Seismic behavior of steel MRFs with damage-controllable mechanical hinges

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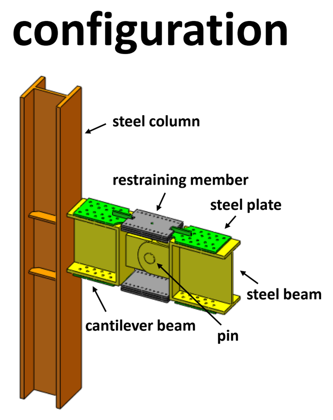
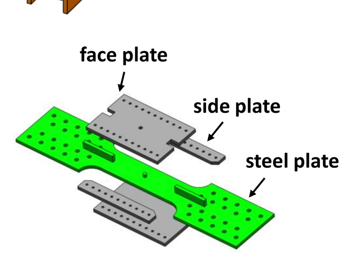
Introduction

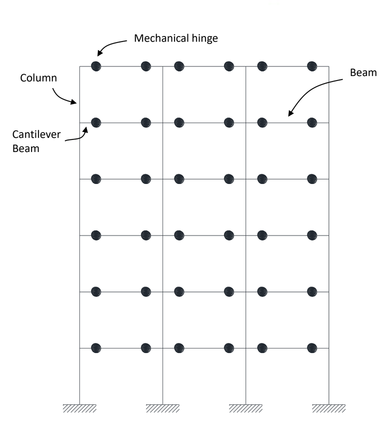
Earthquake-resilient steel structures have become a hot topic in the field of earthquake engineering. Based on the idea of improving structure resilience and seismic damage control, a novel replaceable steel moment connection is proposed. The new steel connection is a mechanical joint with a pin and is equipped with two steel plates that function as the steel fuses. The energy is dissipated through the tension and compression yielding of steel plates. Restraining members are introduced to prevent the buckling of the steel plates under compression force to achieve a stable load-carrying mechanism. A nonlinear numerical models for steel moment frames is validated through the E-Defense shaking table test of an 18 story steel moment frames. Based on the validated numerical models, nonlinear static and time history analyses of a conventional steel moment frame and three innovative steel frames with different MHC configurations are conducted.

Proposed steel connection

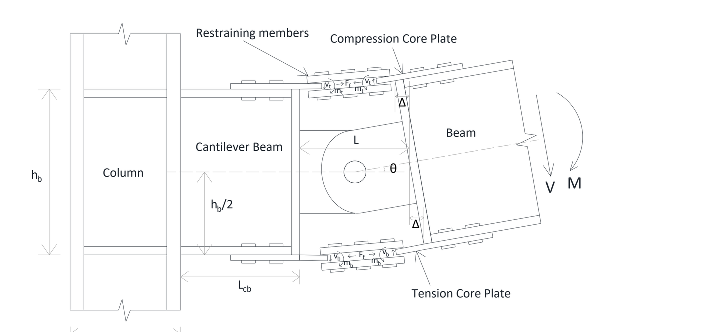
Structural configuration

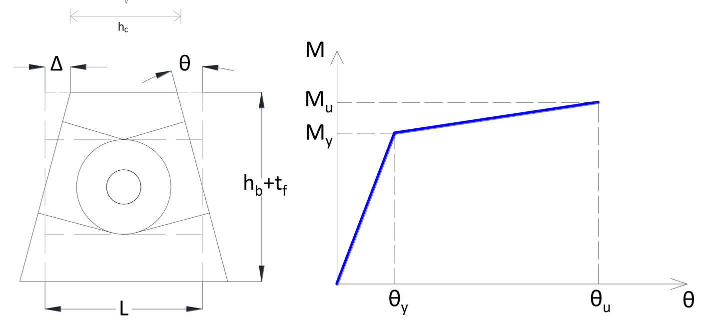






Mechanical behavior





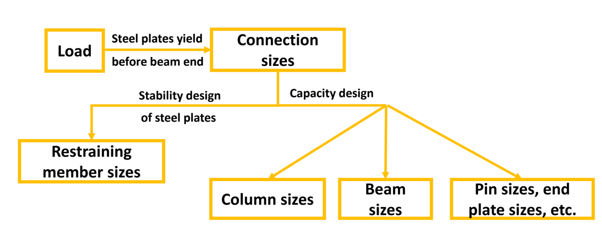
$$M_y = F_c(h_b + t_c) = f_y A_c(h_b + t_c)$$

