked for mean value of demand from seven sets of ground motion records.

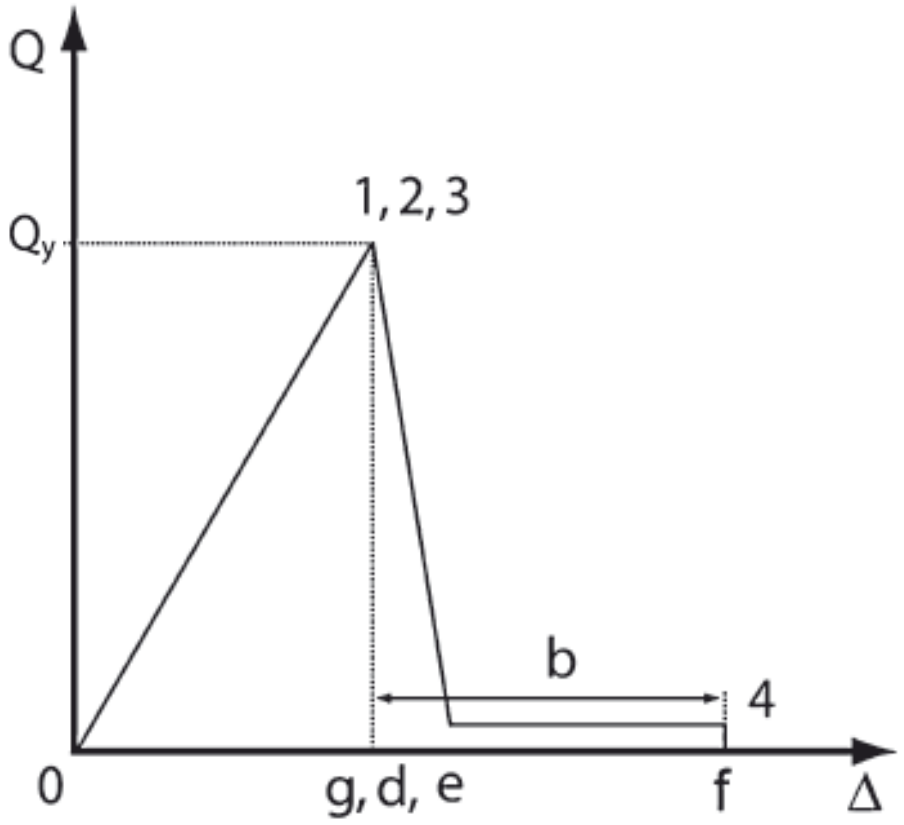


Force-deformation relationship for deformation-controlled actions

Source: ASCE/SEI 41-13

Force-controlled Actions

- Behavior is more brittle and reliable inelastic deformations cannot be reached.
  - **Critical actions**
    - Actions in which failure mode poses severe consequences to structural stability under gravity and/or lateral loads.
    - 1.5 times the mean value of demand from seven sets of ground motions is used.
  - **Non-critical actions**
    - Actions in which failure does not result structural instability or potentially life-threatening damage.
    - Mean value of demand from seven sets of ground motions is used with a factor of 1.



Force-deformation relationship for force-controlled actions

Source: ASCE/SEI 41-13

Classification of Actions

Component	Action	Classification	Criticality
Shear walls	Flexure	Deformation-controlled	N/A
	Shear	Force-controlled	Critical
Coupling beams (Conventional)	Flexure	Deformation-controlled	N/A
	Shear	Force-controlled	Non-critical
Coupling beams (Diagonal)	Shear	Deformation-controlled	N/A
Girders	Flexure	Deformation-controlled	N/A
	Shear	Force-controlled	Non-critical
Columns	Axial-Flexure	Deformation-controlled	N/A
	Shear	Force-controlled	Critical
Diaphragms	Flexure	Force-controlled	Non-critical
	Shear (at podium and basements)	Force-controlled	Critical
	Shear (tower)	Force-controlled	Non-critical
Basement walls	Flexure	Force-controlled	Non-critical
	Shear	Force-controlled	Critical
Mat foundation	Flexure	Force-controlled	Non-critical
	Shear	Force-controlled	Critical
Piles	Axial-Flexure	Force-controlled	Non-critical
	Shear	Force-controlled	Critical

Acceptance Criteria (MCE)

