Effect of the Structural Wall Modeling in the Seismic Response of Buildings with Force-limiting Connections between Diaphragm-to-wall Joints

C. Franco Mayorga, Kyoungyeon Lee, and Georgios Tsampras

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering



June 1, 2022

Acknowledgments

- Chilean National Agency for Research and Development (ANID). Doctoral Scholarship Abroad, Becas Chile, 2020.

- Department of Structural Engineering at University of California San Diego (UCSD). Fellowship 2020-2021.



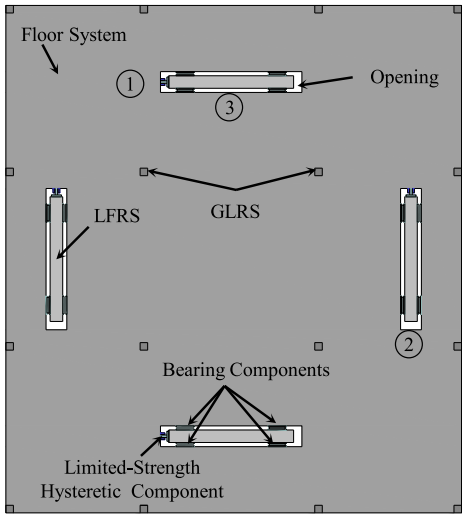
UC San Diego
JACOBS SCHOOL OF ENGINEERING
Structural Engineering

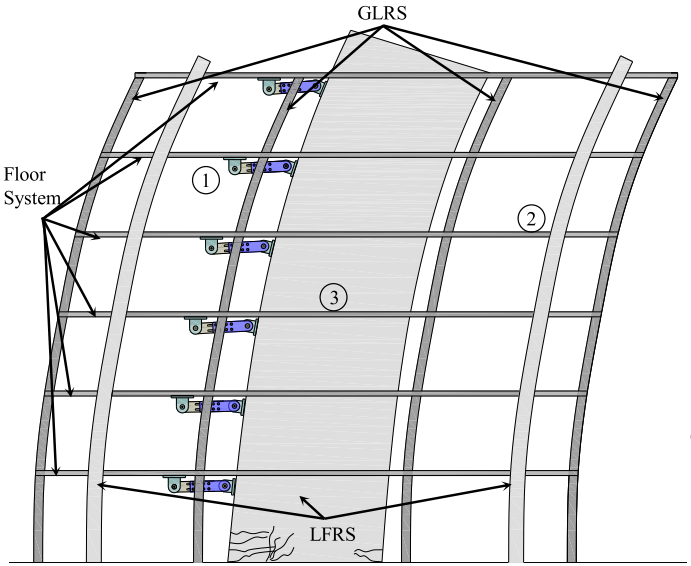
Presentation Objective

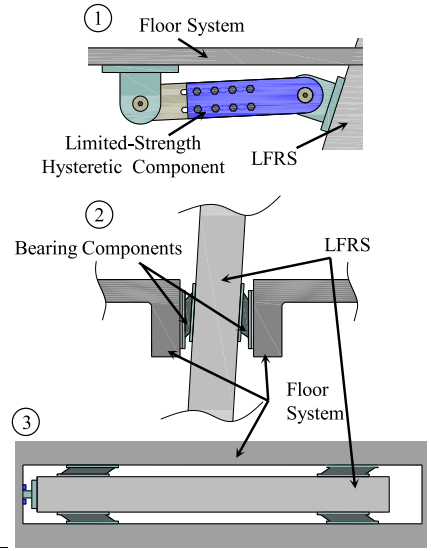
- Show a comparison between two modeling approaches used to model the lateral force resisting system (LFRS) and the effect on the seismic response of buildings with force-limiting connections subjected to design-basis level ground motions.

Buildings with force-limiting connections

- How this system works[1].





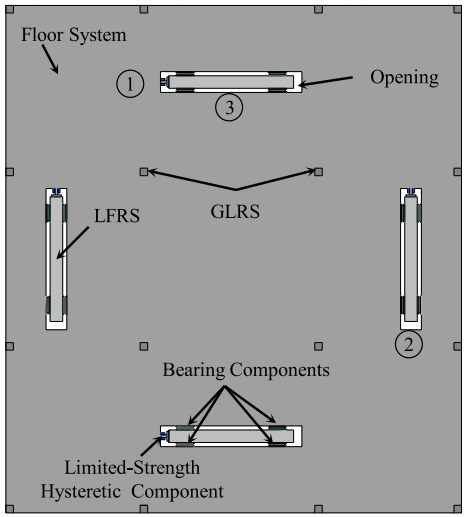


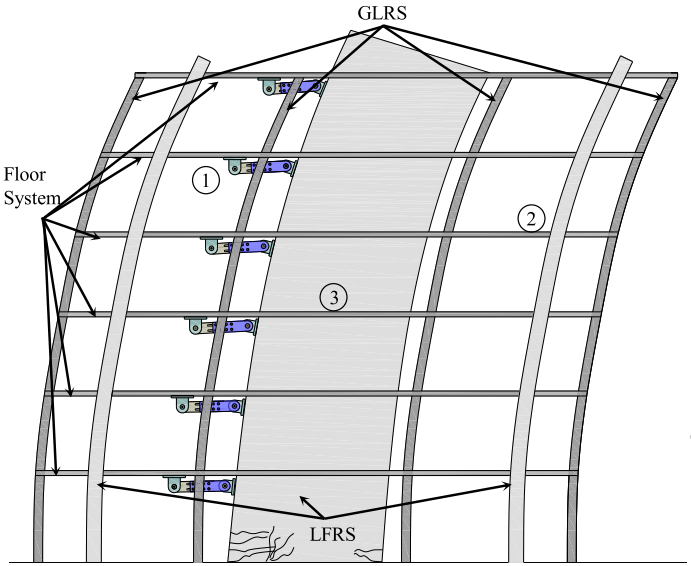


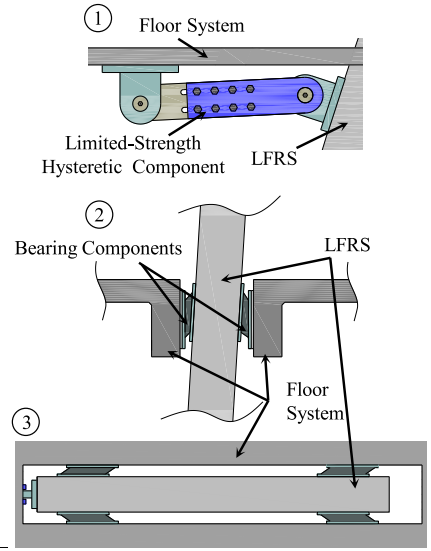
[1] Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei, "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses". 2016

Buildings with force-limiting connections

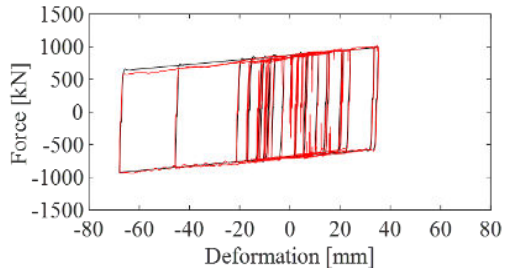
- How this system works[1].







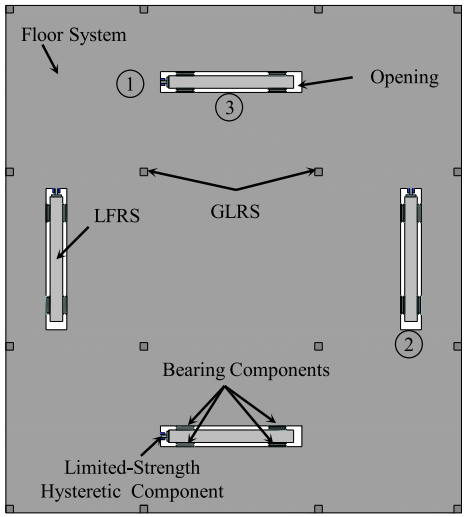


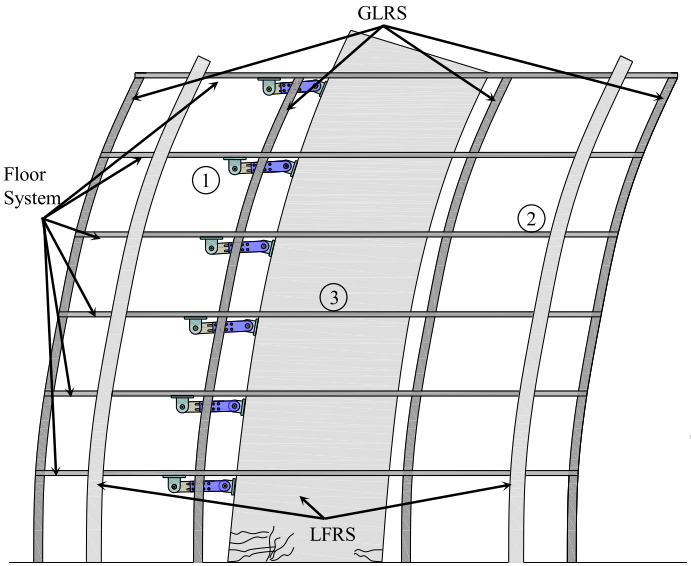


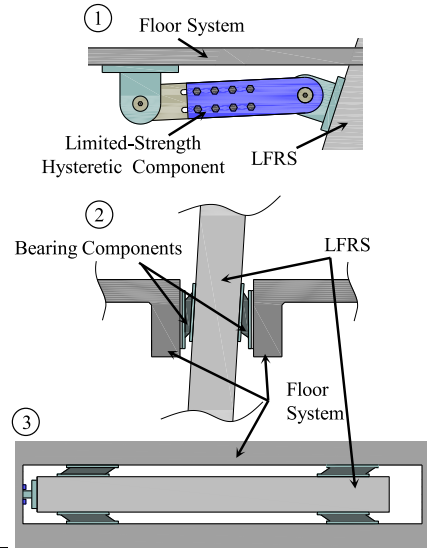
[1] Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei, "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses". 2016

Buildings with force-limiting connections

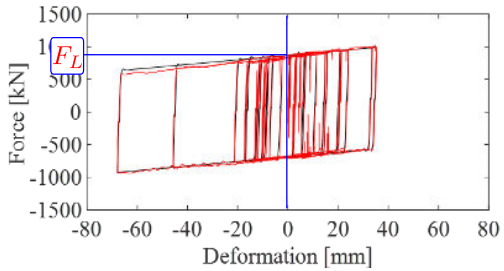
- How this system works[1].









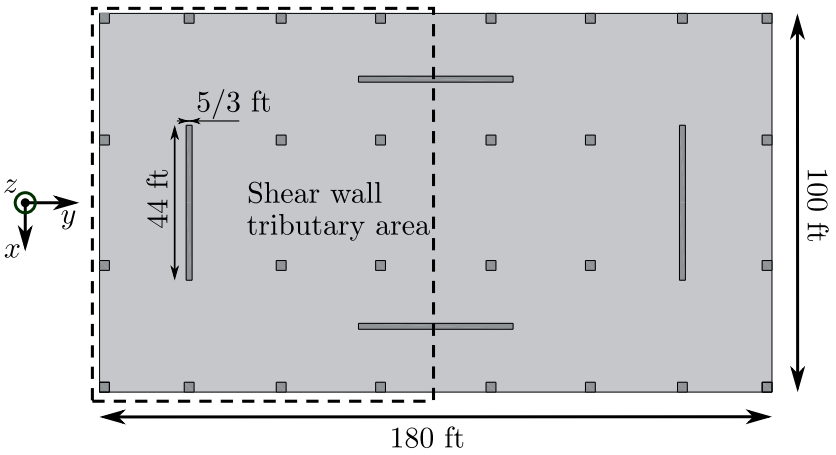


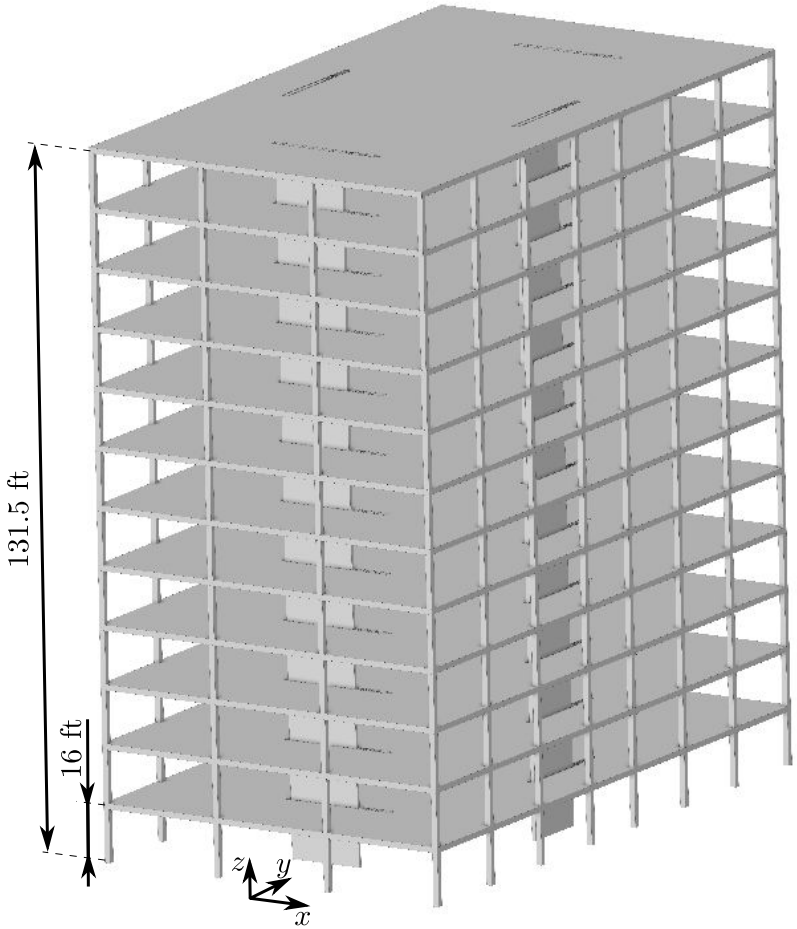
[1] Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei, "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses". 2016

Building Modeling

▶ Studied structural system.

