Structural Behavior of Modular Steel Buildings

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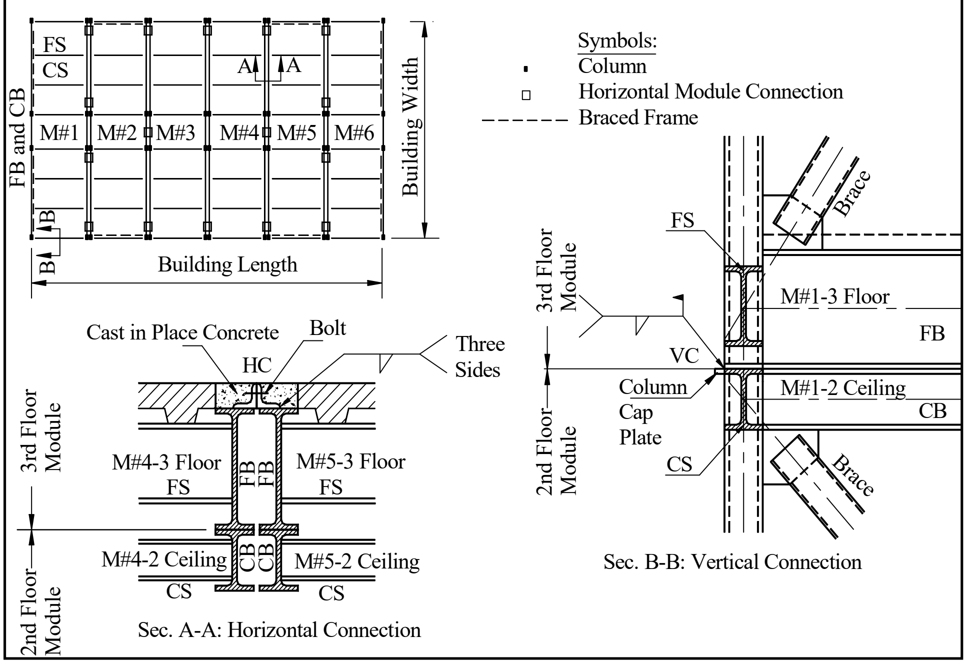
Western Engineering Civil and Environmental Engineering

Outline:

1. Background and Objectives.
2. Behavior Of MSB Floor Grid Structure.
3. Experimental Study of Seismic Performance Of MSB.
4. Inelastic Behavior & Characteristics Of MSB Braced Frames.
5. Seismic Demands & Capacities Of MSB Braced Frames.
6. Significant Research Contributions.
7. Recommendations & Acknowledgements.

Western Engineering   Structural Behavior of MSBs

Background:



Objectives:

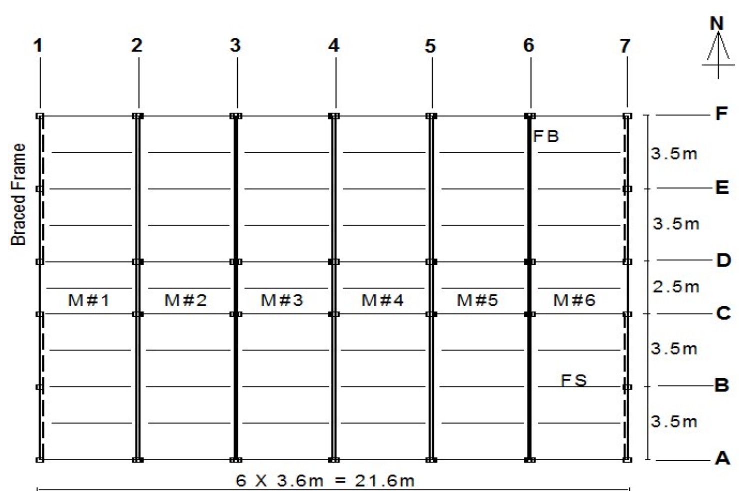
1. To document detailing requirements of MSBs.
2. To understand the effect of direct welding on behavior and design of MSB floor grid structure.
3. To investigate, experimentally, seismic behavior of braced frames of MSBs.
4. To develop and validate an analytical model to predict seismic behavior of MSBs.
5. To analytically study and evaluate inelastic behavior and response characteristics of MSB braced frames.
6. To analytically assess seismic inelastic demands and capacities.