Item	Value
Peak transient drift	Maximum of mean values shall not exceed 3%. Maximum drift shall not exceed 4.5%.
Residual drift	Maximum of mean values shall not exceed 1%. Maximum drift shall not exceed 1.5%.
Coupling beam inelastic rotation	≤0.05 radian for both conventional and diagonal reinforced beams
Column (Axial-flexural interaction and shear)	Flexural rotation ≤ASCE 41-13 limits Remain elastic for shear response. (Column shear will be checked for 1.5 times mean value.)
Shear wall reinforcement axial strain	≤0.05 in tension and ≤0.02 in compression
Shear wall concrete axial compressive strain	Intermediately confined concrete ≤ $0.004 + 0.1\ \rho\ (f_y / f'_c)$ Fully confined concrete ≤ 0.015
Shear wall shear	Remain elastic (Check for 1.5 times mean value)
Girder inelastic rotation	≤ASCE 41-13 limits
Girders shear	Remain elastic.
Mat foundation (Flexure and shear)	Remain elastic. (Mat foundation shear will be checked for 1.5 times mean value.)
Diaphragm (In-plane response)	Remain elastic. (Podium diaphragm shear will be checked for 1.5 times mean value.)
Piles (Axial-flexural interaction and shear)	Remain elastic. (Pile shear will be checked for 1.5 times mean value.)

Stiffness Assumptions in Mathematical Models

Concrete Element	SLE/Wind	DBE	MCE
Core walls/shear walls	Flexural – 0.75 I_g Shear – 1.0 A_g	Flexural – 0.6 I_g Shear – 1.0 A_g	Flexural – ** Shear – 0.2 A_g
Basement walls	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 0.8 I_g Shear – 0.8 A_g	Flexural – 0.8 I_g Shear – 0.5 A_g
Coupling beams (Diagonal-reinforced)	Flexural –0.3 I_g Shear – 1.0 A_g	Flexural –0.2 I_g Shear – 1.0 A_g	Flexural – 0.2 I_g Shear – 1.0 A_g
Coupling beams (Conventional-reinforced)	Flexural –0.7 I_g Shear – 1.0 A_g	Flexural –0.35 I_g Shear – 1.0 A_g	Flexural – 0.35 I_g Shear – 1.0 A_g
Ground level diaphragm (In-plane only)	Flexural – 0.5 I_g Shear – 0.8 A_g	Flexural – 0.25 I_g Shear – 0.5 A_g	Flexural – 0.25 I_g Shear – 0.25 A_g
Podium diaphragms	Flexural – 0.5 I_g Shear – 0.8 A_g	Flexural – 0.25 I_g Shear – 0.5 A_g	Flexural – 0.25 I_g Shear – 0.25 A_g
Tower diaphragms	Flexural – 1.0 I_g Shear – 1.0 A_g	Flexural – 0.5 I_g Shear – 0.5 A_g	Flexural – 0.5 I_g Shear – 0.5 A_g
Girders	Flexural – 0.7 I_g Shear – 1.0 A_g	Flexural – 0.35 I_g Shear – 1.0 A_g	Flexural – 0.35 I_g Shear – 1.0 A_g
Columns	Flexural – 0.9 I_g Shear – 1.0 A_g	Flexural – 0.7 I_g Shear – 1.0 A_g	Flexural – 0.7 I_g Shear – 1.0 A_g

Evaluation of Results

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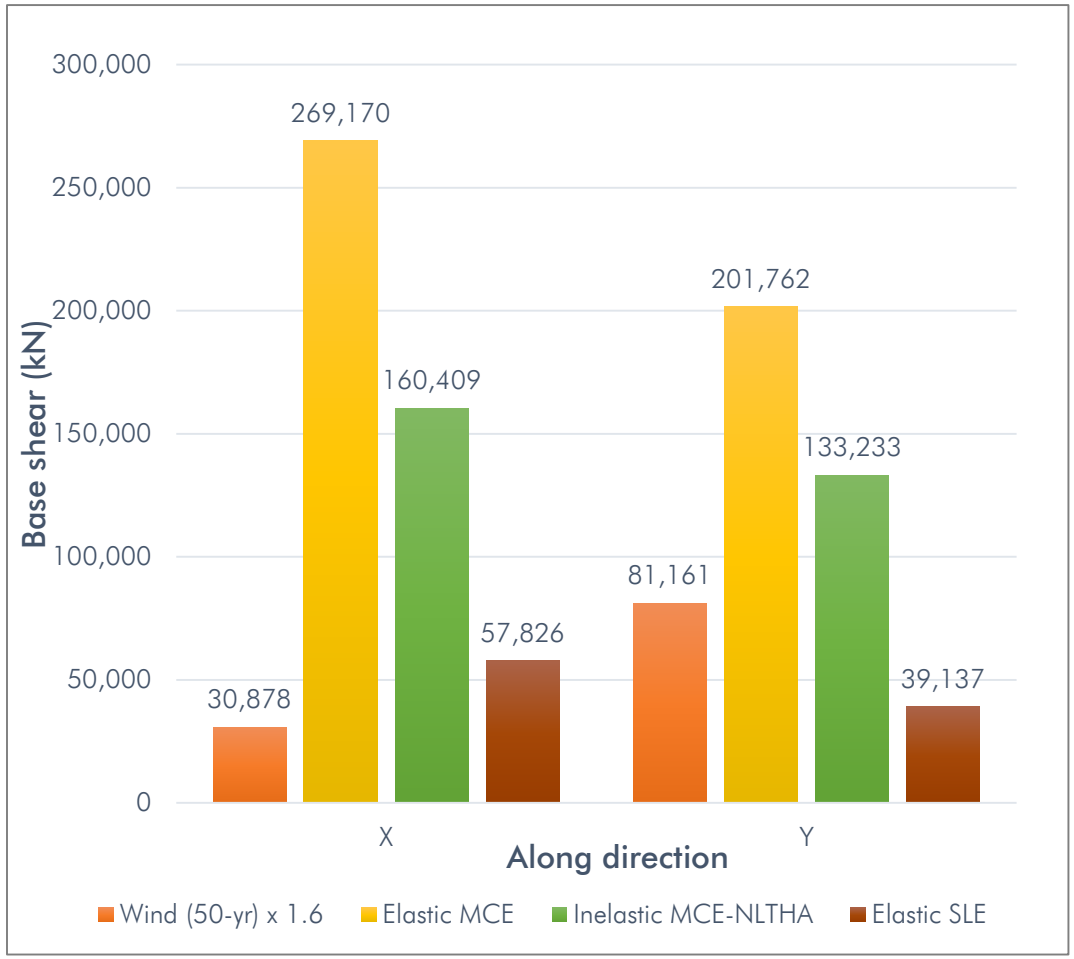
Evaluation of Results