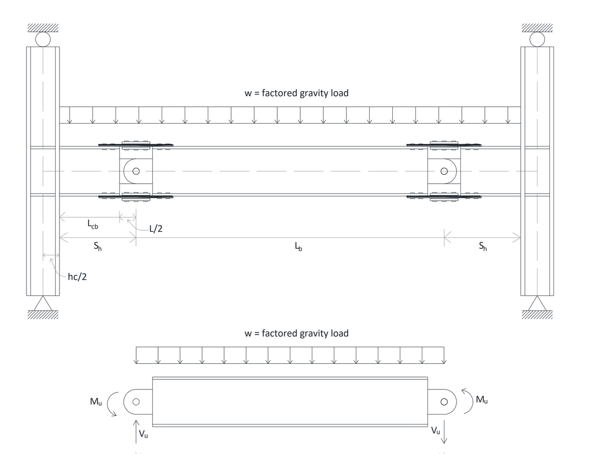
$$\theta_y = 2L_y f_y / (h_b + t_c) E_s$$

$$K_e = M_y / \theta_y = E_s A_c (h_b + t_c)^2 / 2L_y$$

$$M_u = C_{pr} R_y F_y A_c (h_b + t_c)$$

Design method



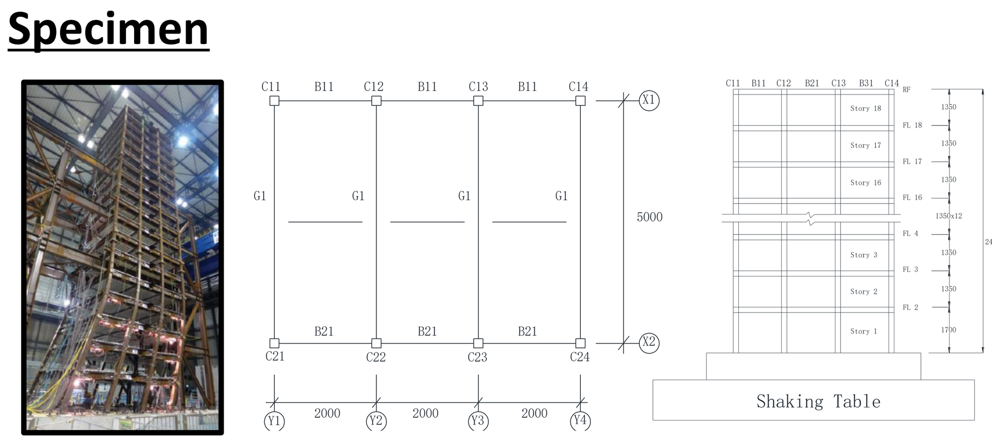


$$V_u = \frac{2M_u}{L_b} + \frac{wL_b}{2}$$

$$M_{cf} = M_u + V_u s_h \leq W_b f_{yb}$$

E-Defense steel MRF shaking table test

Specimen



Structure information
- 1:3 scale 18 story MRF
- Two frames, each frame with three bays of 2m
- Height: h_1=1.7m, h_s=1.35m, h_t=25.35m

Table 1 Frame member cross-section and steel material

Column			Beam		
Story	Cross-section	Steel material	Floor	Cross-section	Steel material
1~6	BB-200x200x12	SM490A	2~9	BH-270x85x6x12	SM490A
7~12	B-200x200x12	BCR295	10~13	BH-270x95x6x9	SM490A
13~18	B-200x200x9	BCR295	14~RF	BH-270x85x6x9	SM490A