MSB Floor Grid Structure

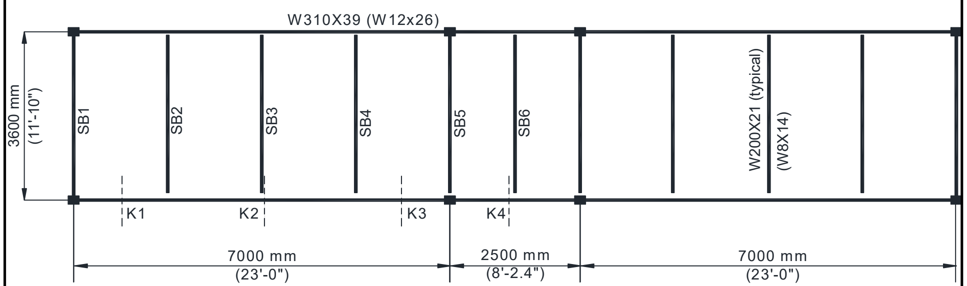
Outline:

- Design of a typical MSB floor grid structure
- Model and analysis of MSB floor system
- Development of analytical model

Floor System:



Floor System:



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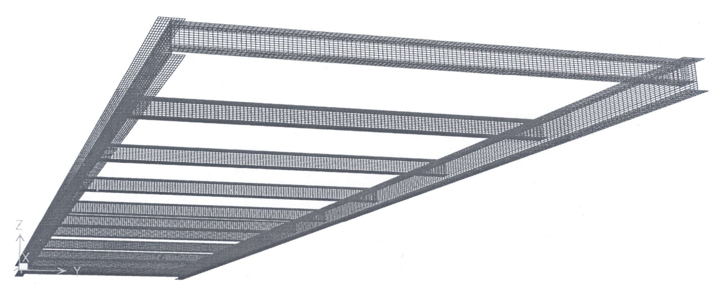
FE Model:



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Parameters:

t_w^b / t_w^s	d_b / d_s	L_s / d_s	L_w / d_s
1.16	1.5	17.7	0.4
2.32	2.3	35.4	0.8
3.48	3.0	53.2	1.0

b: Floor Beam
s: Floor Stringer
t_w: web thickness

d: depth
L: Length
L_w: weld length

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Results (Stringers):

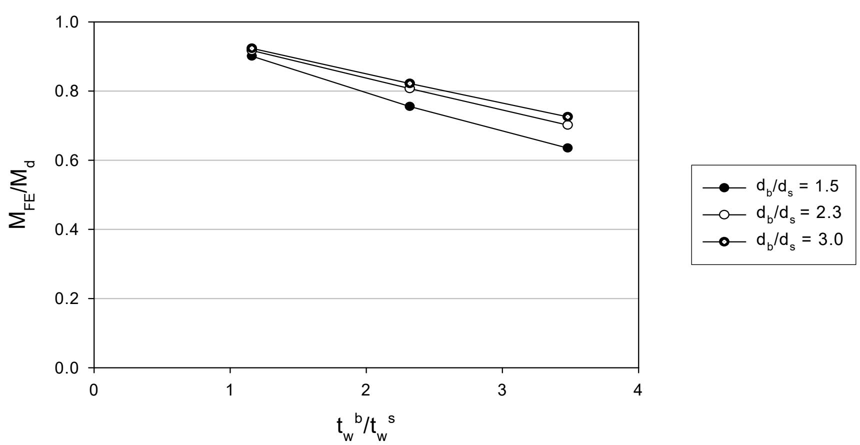
Configuration Considered $d_b/d_s = 1.5$ $t_w^b/t_w^s = 1.16$ $L_s/d_s = 17.7$ $L_w/d_s = 0.8$	FLOOR STRINGERS					
	SB1	SB2	SB3	SB4	SB5	SB6
Mid-Span Moment (Design) M_d, (kNm)	22.28	22.03	22.03	22.03	30.8	18.26
Mid-Span Moment (FE) M_{FE}, (kNm)	20.2	20.09	20.14	20.05	27.75	16.54
M_{FE} as a percentage of M_d (%)	**90.66**	**91.19**	**91.42**	**91**	**90.1**	**90.58**
Hogging Moment at end of span (Design) M_h, (kNm)	0	0	0	0	0	0
Hogging Moment at end of span (FE) M_n, (kNm)	2.08	1.94	1.89	1.98	3.05	1.72
M_n as a percentage of M_d (%)	**9.34**	**8.81**	**8.58**	**9**	**9.9**	**9.42**
Axial Force (Design) N_d, (kN)	0	0	0	0	0	0
Axial Tensile Force (FE) N_{FE}, (kN)	15.16	18.55	19.08	18.14	21.79	13.84
Total Load on Beams excl. self wt. W (kN)	48.74	48.2	48.2	48.2	67.68	39.82
N_{FE} as a percentage of W (%)	**31.1**	**38.49**	**39.59**	**37.63**	**32.2**	**34.76**