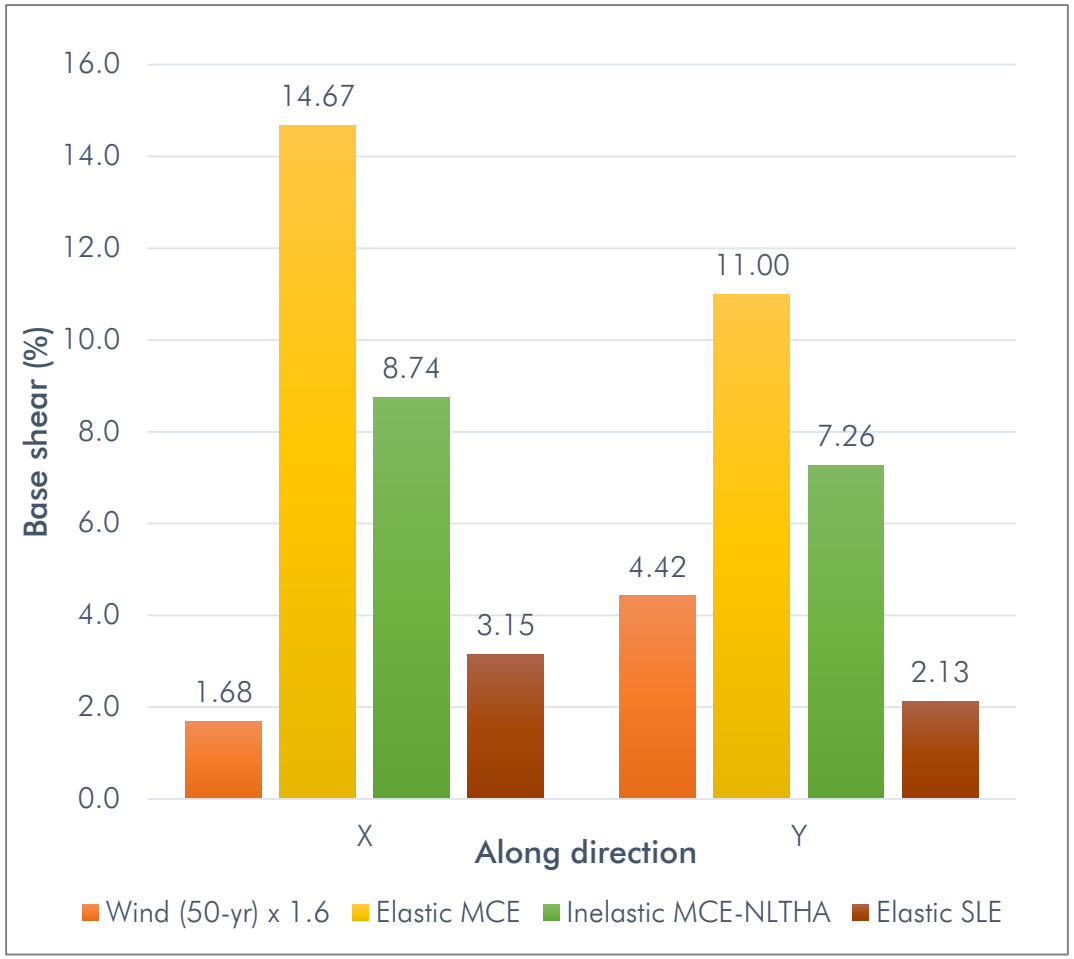
- Results extraction, processing and converting them into presentable form takes additional time.
- Results interpretation i.e. converting “numbers we have already crunched” into “meaningful outcome for decision-making”.
- Since each of these performance levels are associated with a physical description of damage, obtained results are compared and evaluated based on this criterion to get performance insight.