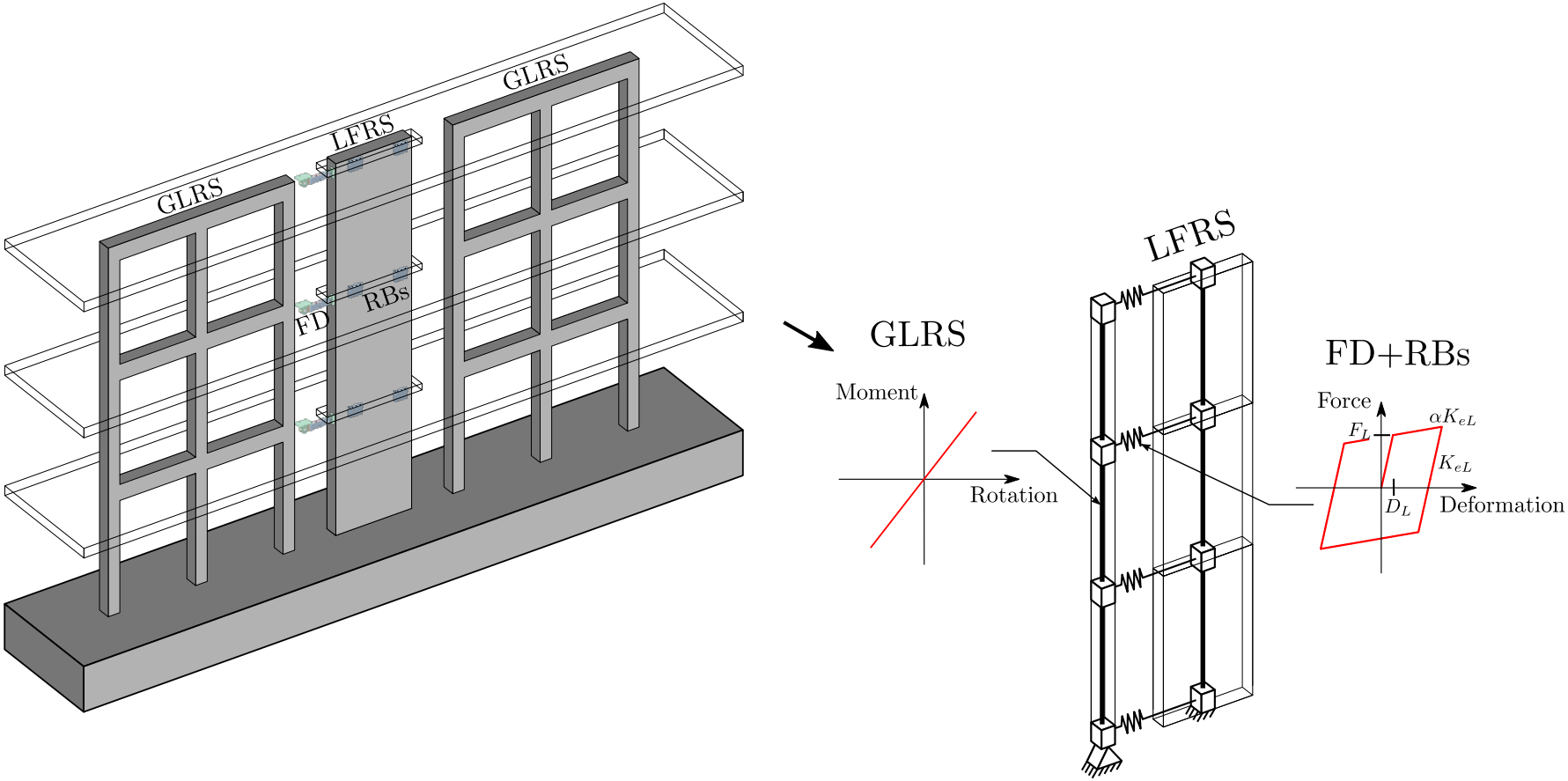
- 12-Story RC building with force-limiting connections.
  - 48 friction devices (FDs).
  - 96 rubber bearings (RBs).
- 4 RC rectangular walls as LFRS.
- 28 RC squared gravity columns.
  - 32×32 in^2 columns in the first seven stories.
  - 22×22 in^2 columns in higher stories.





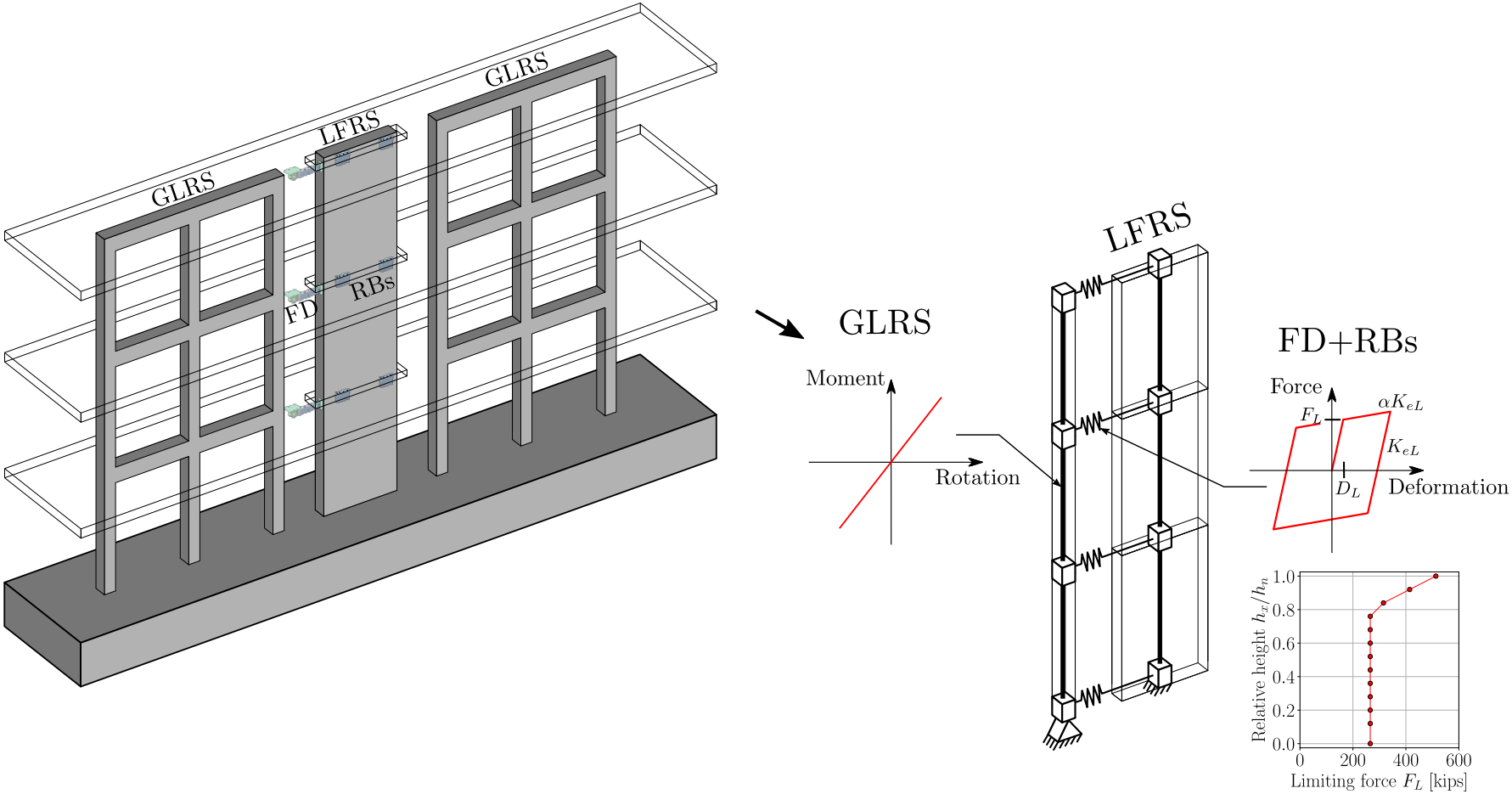
Building Modeling

- GLRS and force-limiting connection modeling.



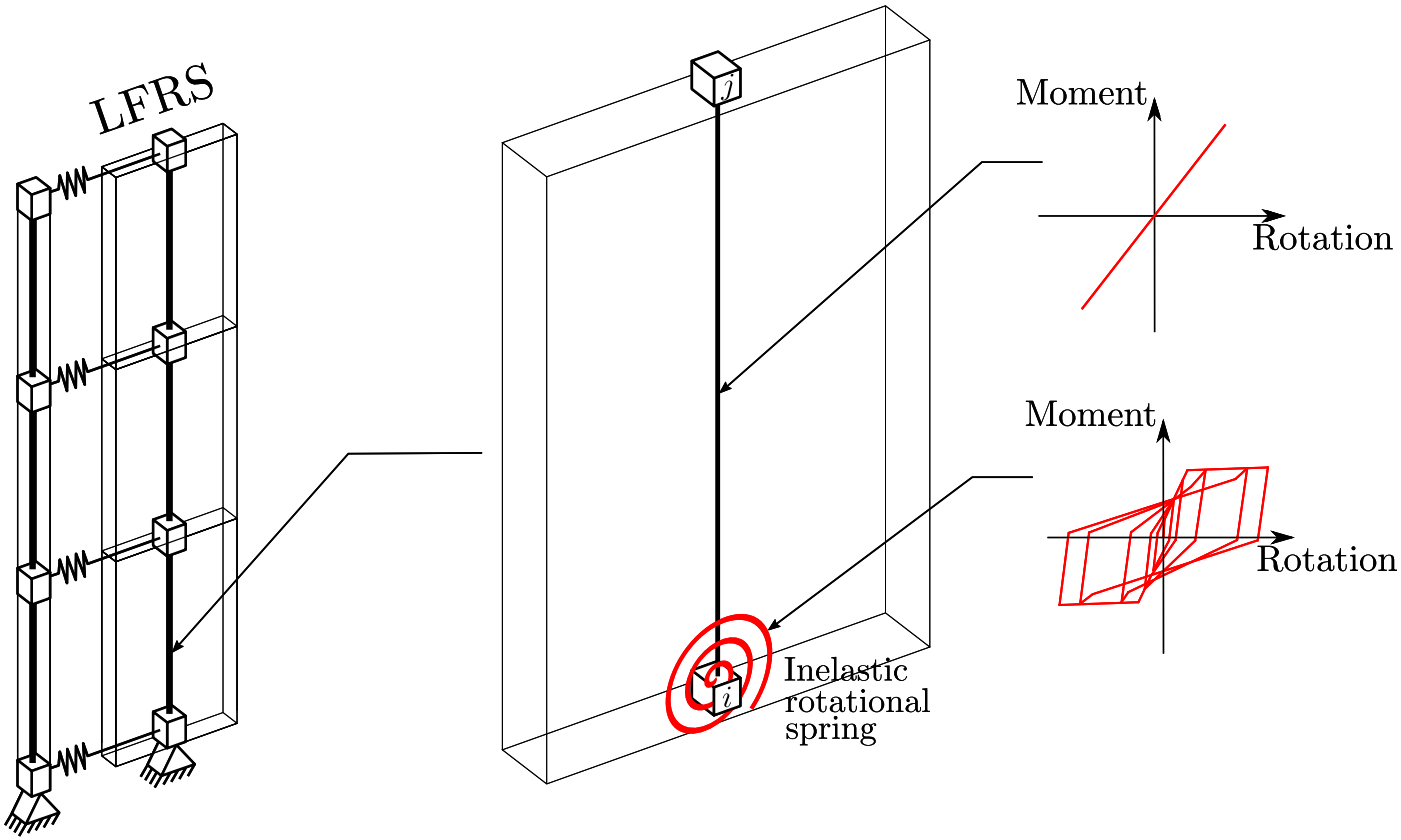
Building Modeling

- GLRS and force-limiting connection modeling.