Western Engineering MSB Floor Grid Structure

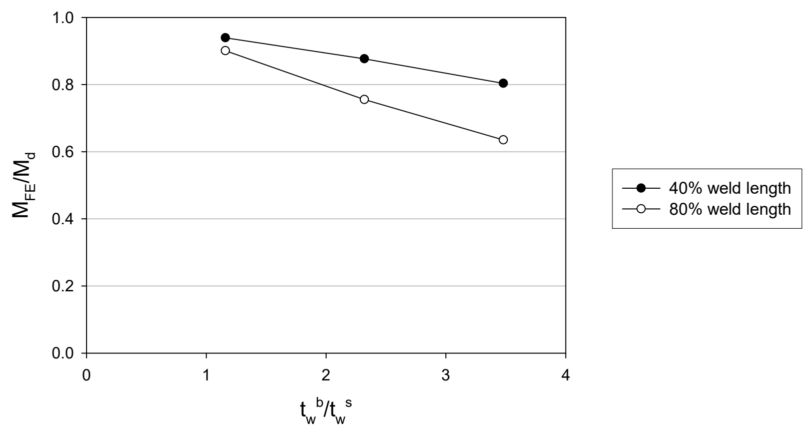
Results (Floor Beam):

Configuration Considered	Sections of Main Beam, measured from point A (mm)			
$d_b/d_s=1.5$ $t_w^b/t_w^s=1.16$ $L_s/d_s=17.7$ $L_w/d_s=0.8$	**900 (K1)**	**3550 (K2)**	**6100 (K3)**	**8100 (K4)**
Bending Moment at section (Design) M_d, (kNm)	44.83	91.57	-21.93	71
Bending Moment at section (FE) M_a, (kNm)	44.44	91.34	-21.34	69.22
M_a as a percentage of M_d (%)	**99.13**	**99.75**	**97.3**	**97.49**

Web Thickness:



Weld Length:



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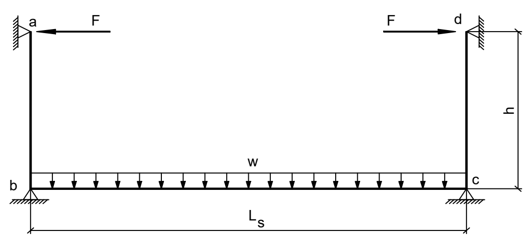
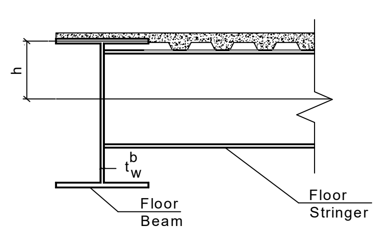
Proposed Model:





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Effective Web Width (B):

$$\ln\left(\frac{B}{t_w^b}\right) = -1.0723\ln\left(\frac{L_s}{d_s}\right) + 0.7758\ln\left(\frac{L_w}{d_s}\right) - 3.4783\ln\left(\frac{t_w^b}{t_w^s}\right) + 1.0410\ln\left(\frac{d_b}{d_s}\right) + 9.7399$$