Overall Response

- Base shear
- Ratio between inelastic base shear and elastic base shear
- Story drift (Transient drift, residual drift)
- Lateral displacement
- Floor acceleration
- Energy dissipation of each component type
- Energy error

Base Shear





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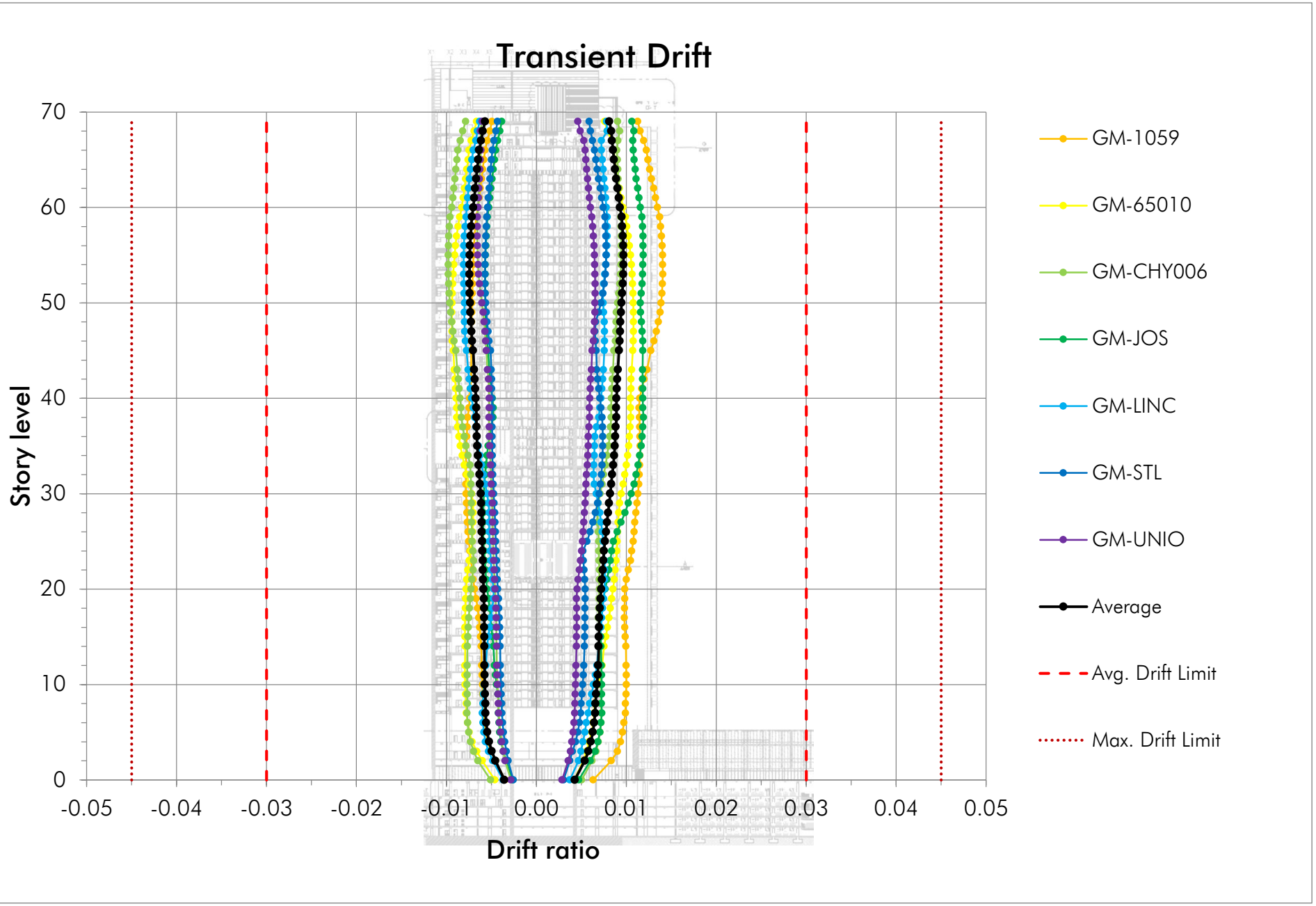
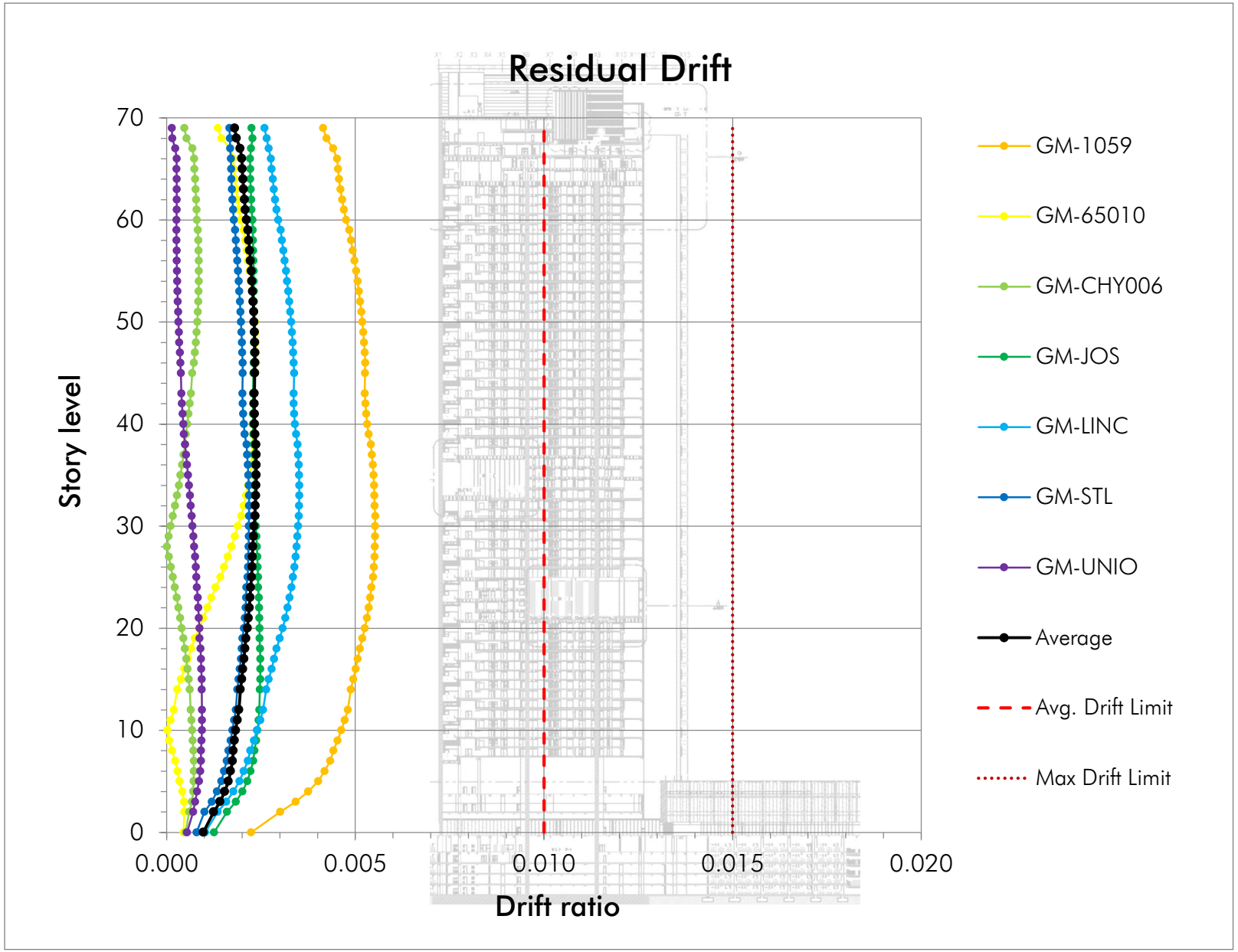