Building Modeling

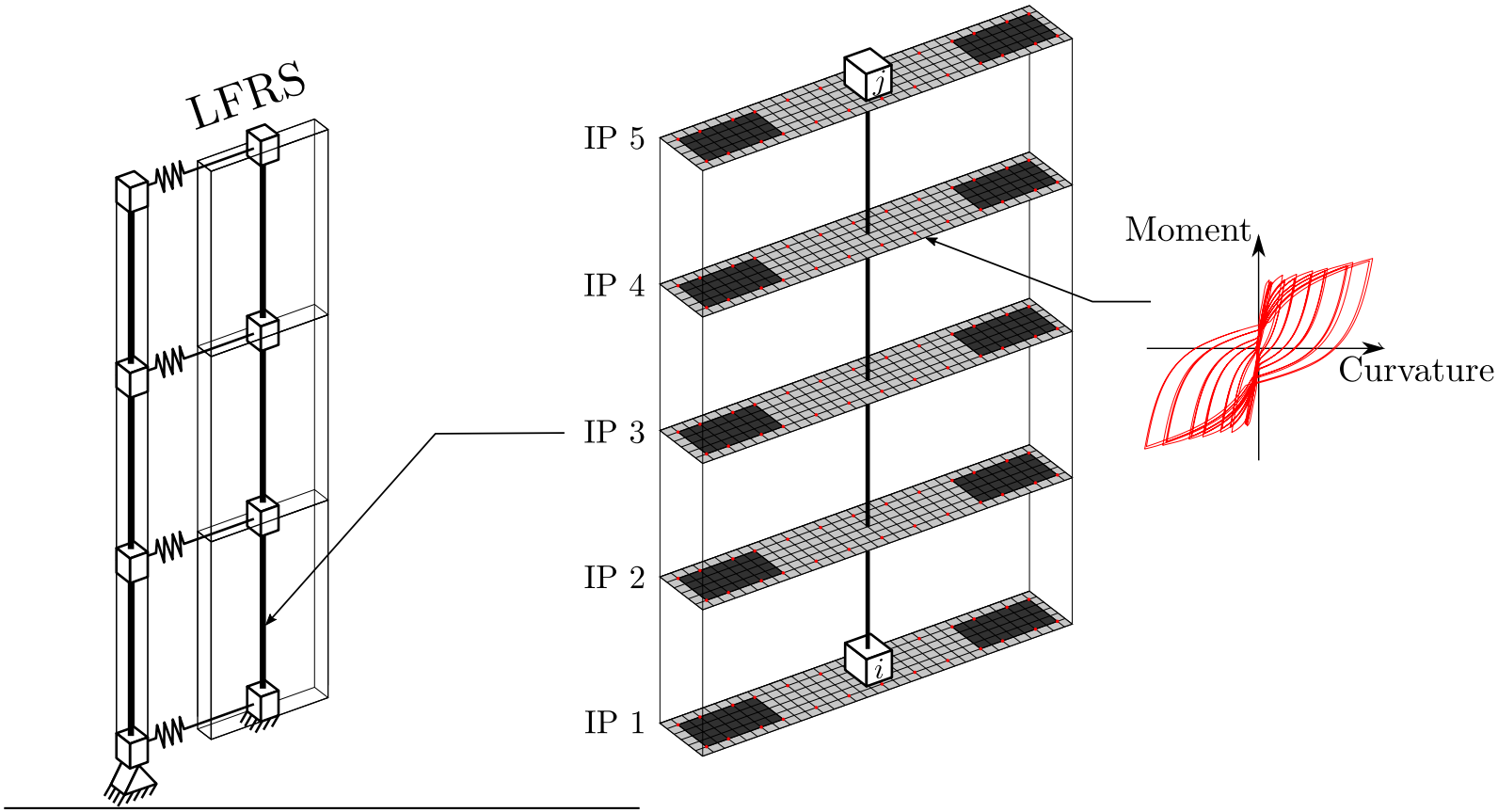
- LFRS modeling approach 1: Lumped plasticity.
  - Zero length element with Pinching4 material in *Opensees*[2].



[2] Frank McKenna, Michael H. Scott, and Gregory L. Fenves, "Nonlinear Finite-Element Analysis Software Architecture Using Object Composition". 2010

Building Modeling

- LFRS modeling approach 2: Distributed plasticity.
  - Force-Based Beam-Column element in *Opensees*[2,3].



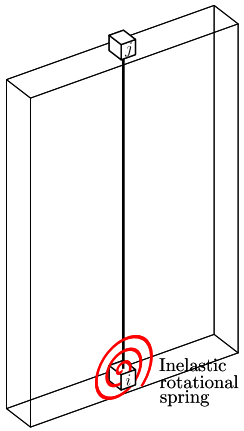
[2] Frank McKenna, Michael H. Scott, and Gregory L. Fenves, "Nonlinear Finite-Element Analysis Software Architecture Using Object Composition". 2010

[3] Fabio Taucer, Enrico Spacone, and Filip Filippou, "A Fiber Beam-Column Element for Seismic Response Analysis of Reinforced Concrete Structures". 1991

Building Modeling

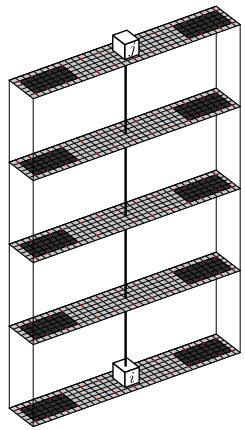
LFRS Modeling approach 1:

- Definition of cross-section geometry properties is required.
- Multi-linear inelastic material constitutive law for the rotational spring and linear material properties for the beam/column elements are required.
- Stiffness reduction factors to consider cracked condition are included.
- Shear response is not modeled.



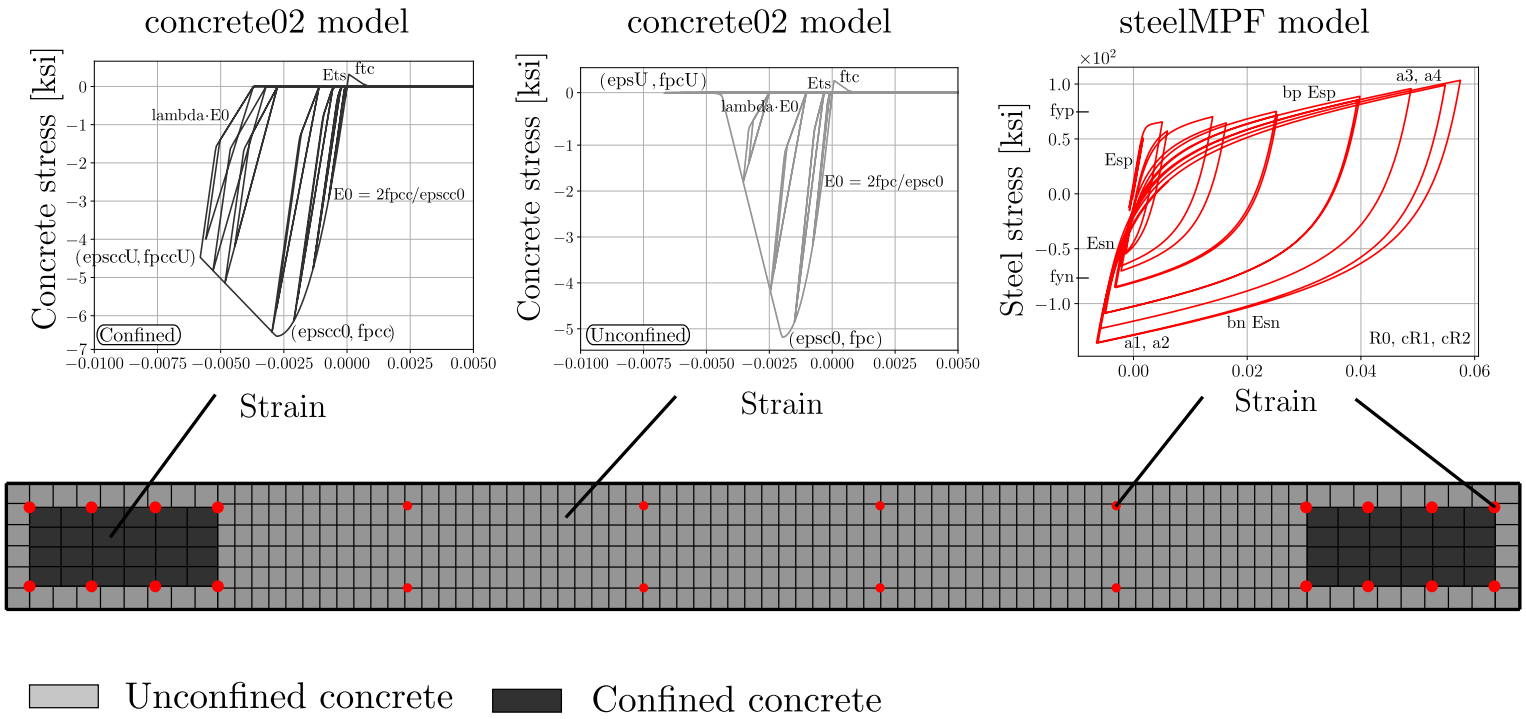
LFRS Modeling approach 2:

- Definitions are required for coss-section geometry and fiber discretization.
- Nonlinear inelastic fiber material constitutive laws are required.
- Cracking is explicitly captured by the model.
- Shear response is not modeled.



RC Fiber Model Calibration

- Material constitutive laws[4,5].



[4] M. Menegotto and P. E. Pinto, "Method of Analysis for Cyclic Loaded R. C. Plane Frame Including Changes in Geometry and Non-Elastic Behaviour of Elements under Combined Normal Force and Bending". 1973

[5] Mohd Hisham Mohd Yassin, "Nonlinear analysis of prestressed concrete structures under monotonic and cyclic loads". 1994

RC Fiber Model Calibration

- Steel model parameters.
  - Multivariate normal distribution proposed by Birrel et al.[6] for A615 Grade 60 steel

Parameter	Mean	C.o.v. (%)
F_y ksi	74.3	5.0
E_s ksi	29969.0	4.0
b	0.023	27.0
cR_1	0.893	1.0
cR_2	0.093	31.0
a_1	0.035	45.0
a_2	0.022	51.0

Correlation matrix

$$\begin{bmatrix} 1 & 0.3 & -0.2 & 0.2 & -0.4 & -0.9 & -0.7 \\ & 1 & -0.4 & 0.7 & 0 & -0.2 & -0.2 \\ & & 1 & -0.8 & -0.3 & 0 & 0 \\ & & & 1 & 0.3 & 0 & 0 \\ & Sym. & & & 1 & 0.4 & 0.4 \\ & & & & & 1 & 0.8 \\ & & & & & & 1 \end{bmatrix}$$

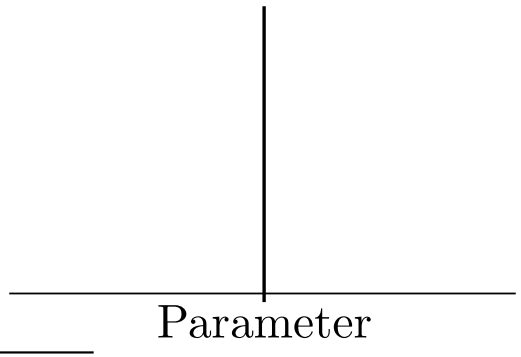
[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier, "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". 2021



RC Fiber Model Calibration

- Steel model parameters.
  - Multivariate normal distribution proposed by Birrel et al.[6] for A615 Grade 60 steel

Parameter	Mean	C.o.v. (%)	Correlation matrix
F_y ksi	74.3	5.0	$\begin{bmatrix} 1 & 0.3 & -0.2 & 0.2 & -0.4 & -0.9 & -0.7 \\ & 1 & -0.4 & 0.7 & 0 & -0.2 & -0.2 \\ & & 1 & -0.8 & -0.3 & 0 & 0 \\ & & & 1 & 0.3 & 0 & 0 \\ & Sym. & & & 1 & 0.4 & 0.4 \\ & & & & & 1 & 0.8 \\ & & & & & & 1 \end{bmatrix}$
E_s ksi	29969.0	4.0	
b	0.023	27.0	
cR_1	0.893	1.0	
cR_2	0.093	31.0	
a_1	0.035	45.0	
a_2	0.022	51.0	



[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier, "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". 2021