Ground motion input

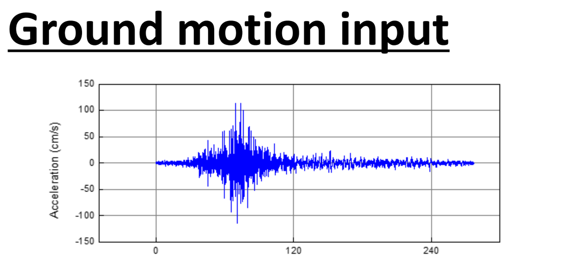


Fig. 8. Input ground motion acceleration time history curve at design level (pSv 40cm/s)

- A long-duration and long-period ground motion
- 14 ground motions excited sequentially
- Scaled by the maximum pseudo response velocity (pSv) :40cm/s to 420 cm/s,

Structure behavior

Structure behavior under different ground motion

No.	Test	pSv (cm/s)	Description of input level	Max. story drift angle (floor)	Damage to specimen
1	pSv40	40	Design level 1	1/171 (14F)	None (elastic)
2	pSv80	81	Design level 2	1/110 (3,14F)	Full plastic of beam end (2-4F)
3	pSv110-1	110	Average of prediction	1/90 (14F)	Full plastic of beam end (2-7F) and column base (2-5F)
4	pSv110-2	110	Average of prediction	1/91 (14F)	ditto
5	pSv180-1	180	Max. of prediction	1/62 (11F)	Full plastic of beam end (2-14F), Crack initiation beam end (2-5F)
6	pSv180-2	180	Max. of prediction	1/55 (11F)	Crack progress beam end (2-5F)
7	pSv220	220	Over max. of prediction	1/48 (9F)	Fracture of beam flange (2F)
8	pSv250	250	Over max. of prediction	1/45 (2F)	Fracture of beam flange (2-3F)
9	pSv300	300	Over max. of prediction	1/30 (2F)	Fracture of beam flange (2-5F)
10	pSv340-1	340	Over max. of prediction	1/16 (2F)	Fracture of beam flange (upper Fl.)
11	pSv340-2	340	Over max. of prediction	1/13 (2F)	Local buckling of column base (1F)
12	pSv420-1	420	Over max. of prediction	1/10 (2F)	Total fracture of beam end (2-5F)
13	pSv420-2	420	Over max. of prediction	1/6 (2F)	Fracture of column base (1F)
14	pSv420-3	420	Over max. of prediction	Collapse	Collapse

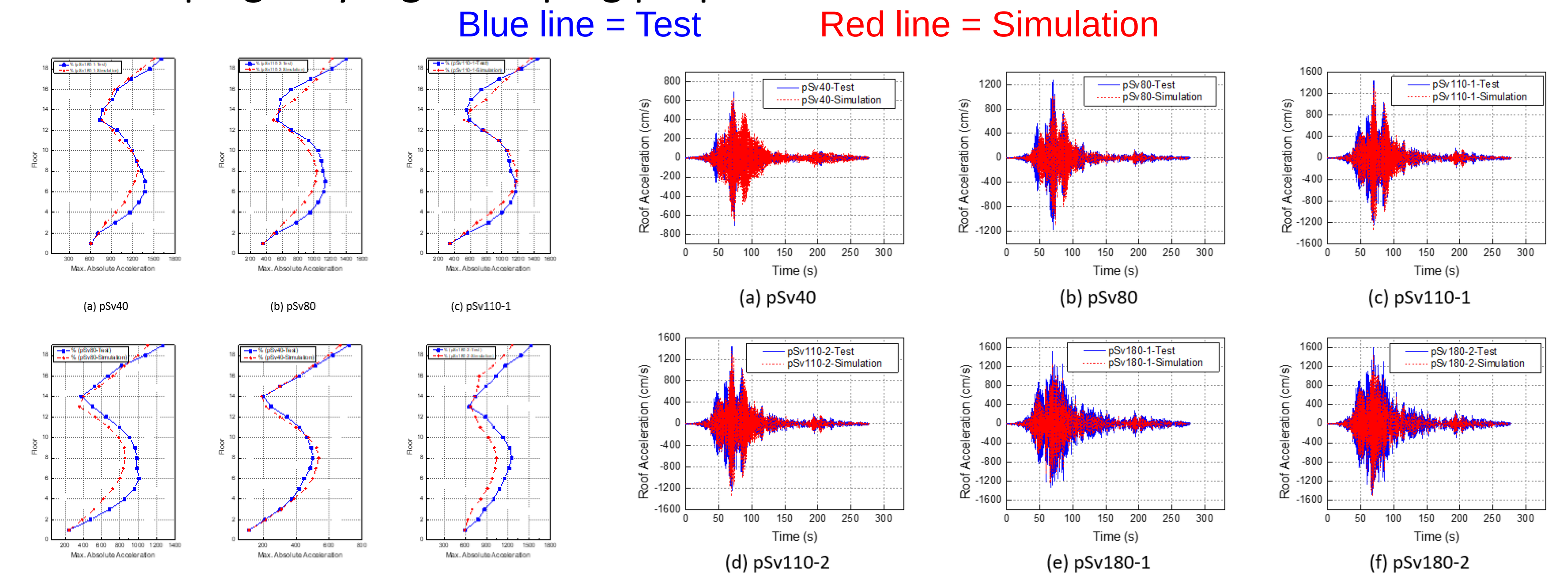
- ~pSv40: elastic
- ~pSv110-2: beam end full plastic
- ~pSv180-2: beam end crack
- ~pSv340-1: beam flange fracture
- ~pSv340-2: column local buckling
- ~pSv420: collapse