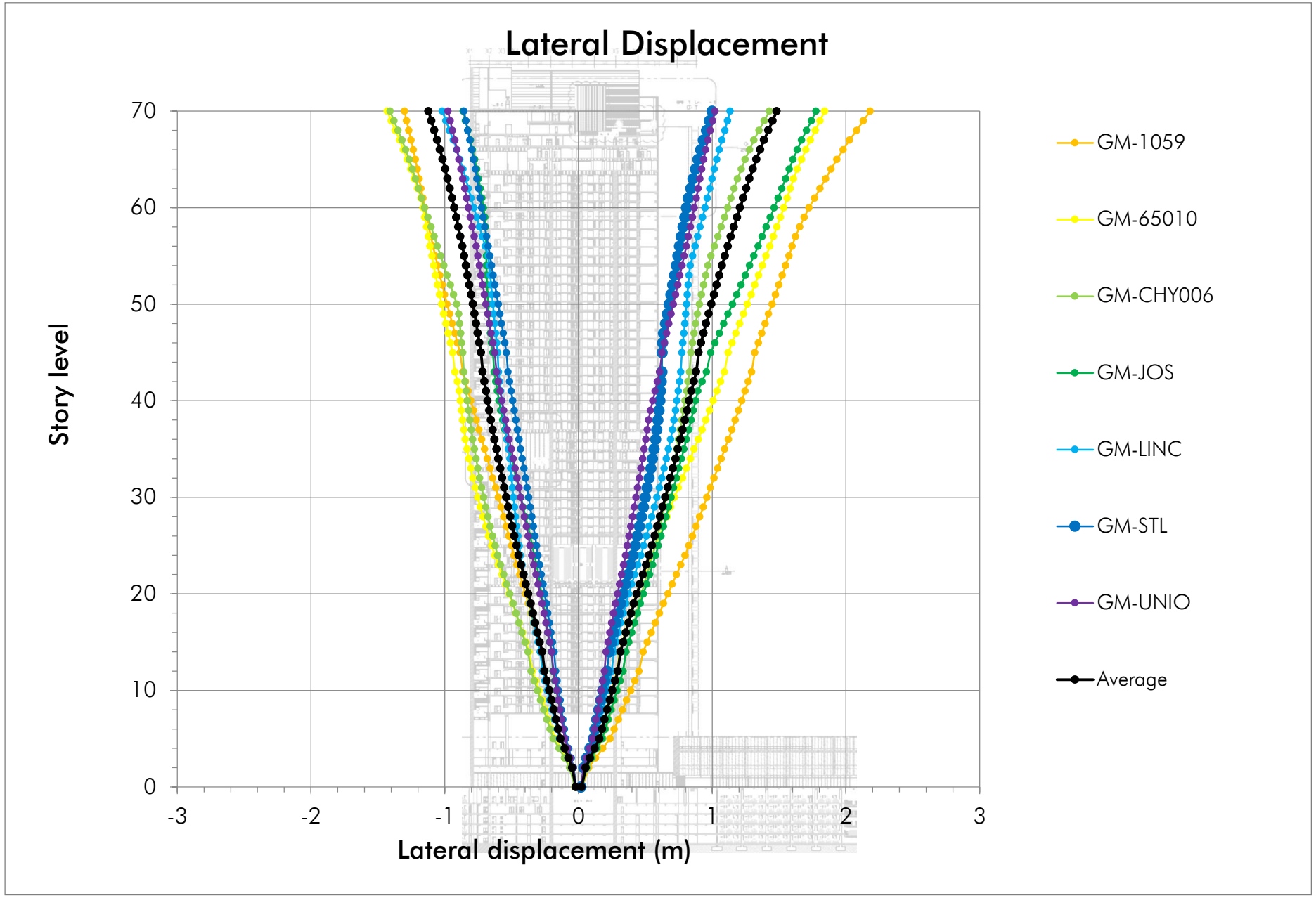
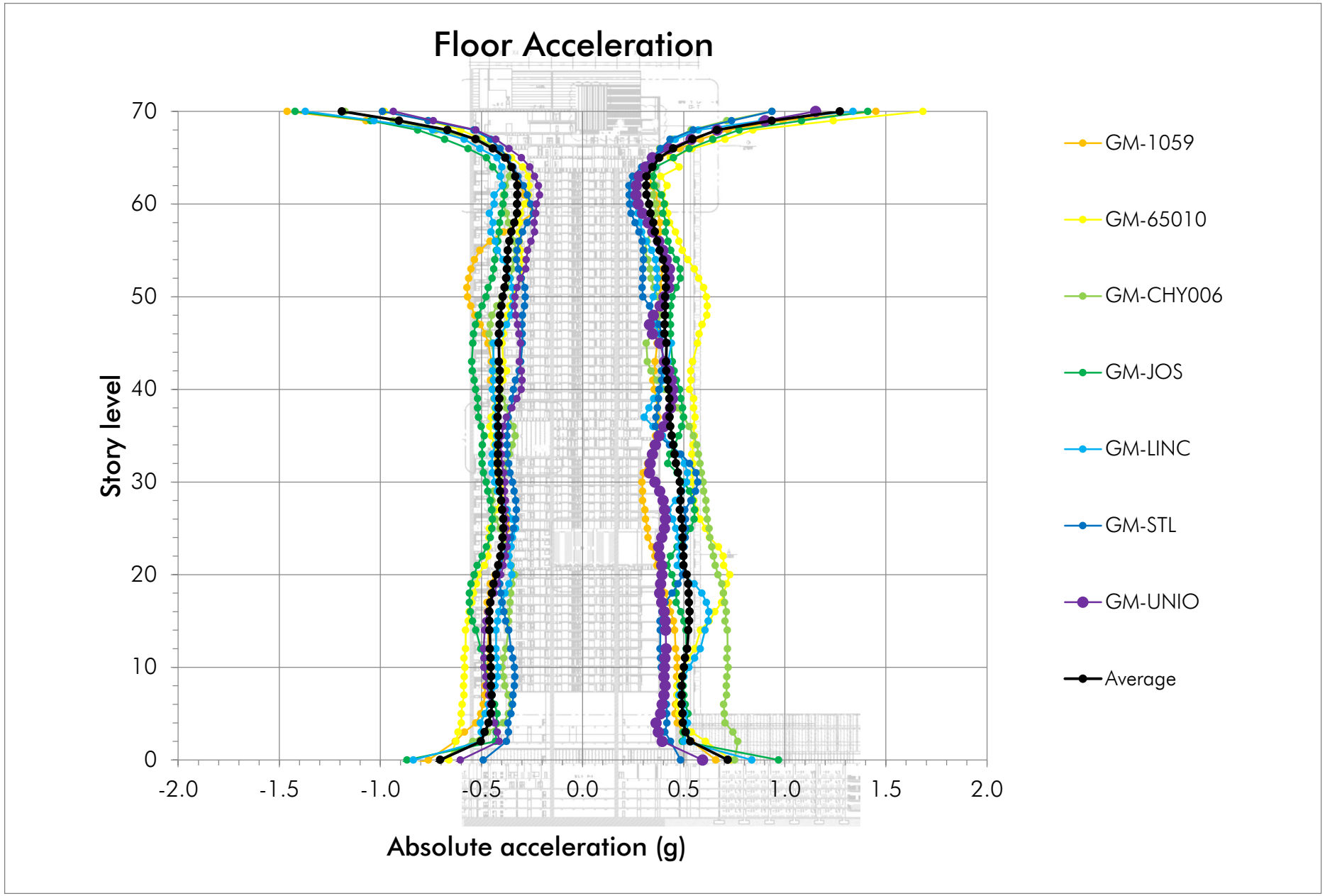
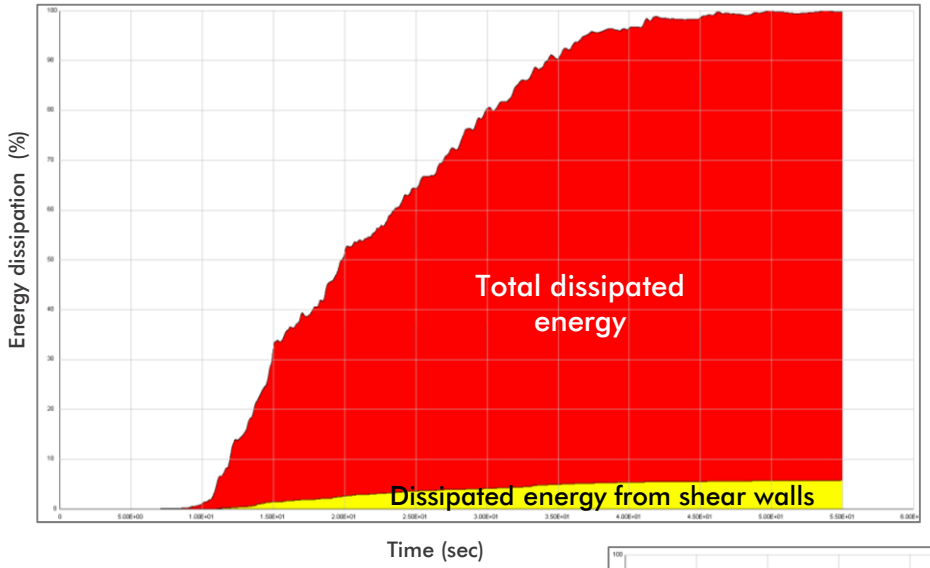