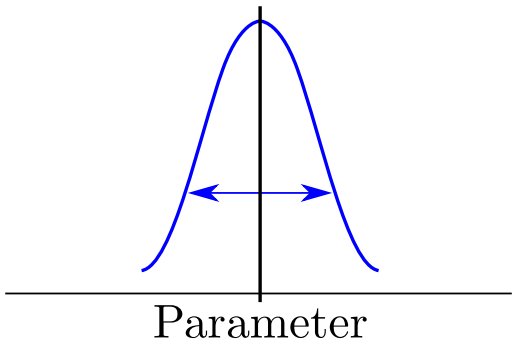
RC Fiber Model Calibration

- Steel model parameters.
  - Multivariate normal distribution proposed by Birrel et al.[6] for A615 Grade 60 steel

Parameter	Mean	C.o.v. (%)
F_y ksi	74.3	5.0
E_s ksi	29969.0	4.0
b	0.023	27.0
cR_1	0.893	1.0
cR_2	0.093	31.0
a_1	0.035	45.0
a_2	0.022	51.0

Correlation matrix

$$\begin{bmatrix} 1 & 0.3 & -0.2 & 0.2 & -0.4 & -0.9 & -0.7 \\ & 1 & -0.4 & 0.7 & 0 & -0.2 & -0.2 \\ & & 1 & -0.8 & -0.3 & 0 & 0 \\ & & & 1 & 0.3 & 0 & 0 \\ & Sym. & & & 1 & 0.4 & 0.4 \\ & & & & & 1 & 0.8 \\ & & & & & & 1 \end{bmatrix}$$



[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier, "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". 2021

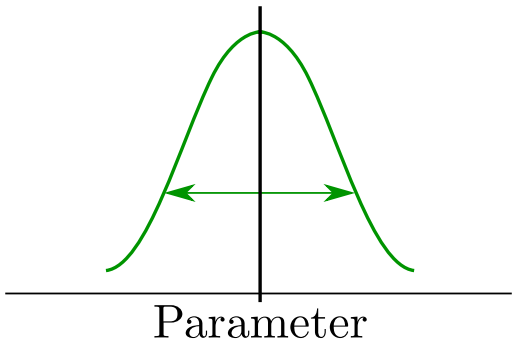
RC Fiber Model Calibration

- Steel model parameters.
  - Multivariate normal distribution proposed by Birrel et al.[6] for A615 Grade 60 steel

Parameter	Mean	C.o.v. (%)
F_y ksi	74.3	5.0
E_s ksi	29969.0	4.0
b	0.023	27.0
cR_1	0.893	1.0
cR_2	0.093	31.0
a_1	0.035	45.0
a_2	0.022	51.0

Correlation matrix

$$\begin{bmatrix} 1 & 0.3 & -0.2 & 0.2 & -0.4 & -0.9 & -0.7 \\ & 1 & -0.4 & 0.7 & 0 & -0.2 & -0.2 \\ & & 1 & -0.8 & -0.3 & 0 & 0 \\ & & & 1 & 0.3 & 0 & 0 \\ & Sym. & & & 1 & 0.4 & 0.4 \\ & & & & & 1 & 0.8 \\ & & & & & & 1 \end{bmatrix}$$



[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier, "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". 2021

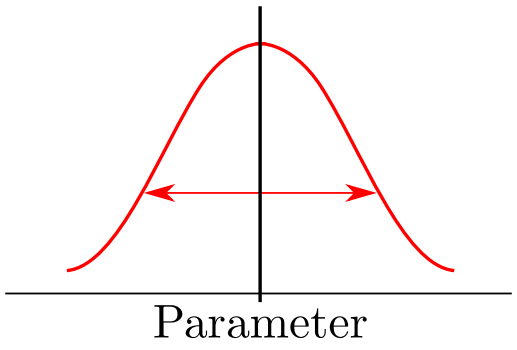
RC Fiber Model Calibration

- Steel model parameters.
  - Multivariate normal distribution proposed by Birrel et al.[6] for A615 Grade 60 steel

Parameter	Mean	C.o.v. (%)
F_y ksi	74.3	5.0
E_s ksi	29969.0	4.0
b	0.023	27.0
cR_1	0.893	1.0
cR_2	0.093	31.0
a_1	0.035	45.0
a_2	0.022	51.0

Correlation matrix

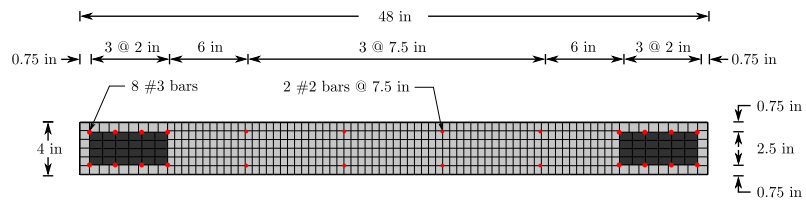
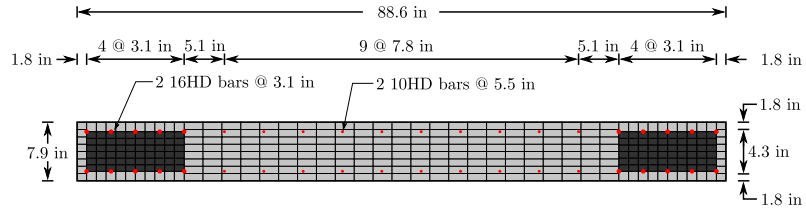
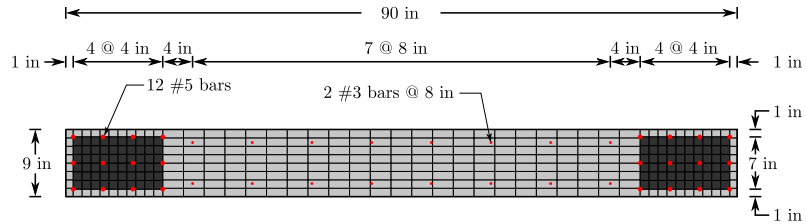
$$\begin{bmatrix} 1 & 0.3 & -0.2 & 0.2 & -0.4 & -0.9 & -0.7 \\ & 1 & -0.4 & 0.7 & 0 & -0.2 & -0.2 \\ & & 1 & -0.8 & -0.3 & 0 & 0 \\ & & & 1 & 0.3 & 0 & 0 \\ & Sym. & & & 1 & 0.4 & 0.4 \\ & & & & & 1 & 0.8 \\ & & & & & & 1 \end{bmatrix}$$



[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier, "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". 2021

RC Fiber Model Calibration

- Structural wall test results used for modeling validation.

Project	Author/PI	Specimen	Height h_w [in]	Shear Span Ratio $M/(VL)$	Axial Load [%]	Model/Geometry
Thomsen 1995[7]	Thomsen and Wallace	RW2	144.0	3.0	7.2	
MBIE-1607[8]	Kenneth Elwood	C10	137.8	4.6	9.2	
NEESR-1628[9]	John Wallace	WP7	84.0	3.5	10.0	

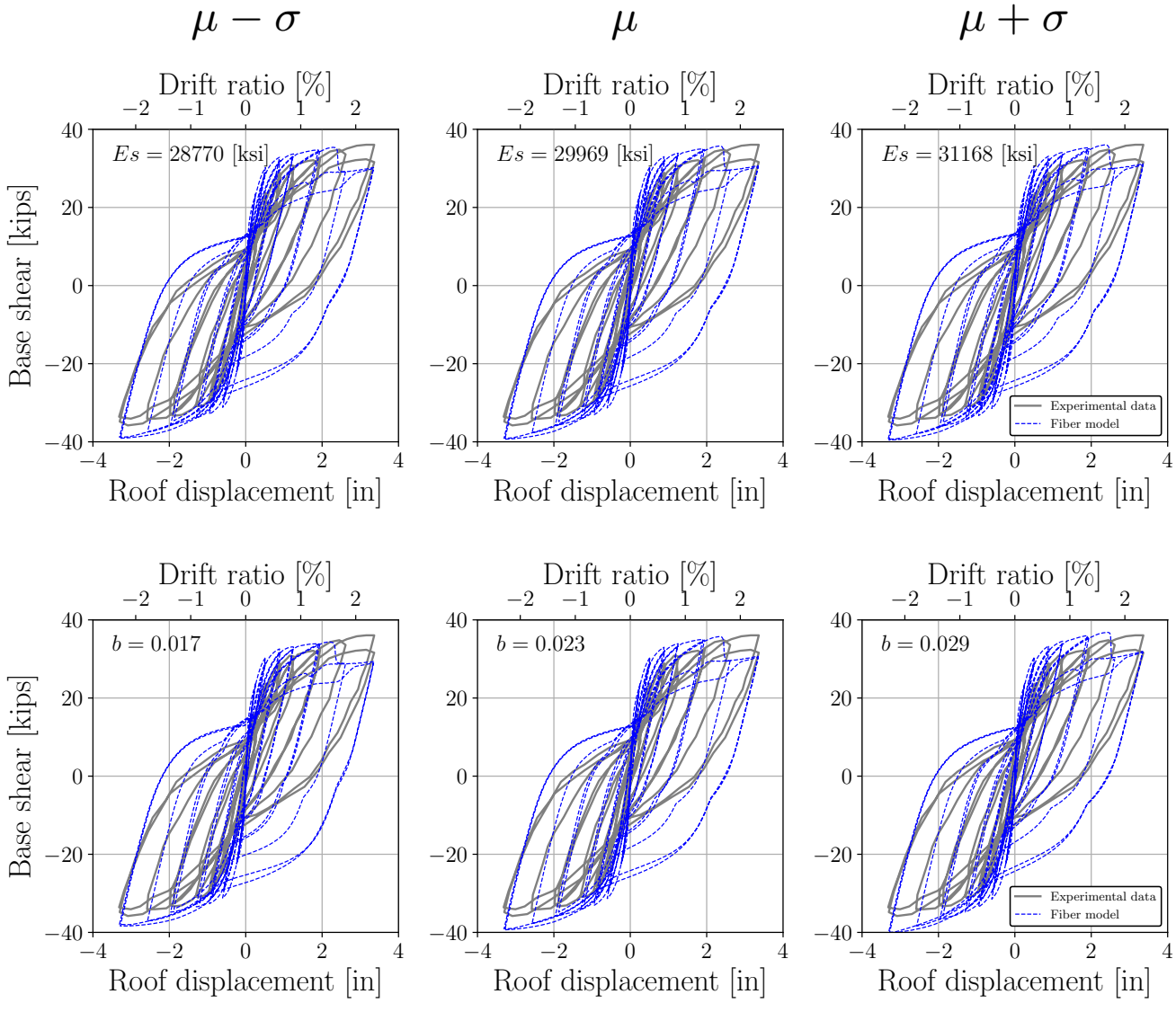
[7] John H. Thomsen and John W. Wallace, *Displacement-based Design of RC Structural Walls*. 1995

[8] Kenneth Elwood, "University of Auckland High Axial Load Wall Tests". 2018

[9] John Wallace, Carlos Arteta, and Christopher Segura, "NEESR". 2018

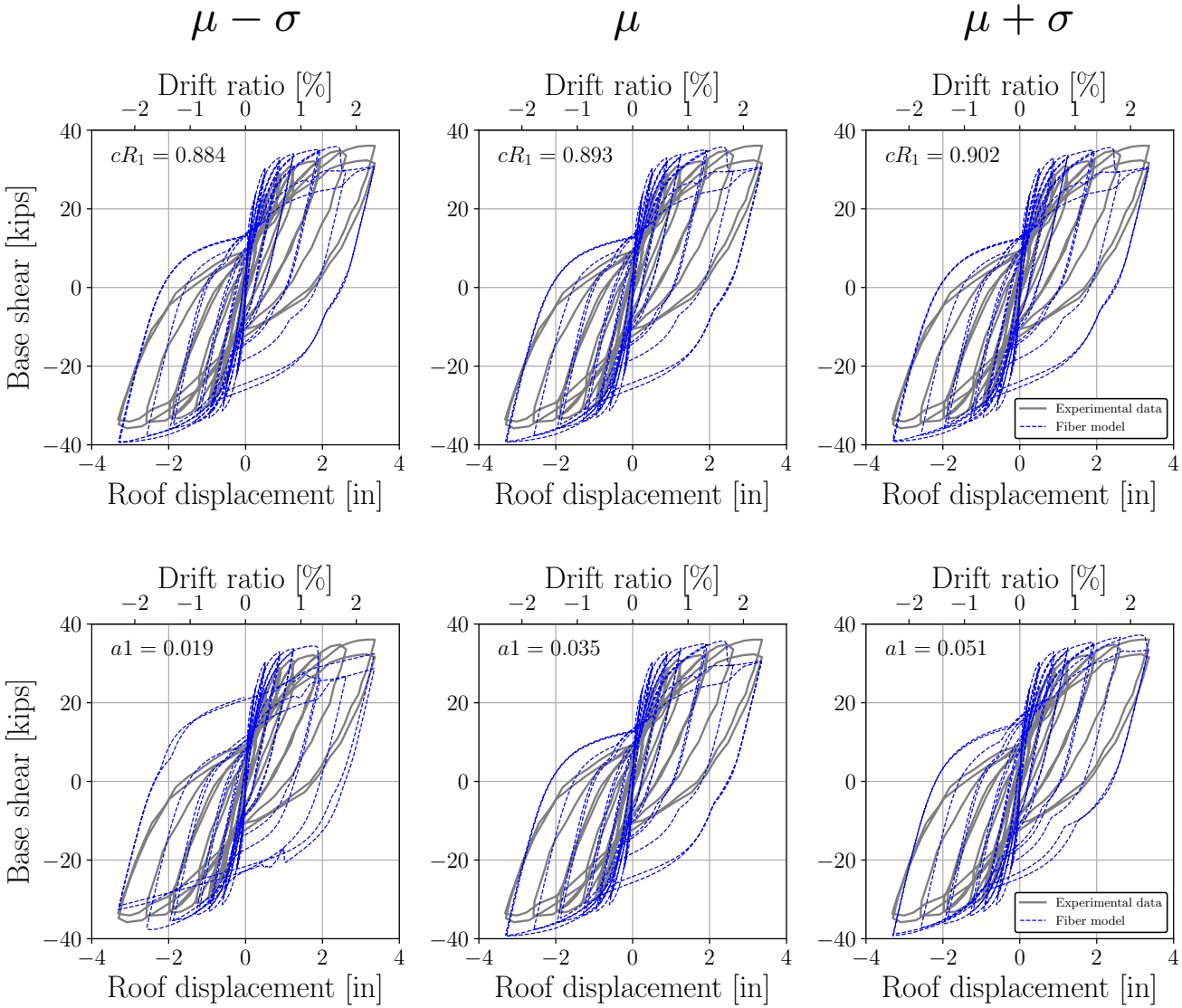
RC Fiber Model Calibration

- Sensitivity analysis of steel model parameters in RW2 Specimen ($\mu \pm \sigma$ variation).