OpenSees Simulation

OpenSees Models

- Model: 2D centerline model
- Columns, Beams: force-based BC elements; Panel zone: joint rigid off;
- Material: steel02; Mass: lumped at joints;
- Damping: Rayleigh damping proportional to the mass and to initial stiffness

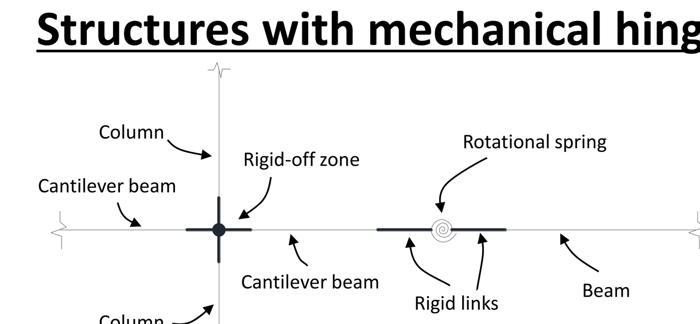
Blue line = Test   Red line = Simulation



Max. story accelerations   Roof acceleration time history

Steel MRFs with mechanical hinges

Structures with mechanical hinges

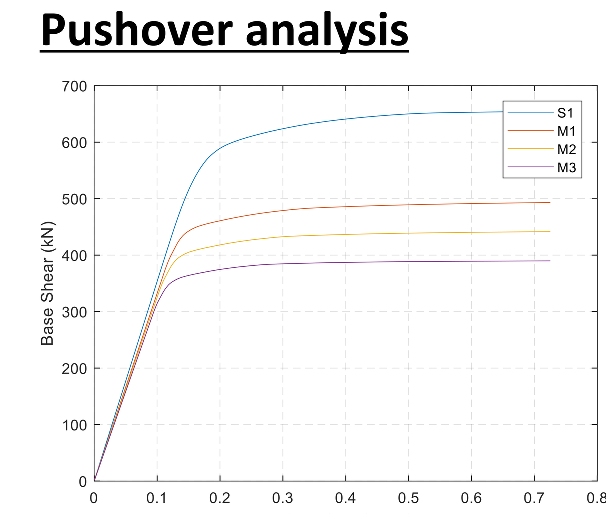


Mechanical hinge connection model

Models	$M_u/M_{u.max}$	M_u/M_{by}	First periods (s)
S1	-	-	1.163
M1	1.0	0.72	1.203
M2	0.9	0.65	1.217
M3	0.8	0.58	1.235