Transient Drift
Story level
70
60
50
40
30
20
10
0
-0.05
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
Drift ratio
GM-1059
GM-65010
GM-CHY006
GM-JOS
GM-LINC
GM-STL
GM-UNIO
Average
Avg. Drift Limit
Max. Drift Limit

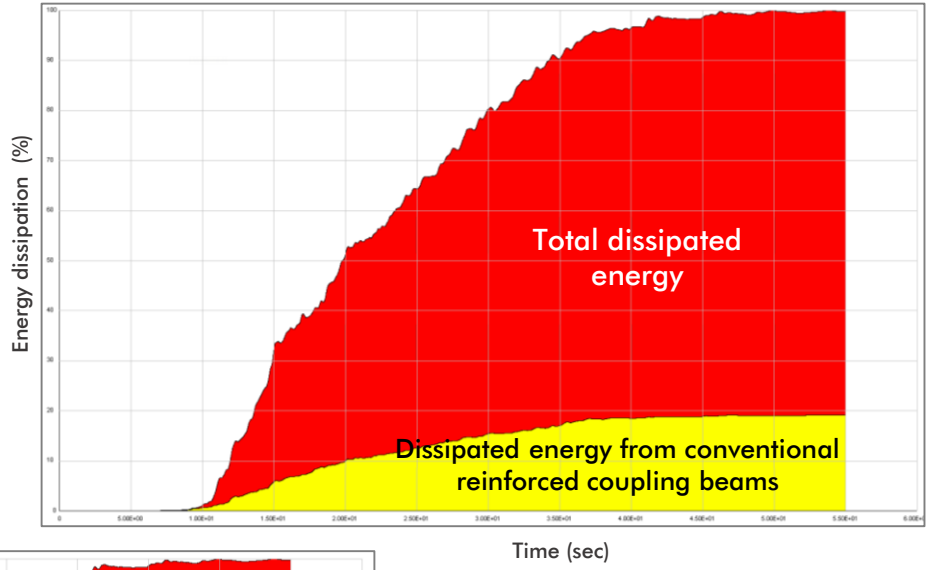

Residual Drift
Story level
70
60
50
40
30
20
10
0
0.000
0.005
0.010
0.015
0.020
Drift ratio
GM-1059
GM-65010
GM-CHY006
GM-JOS
GM-LINC
GM-STL
GM-UNIO
Average
Avg. Drift Limit
Max Drift Limit

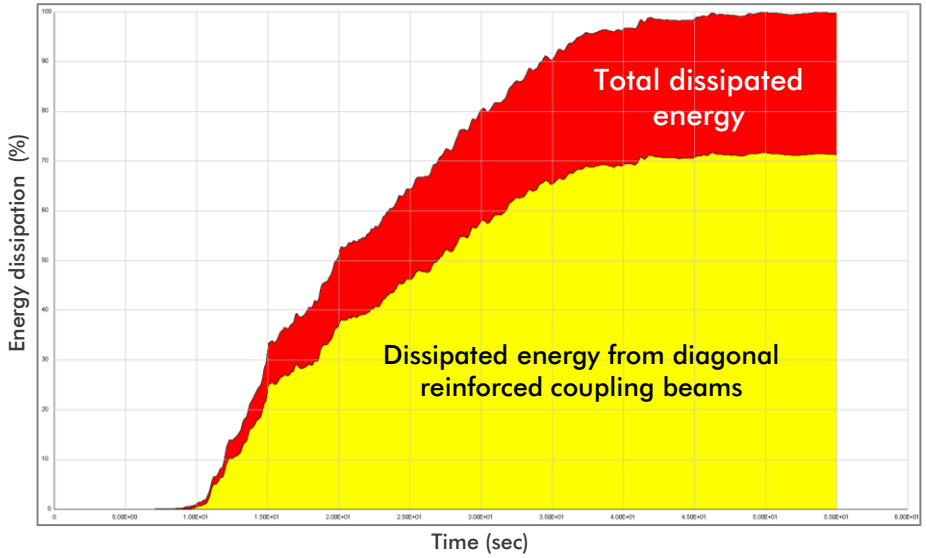

Lateral Displacement
Story level
70
60
50
40
30
20
10
0
-3
-2
-1
0
1
2
3
Lateral displacement (m)
GM-1059
GM-65010
GM-CHY006
GM-JOS
GM-LINC
GM-STL
GM-UNIO
Average


Floor Acceleration
Story level
70
60
50
40
30
20
10
0
-2.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
Absolute acceleration (g)
GM-1059
GM-65010
GM-CHY006
GM-JOS
GM-LINC
GM-STL
GM-UNIO
Average

Energy Dissipation







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Component Responses

Component	Response
Pile foundation	Bearing capacity, pullout capacity, PMM, shear
Mat foundation	Bearing capacity, flexure, shear
Shear wall	Flexure (axial strain), shear
Column	PMM or flexural rotation, axial, shear
Beams	Flexural rotation, shear
Conventional reinforced coupling beam	Flexural rotation, shear
Diagonal reinforced coupling beam	Shear rotation, shear
Flat slab	Flexural rotation, punching shear
Basement wall	In-plane shear, out-of-plane flexure and shear
Diaphragm	Shear, shear friction, tension and compression

Peer Review

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Peer Review Scope

- Earthquake hazard determination
- Ground motion characterizations
- Seismic design methodology
- Seismic performance goals
- Acceptance criteria
- Mathematical modeling and simulation
- Seismic design and results, drawings and specifications

Peer Review

- Involve as early in the structural design phase
- Establish the frequency and timing of peer review milestones
- Peer reviewer provides written comments to EOR
- EOR shall provide written responses
- Peer review maintains the log that summarizes reviewer's comments, EOR responses to comments, and resolution of comments
- At the conclusion of the review, peer reviewer shall submit the references the scope of the review, includes the comment log, and indicates the professional opinions of the peer reviewer regarding the design's general conformance to the requirements and guidelines in this document

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Thank You