RC Fiber Model Calibration

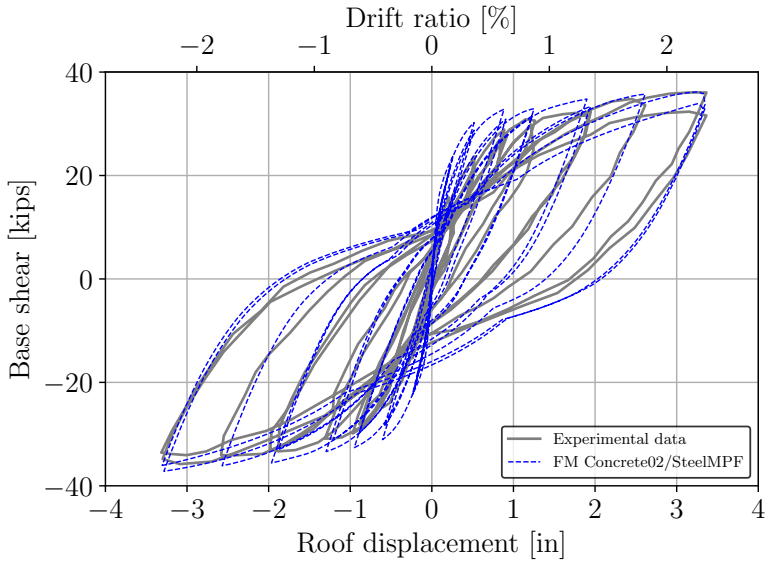
- Sensitivity analysis of steel model parameters in RW2 Specimen ($\mu \pm \sigma$ variation).



RC Fiber Model Calibration

- Calibrated steel model parameters[6]. RW2 Specimen

Parameter	Mean value	c.o.v. (%)	Used value
E_s	29969	4.0	29969
b	0.023	27.0	0.029
cR_1	0.893	1.0	0.947
cR_2	0.093	31.0	0.093
a_1	0.035	45.0	0.051
a_2	0.022	51.0	0.022

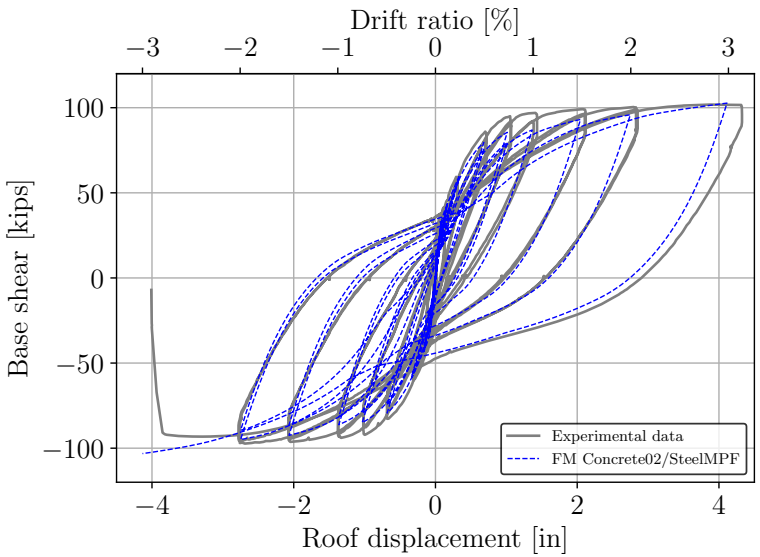


- Parameters b, cR_1, and a_1 are varied respect to their mean values.

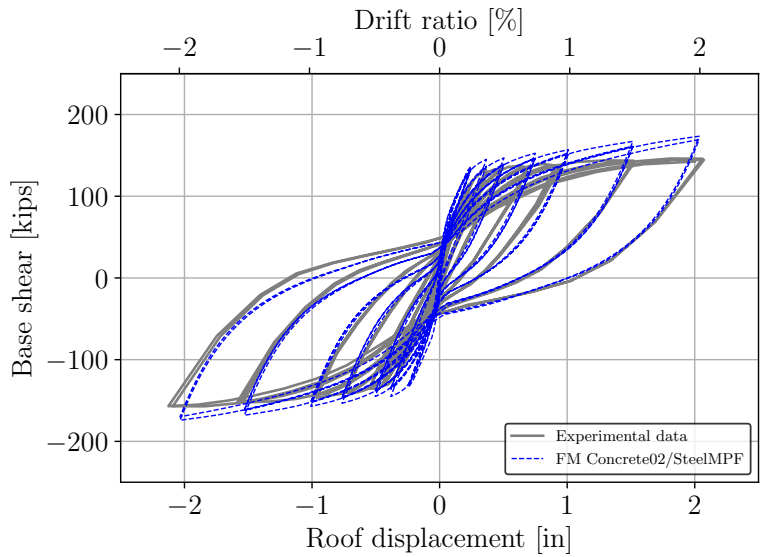
[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier, "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". 2021

RC Fiber Model Calibration

- Tested and modeled responses.



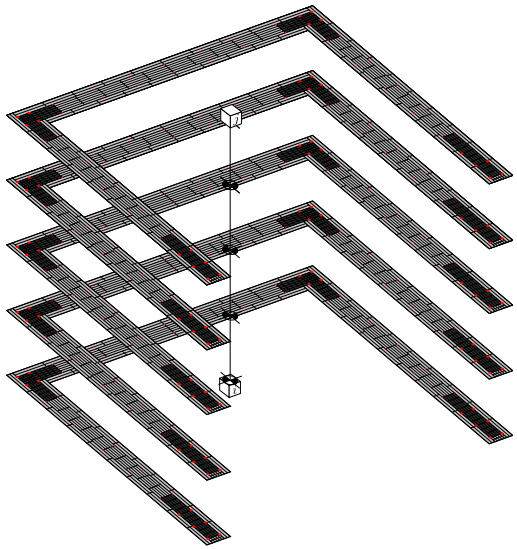
C10 Specimen

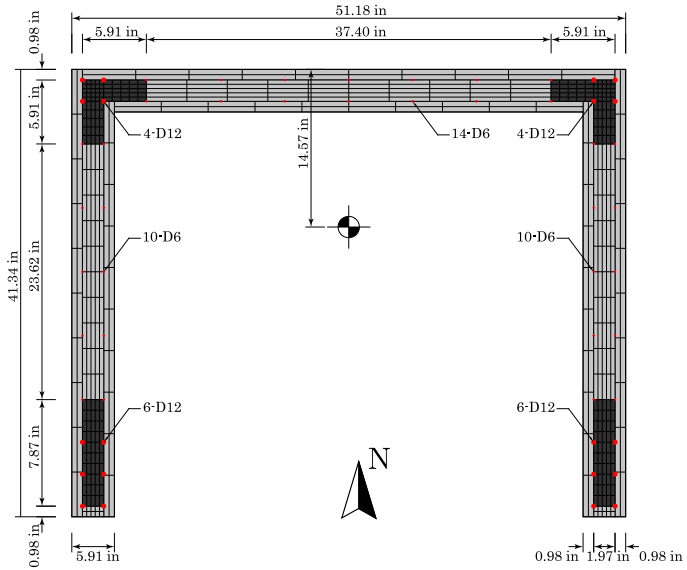


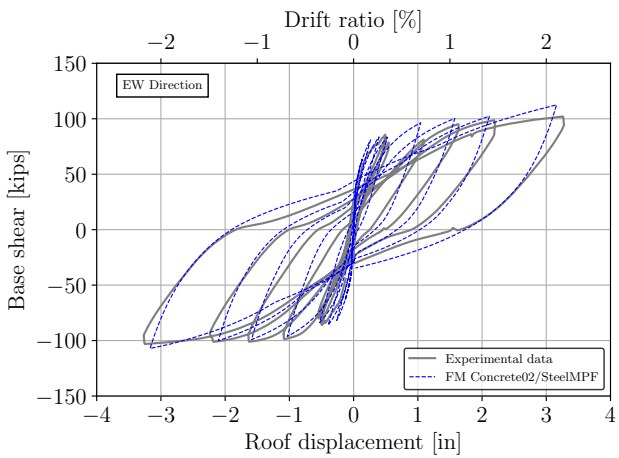
WP7 Specimen

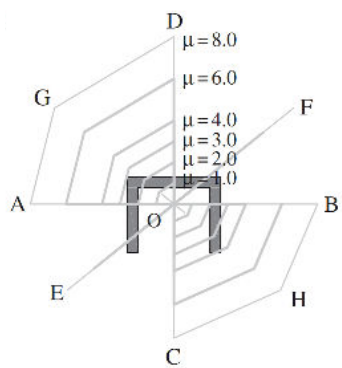
RC Fiber Model Calibration

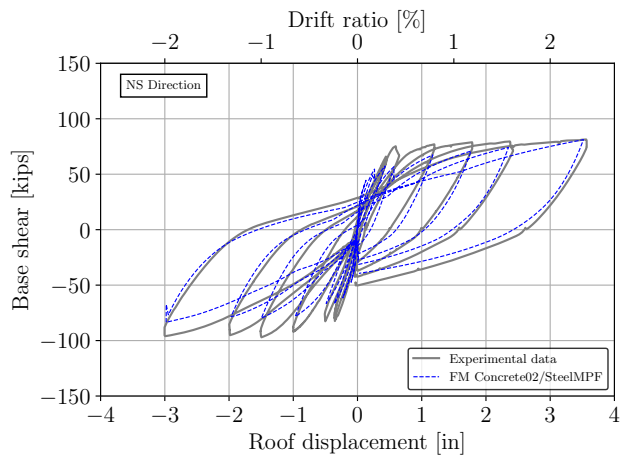
- Tested and modeled responses. C Wall Specimen[10].







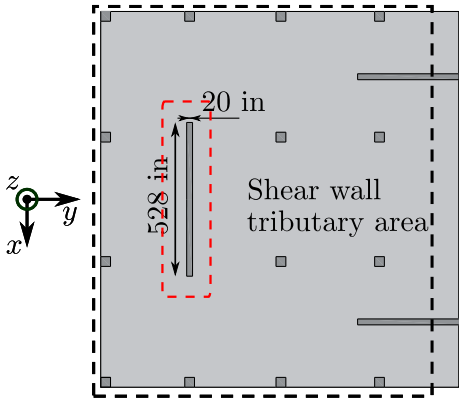




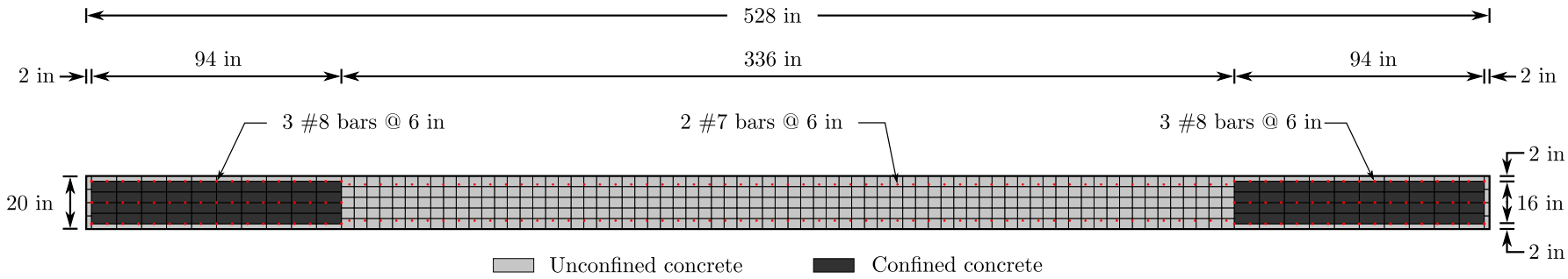
[10] K. Beyer, A. Dazio, and M. J. N. Priestley, "Quasi-Static Cyclic Tests of Two U-Shaped Reinforced Concrete Walls". 2008

Distributed plasticity model (Modeling approach 2)

- RC fiber model in the studied structural system.