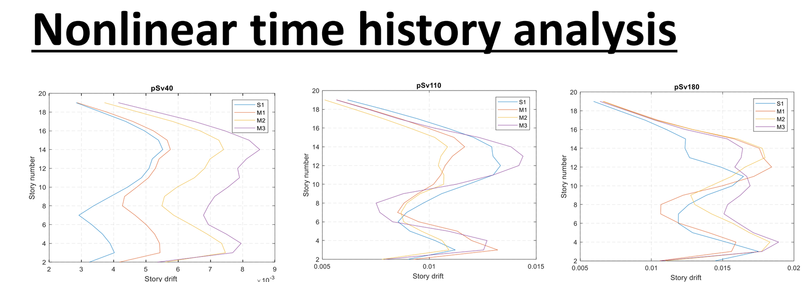
Model properties and periods

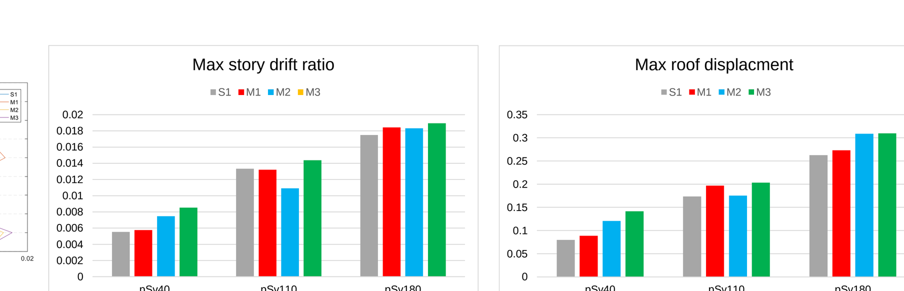
Pushover analysis



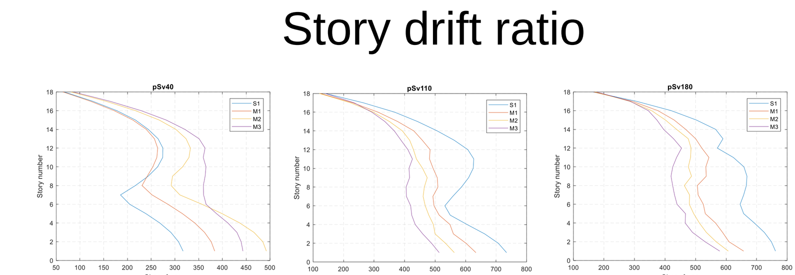
Models	Initial yield ϑ	Initial stiffness reduction	Yield base shear reduction	Ultimate strength reduction
S1	0.02	-	-	-
M1	0.155	5.96%	24.3%	24.7%
M2	0.143	7.97%	31.8%	32.5%
M3	0.123	10.43%	40.3%	40.5%

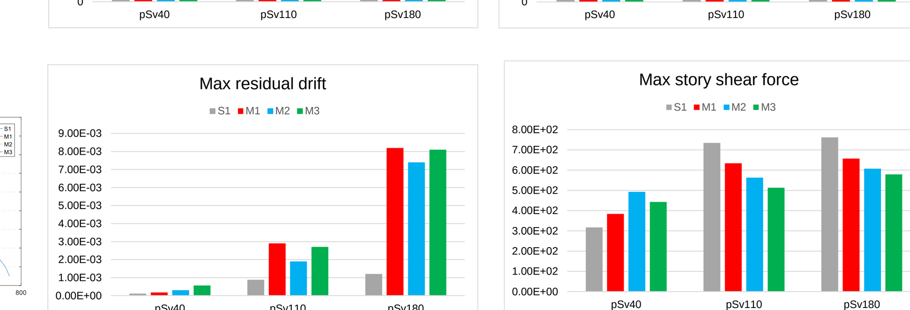
Nonlinear time history analysis





Story drift ratio





Story shear force

Conclusions

- An innovative replaceable steel moment connection is proposed and a numerical model in OpenSees is developed and validated for the shaking table test of an 18 story E-Defense steel moment frame. Nonlinear analysis is conducted on conventional MRF and MRF with different mechanical hinge configurations.
- Pushover analysis shows that mechanical hinge generally decreases the initial yield θ, initial stiffness, yield and ultimate base shear.
- Time history analysis shows that mechanical hinge general increases minor max. story drift ratio and max. roof story displacement, much max. residual story drift, but reduces max. story shear force.

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