Height h_w [ft]	Length l_w [in]	Width b_w [in]	Aspect ratio	Axial load [kips]	Axial load [%]
131.5	528.0	20.0	3.0	1380.75	2.62

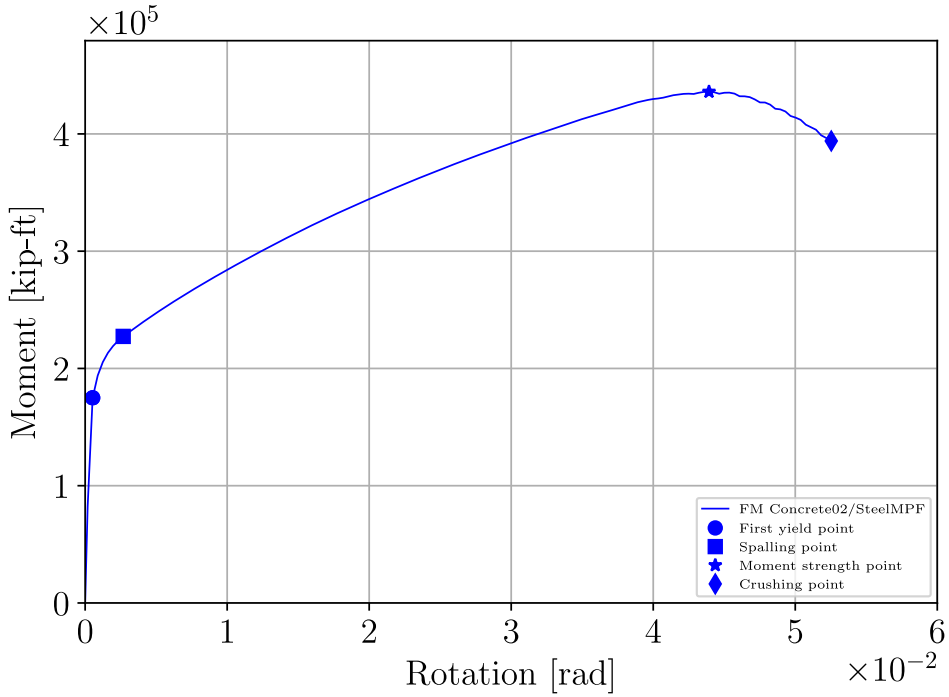


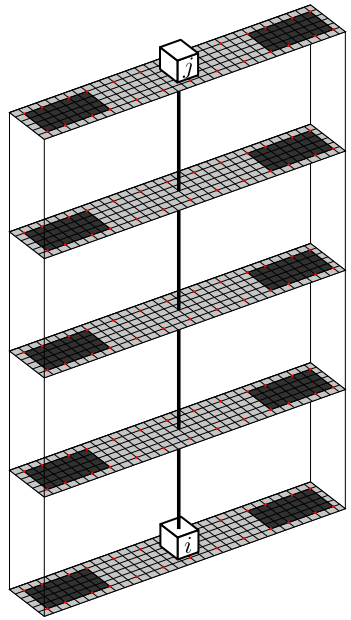
$\rho_{bound.}$ [%]	ρ_{web} [%]	$f_{y,\text{Design}}$ [ksi]	$f_{y,\text{Analysis}}$ [ksi]	f'_c [ksi]	f'_{cc} [ksi]
1.975	1.00	60.0	74.2	5.0	9.48

- The calibrated steel model parameters are used.

Distributed plasticity model (Modeling approach 2)

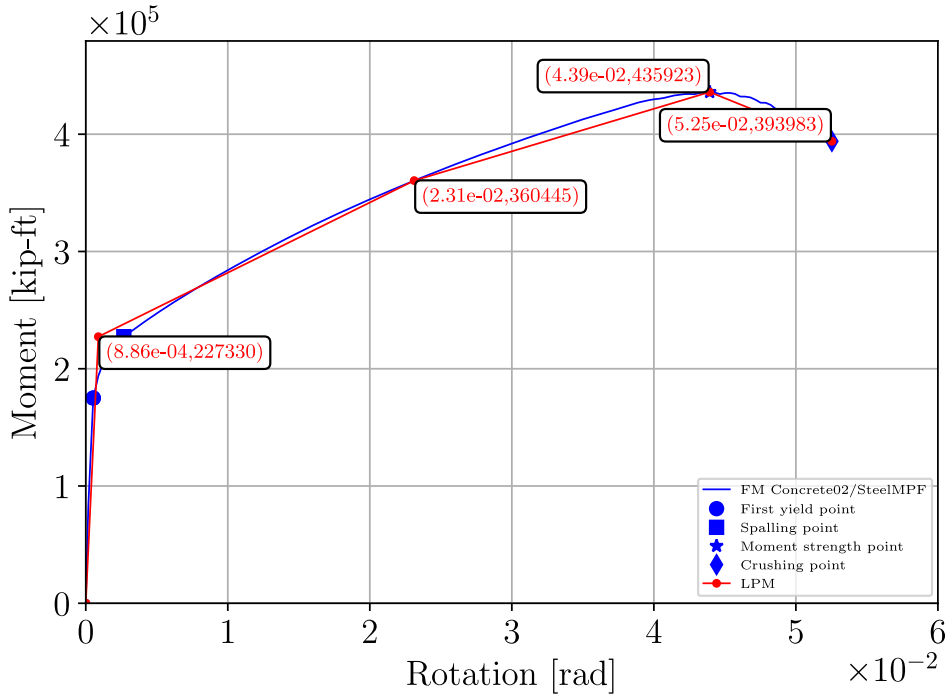
- Moment vs rotation response.

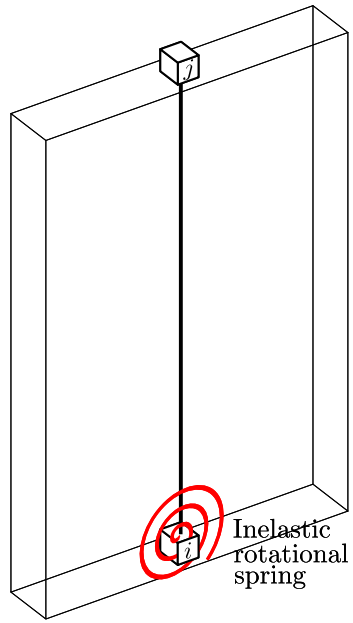




Lumped plasticity model (Modeling approach 1)

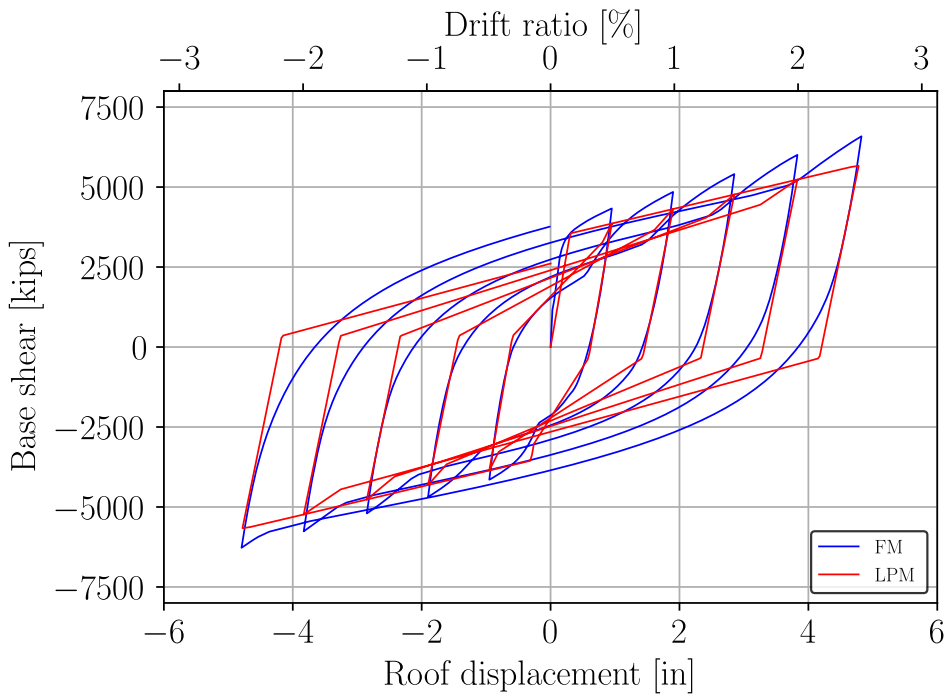
- Moment vs rotation response (Pinching4 material model).

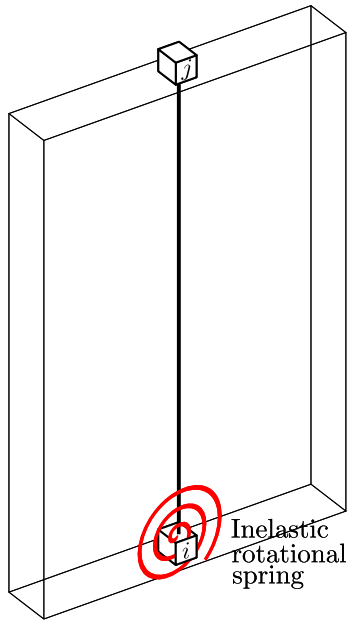




Lumped plasticity model (Modeling approach 1)

- Base shear vs roof displacement response (Pinching4 material model).

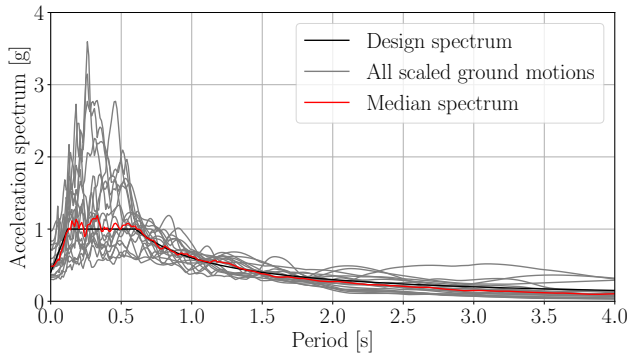




Loading

- 18 design-basis level time-history ground motions[1].

Number	Event	Magnitude	Distance [Km]	Soil typ. class	Comp.	Scale Factor
1	Friuli Italy	6.5	15.0	C	A-TMZ000	2.8
2	Duzce Turkey	7.1	12.0	D	BOL000	1.0
3	Superstition Hills	6.5	11.2	D	B-POE270	1.9
4	Superstition Hills	6.5	11.2	D	B-POE360	2.0
5	Chi-Chi Taiwan	7.6	10.0	D	CHY101-E	1.3
6	Chi-Chi Taiwan	7.6	10.0	D	CHY101-N	0.8
7	Landers	7.3	19.7	D	CLW-LN	2.5
8	Imperial Valley	6.5	22.0	D	H-DLT262	1.9
9	Imperial Valley	6.5	22.0	D	H-DLT352	1.3
10	Imperial Valley	6.5	12.5	D	H-E11230	2.1
11	Northridge	6.7	9.4	D	MUL279	0.7
12	Superstition Hills	6.5	18.2	D	ICC000	1.4
13	Loma Prieta	6.9	12.2	D	G03090	1.4
14	Kocaeli Turkey	7.5	13.6	D	DZC180	1.5
15	Kocaeli Turkey	7.5	13.6	D	DZC270	0.9
16	Cape Mendocino	7.0	7.9	D	RIO270	1.3
17	Kobe Japan	6.9	19.1	D	SHI090	1.7
18	Landers	7.3	23.6	D	YER270	1.2



[1] Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei, "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses". 2016

Numerical Results

- Peak GLRS-to-LFRS connection force responses and statistics.

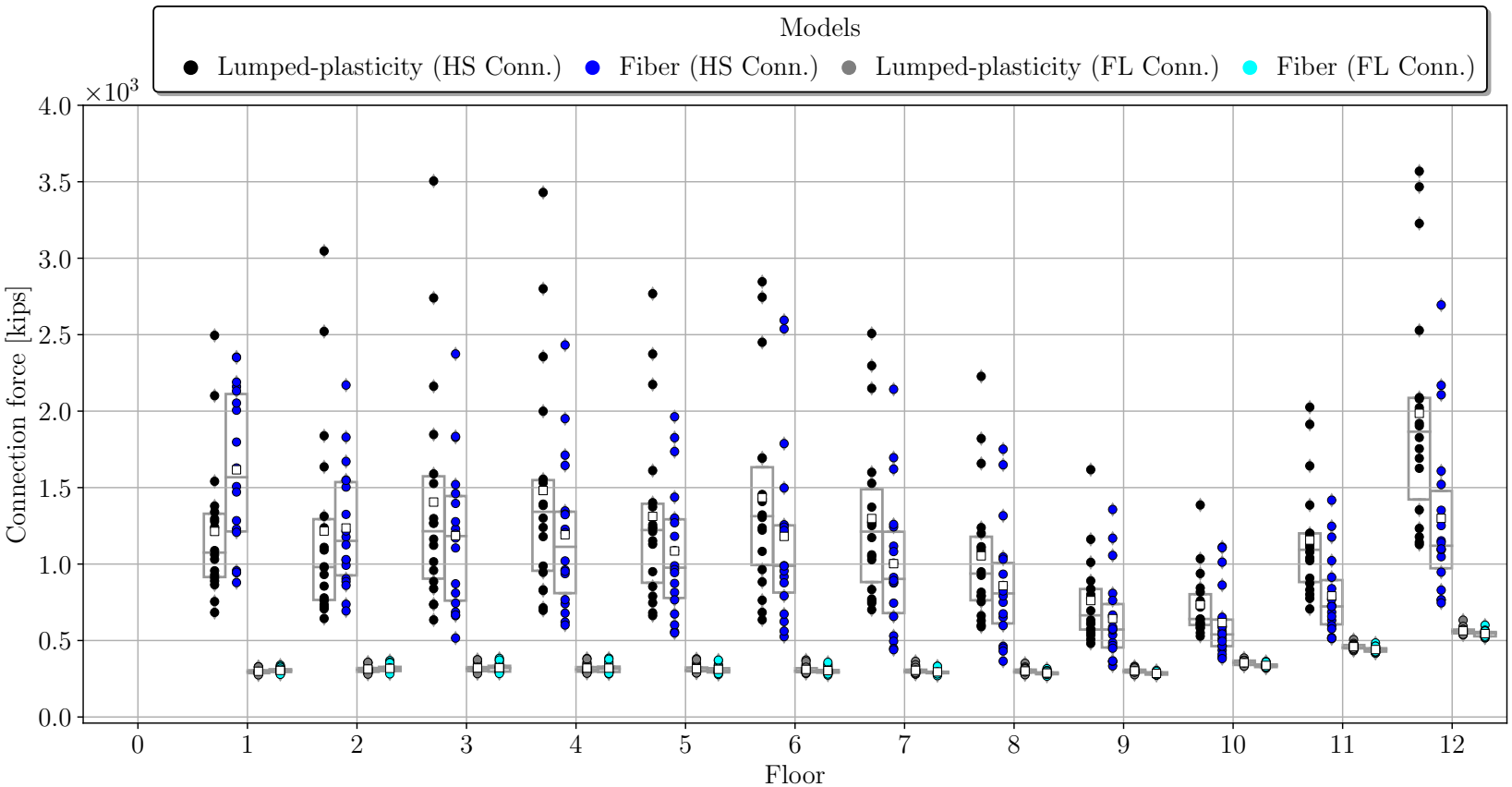


Table: Maximum median value, standard deviation, and coefficient of variation indicating the floor location.

Model	Floor	Mean value [kips]	Std. deviation [kips]	Cov [-]
Lumped-plasticity (HS Conn.)	12	**1985.6**	**764.1**	0.385
	2	1215.9	661.6	**0.544**
Fiber (HS Conn.)	1	**1616.3**	525.1	0.325
	6	1180.9	**600.9**	**0.509**
Lumped-plasticity (FL Conn.)	12	**563.9**	23.1	0.041
	4	319.6	**29.1**	**0.091**
Fiber (FL Conn.)	12	**545.2**	21.1	0.039
	4	319.3	**31.3**	**0.098**

Numerical Results

- Peak floor acceleration responses and statistics.

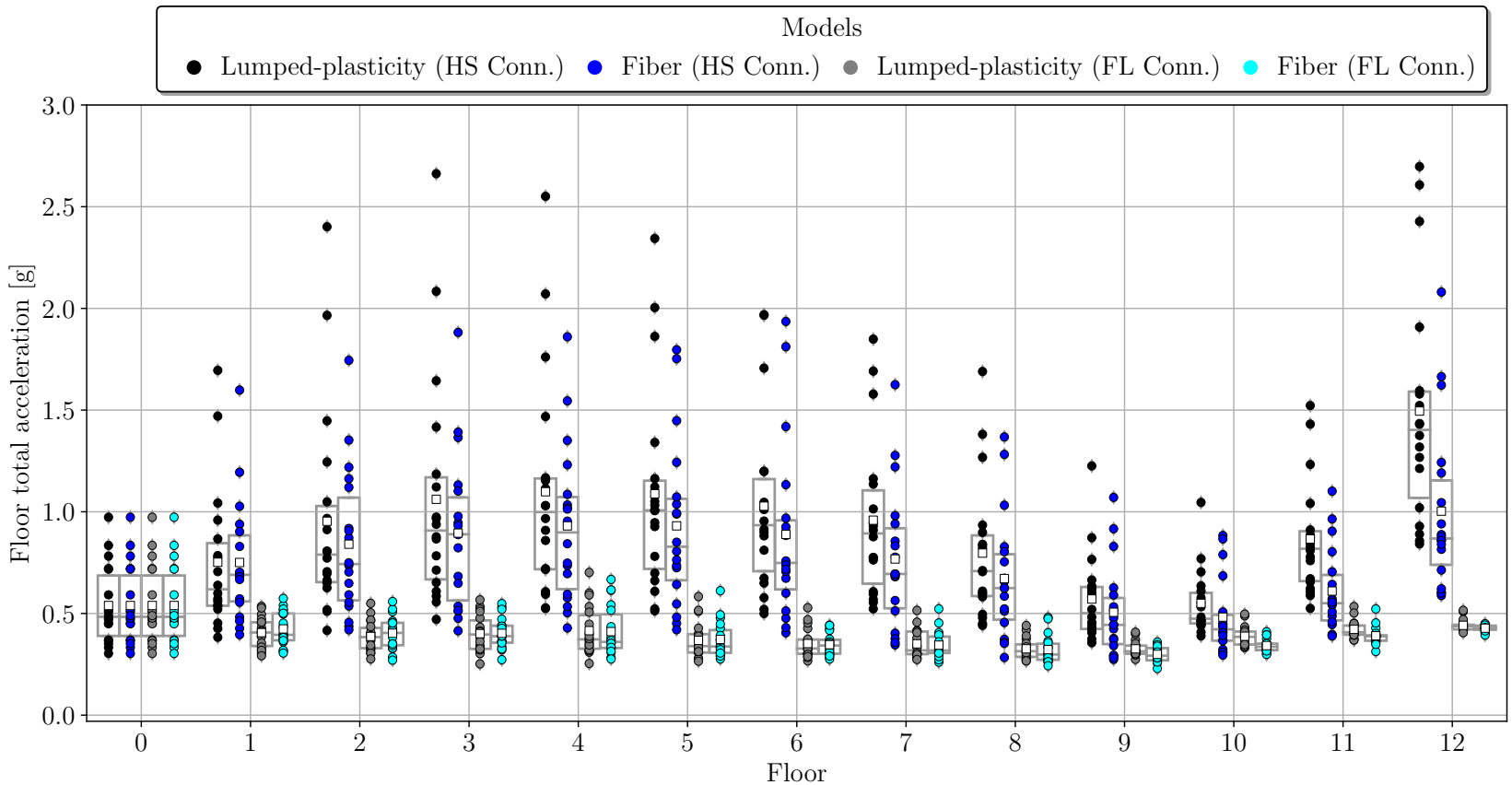


Table: Maximum median value, standard deviation, and coefficient of variation indicating the floor location.

Model	Floor	Mean value [g]	Std. deviation [g]	Cov [-]
Lumped-plasticity (HS Conn.)	12	**1.495**	**0.578**	0.386
	2	0.953	0.521	**0.547**
Fiber (HS Conn.)	12	**1.003**	0.415	0.414
	6	0.889	**0.440**	**0.495**
Lumped-plasticity (FL Conn.)	12	**0.442**	0.030	0.068
	4	0.415	**0.122**	**0.294**
Fiber (FL Conn.)	12	**0.428**	0.015	0.036
	4	0.411	**0.124**	**0.302**

Numerical Results

- Peak LFRS story shear responses and statistics.

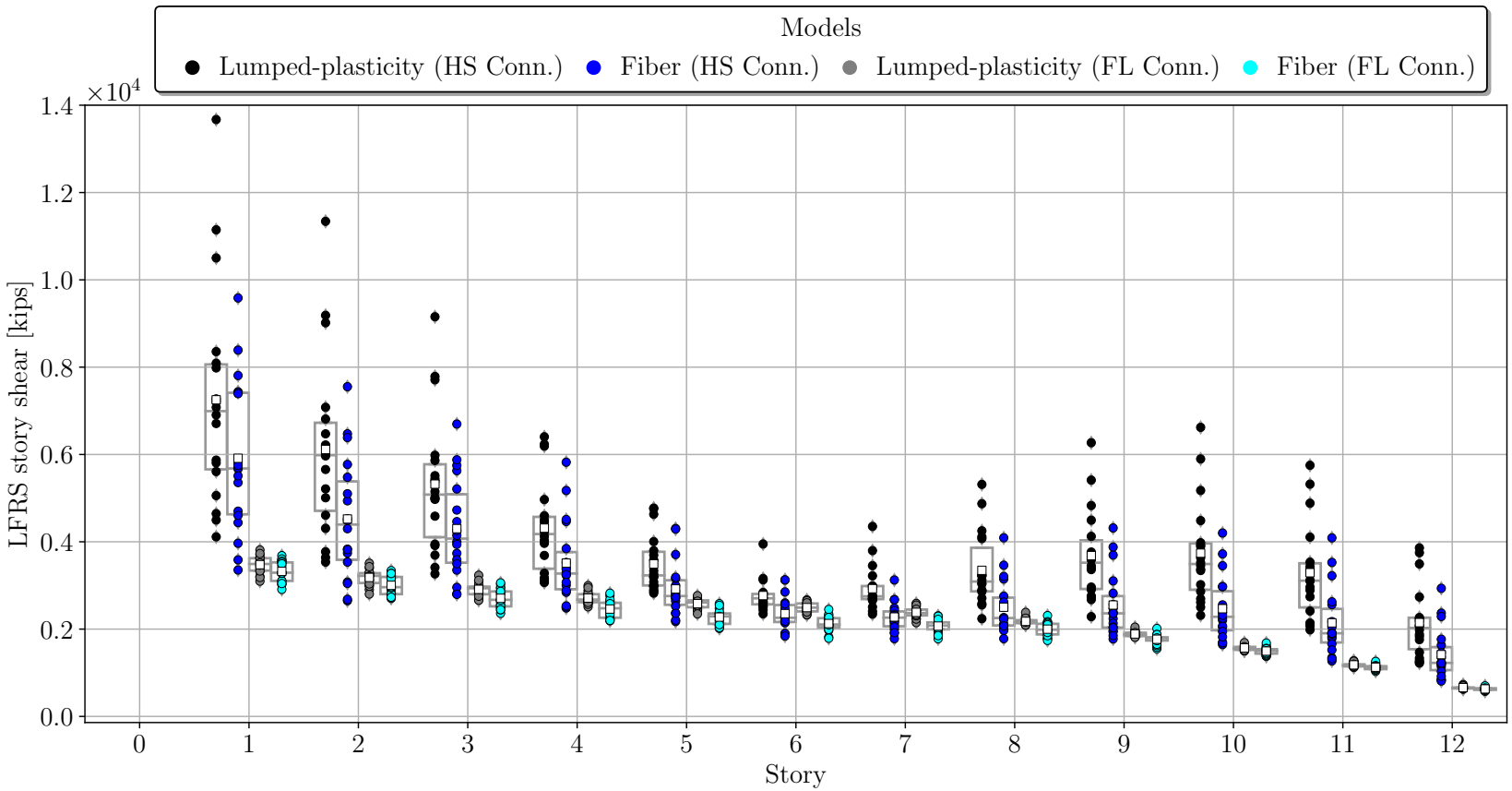


Table: Maximum median value, standard deviation, and coefficient of variation indicating the story location.

Model	Story	Mean value [kips]	Std. deviation [kips]	Cov [-]
Lumped-plasticity (HS Conn.)	1	**7251.8**	**2492.0**	0.344
	12	2148.7	826.4	**0.385**
Fiber (HS Conn.)	1	**5913.2**	**1744.4**	0.295
	12	1414.8	586.4	**0.414**
Lumped-plasticity (FL Conn.)	1	**3475.8**	**199.0**	0.057
	2	3183.2	184.4	**0.058**
Fiber (FL Conn.)	1	**3322.0**	**240.1**	0.072
	4	2459.3	205.1	**0.083**

Numerical Results

- Peak LFRS story drift responses and statistics.

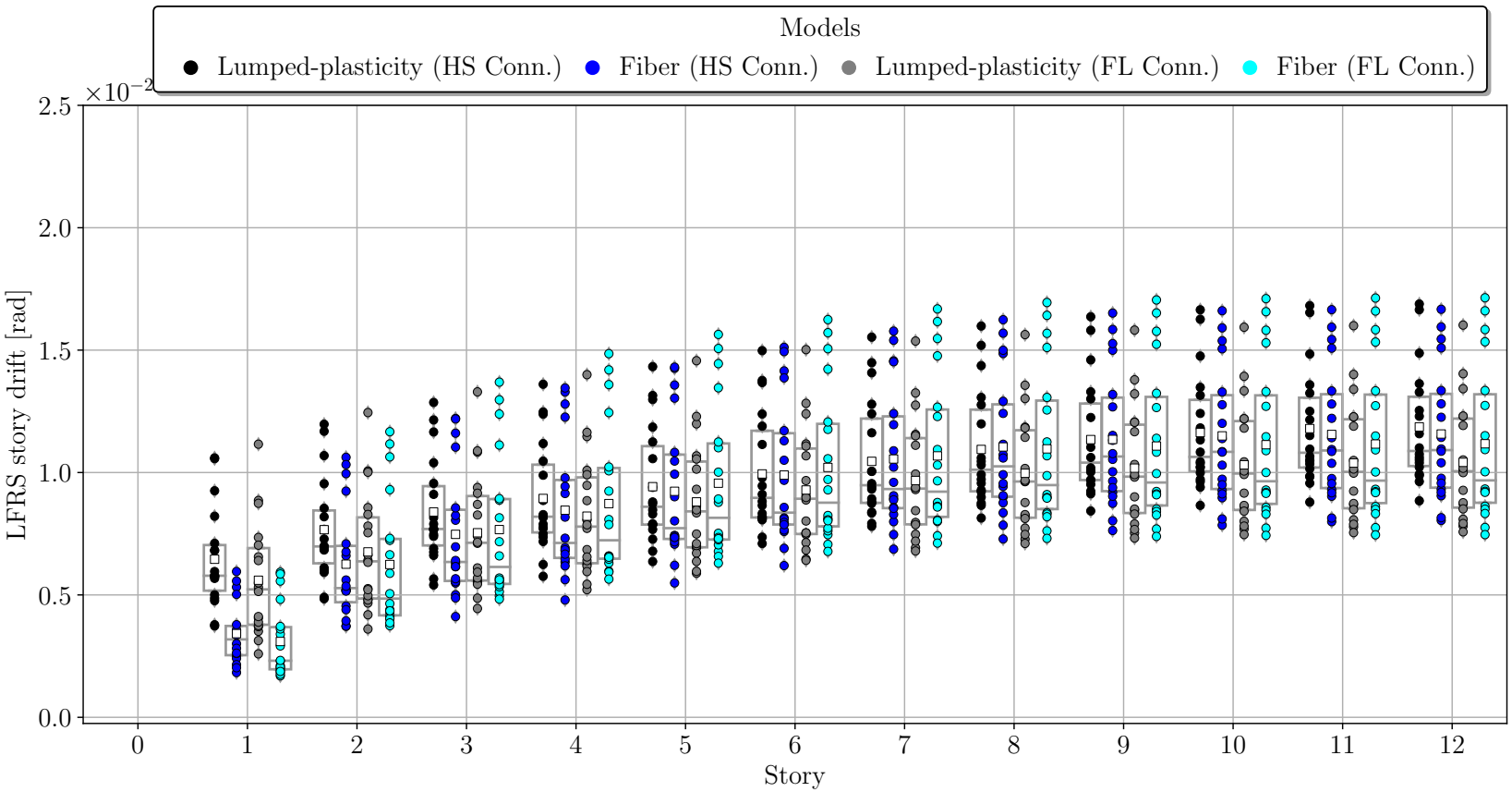


Table: Maximum median value, standard deviation, and coefficient of variation indicating the story location.

Model	Story	Mean value [rad]	Std. deviation [rad]	Cov [-]
Lumped-plasticity (HS Conn.)	12	**0.012**	0.002	0.199
	6	0.010	**0.002**	0.243
	1	0.006	0.002	**0.315**
Fiber (HS Conn.)	12	**0.012**	0.003	0.238
	6	0.010	**0.003**	0.295
	1	0.003	0.001	**0.370**
Lumped-plasticity (FL Conn.)	12	**0.010**	0.002	0.233
	5	0.009	**0.002**	0.279
	1	0.006	0.002	**0.416**
Fiber (FL Conn.)	12	**0.011**	**0.003**	0.287
	1	0.003	0.001	**0.483**

Numerical Results

- Peak GLRS story drift responses and statistics.

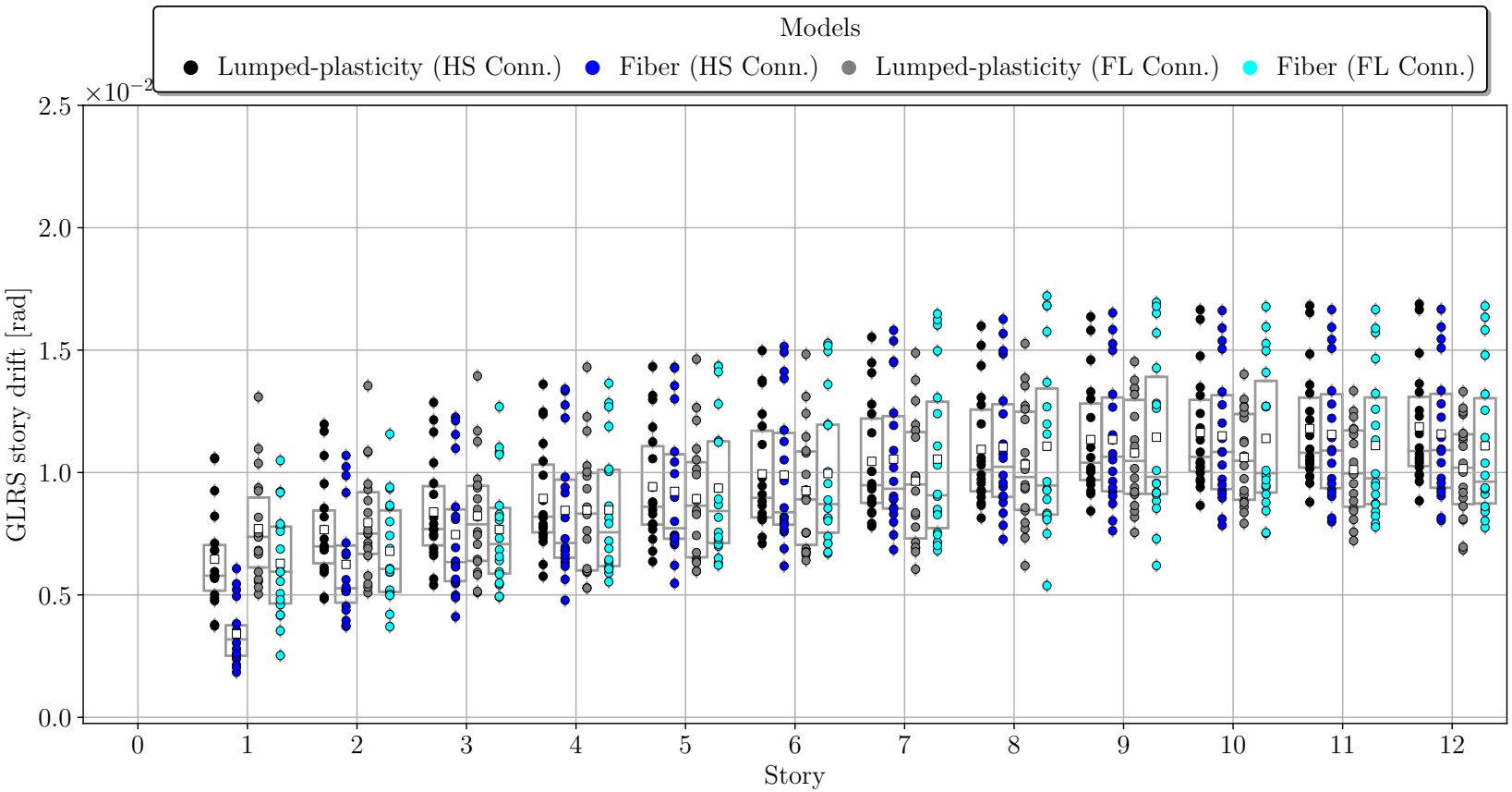


Table: Maximum median value, standar deviation, and coefficient of variation indicating the story location.

Model	Story	Mean value [rad]	Std. deviation [rad]	Cov [-]
Lumped-plasticity (HS Conn.)	12	**0.012**	0.002	0.199
	6	0.010	**0.002**	0.243
	1	0.006	0.002	**0.315**
Fiber (HS Conn.)	12	**0.012**	0.003	0.238
	6	0.010	**0.003**	0.295
	1	0.003	0.001	**0.369**
Lumped-plasticity (FL Conn.)	9	**0.011**	0.002	0.203
	7	0.010	**0.003**	0.273
	4	0.008	0.003	**0.306**
Fiber (FL Conn.)	9	**0.011**	0.003	0.300
	8	0.011	**0.004**	0.330
	1	0.006	0.002	**0.349**

Conclusions

- Buildings without force limiting connections are more sensitive in terms of acceleration and force responses to the modeling approach of the LFRS (structural wall).

- The peak mean values and dispersion of story drift responses of building with and without force-limiting connections are affected by the LFRS modeling approach used, but the effects have not a clear trend over the height.

- Simple models can be used to simulate the seismic response of buildings with force limiting connections obtaining low dispersion in acceleration and force responses.



References I

[1] Georgios Tsampras, Richard Sause, Dichuan Zhang, Robert B. Fleischman, Jose I. Restrepo, David Mar, and Joseph Maffei. "Development of deformable connection for earthquake-resistant buildings to reduce floor accelerations and force responses". In: *Earthquake Engineering & Structural Dynamics* 45.9 (2016), pp. 1473–1494. ISSN: 1096-9845. DOI: 10.1002/eqe.2718.

[2] Frank McKenna, Michael H. Scott, and Gregory L. Fenves. "Nonlinear Finite-Element Analysis Software Architecture Using Object Composition". In: *Journal of Computing in Civil Engineering* 24.1 (Jan. 1, 2010), pp. 95–107. ISSN: 0887-3801. DOI: 10.1061/(ASCE)CP.1943-5487.0000002.

[3] Fabio Taucer, Enrico Spacone, and Filip Filippou. "A Fiber Beam-Column Element for Seismic Response Analysis of Reinforced Concrete Structures". In: (Jan. 1, 1991).

[4] M. Menegotto and P. E. Pinto. "Method of Analysis for Cyclic Loaded R. C. Plane Frame Including Changes in Geometry and Non-Elastic Behaviour of Elements under Combined Normal Force and Bending". In: *Proceedings of IABSE Symposium on Resistance and Ultimate Deform ability of Structures Acted On by Well Defined Repeated Loads* 11 (1973), pp. 15–22.

[5] Mohd Hisham Mohd Yassin. "Nonlinear analysis of prestressed concrete structures under monotonic and cyclic loads". PhD thesis. Ann Arbor, Mich.: University of California, Berkeley, 1994.

[6] Matías Birrell, Rodrigo Astroza, Rodrigo Carreño, José I. Restrepo, and Gerardo Araya-Letelier. "Bayesian parameter and joint probability distribution estimation for a hysteretic constitutive model of reinforcing steel". In: *Structural Safety* 90 (May 2021), p. 102062. ISSN: 01674730. DOI: 10.1016/j.strusafe.2020.102062.

[7] John H. Thomsen and John W. Wallace. *Displacement-based Design of RC Structural Walls: An Experimental Investigation of Walls with Rectangular and T-shaped Cross-sections*. Clarkson University, Department of Civil Engineering, 1995. 353 pp.

[8] Kenneth Elwood. "University of Auckland High Axial Load Wall Tests". In: (May 14, 2018). DOI: 10.17603/DS2609N.

[9] John Wallace, Carlos Arteta, and Christopher Segura. "NEESR: Seismic Performance of Conventional and Innovative Special Structural Walls". In: (Sept. 27, 2018). DOI: 10.17603/DS2P41P.



References II

[10] K. Beyer, A. Dazio, and M. J. N. Priestley. "Quasi-Static Cyclic Tests of Two U-Shaped Reinforced Concrete Walls". In: *Journal of Earthquake Engineering* 12.7 (Oct. 2, 2008), pp. 1023–1053. ISSN: 1363-2469. DOI: 10.1080/13632460802003272.