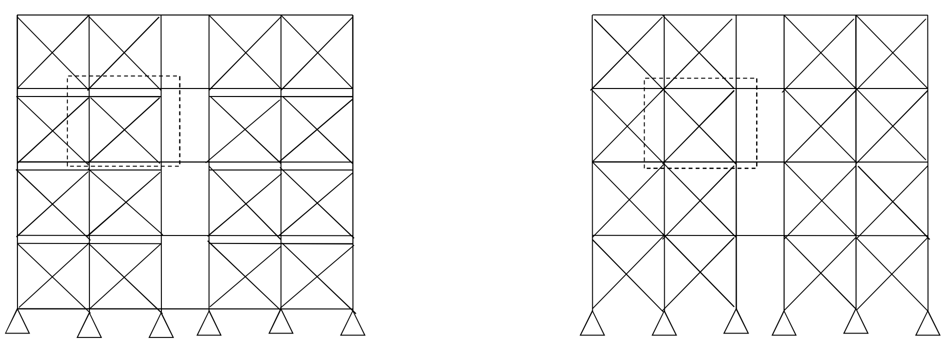
$$r^2 = 97.9\%$$

Experimental Study of Seismic Performance of MSBs

Outline:

- Selection of Test Specimens
- Experimental Program
- Discussion of Test Results
- Development of Analytical Model

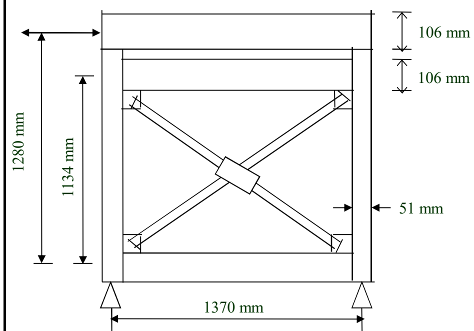
Test Specimens:



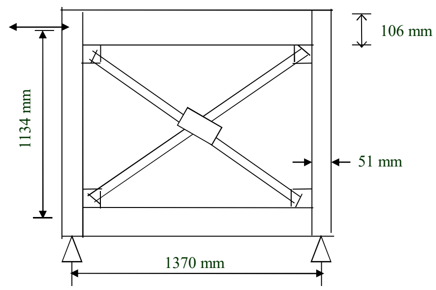
MSB braced frame

Regular braced frame

Test Specimens:

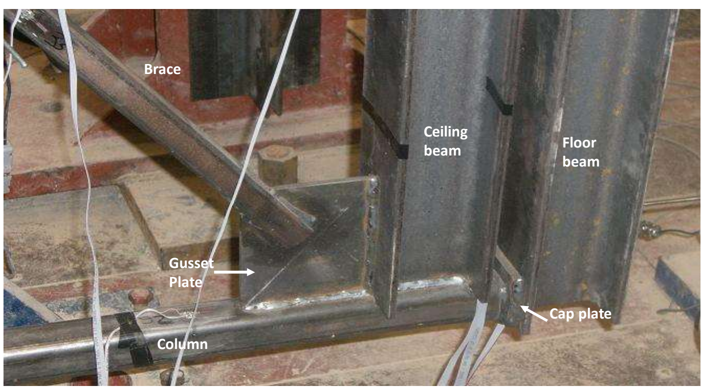


MSB braced specimen

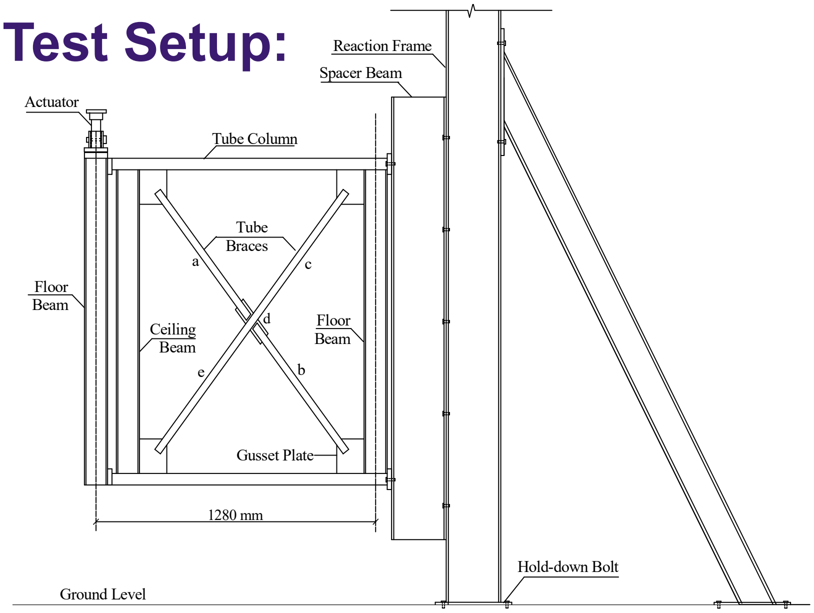


Regular braced specimen

Specimen Details:



Test Setup:



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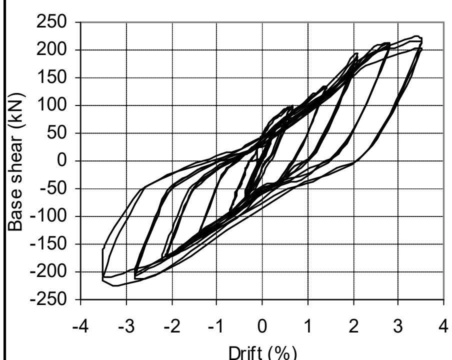
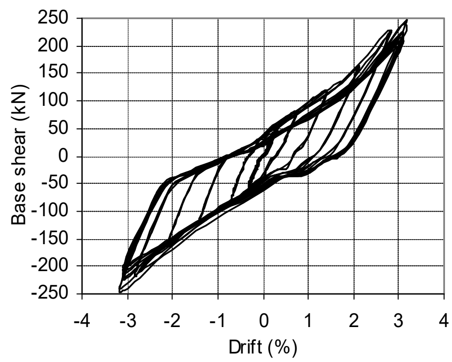
Load-Drift Relationship:



MSB braced specimen



Regular braced specimen

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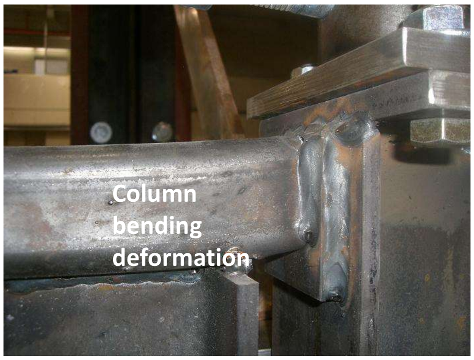
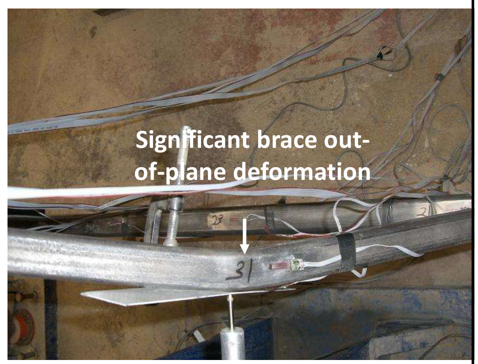
Photos:

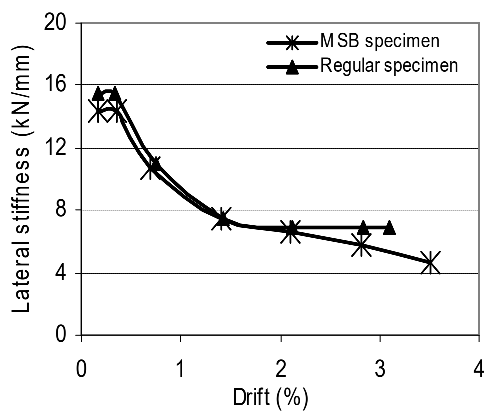




MSB braced specimen

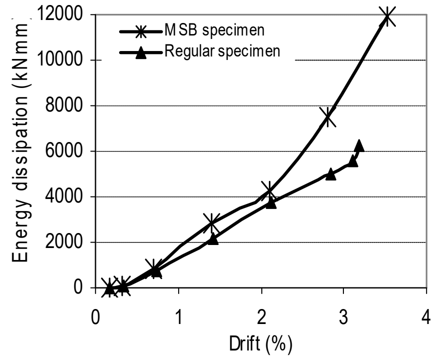
Regular braced specimen

Lateral Stiffness:



Peak drift

Energy Dissipation:



Peak drift

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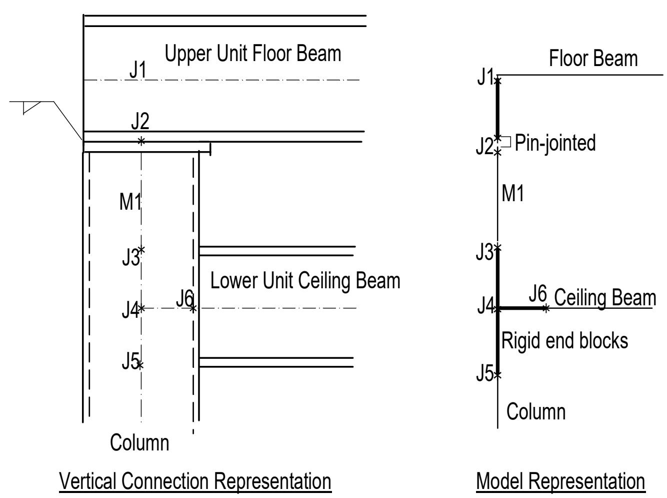
Analytical Model:



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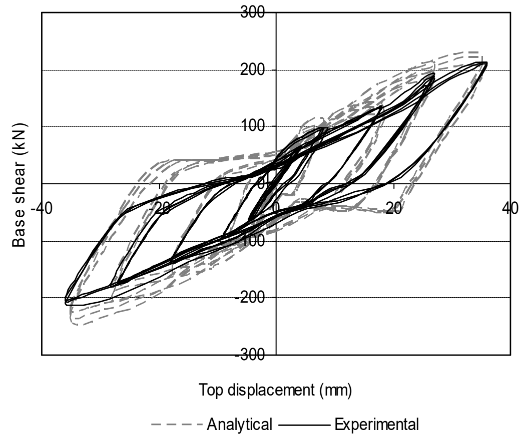
Analytical Predictions:

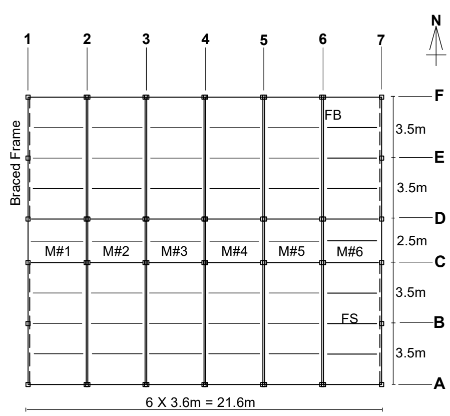


INELASTIC BEHAVIOR & CHARACTERISTICS OF MSB BRACED FRAMES

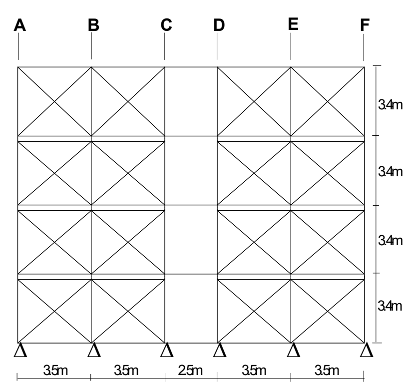
Outline:

- Selection & design of braced frames of a typical MSB.
- Modeling and analysis of MSB braced frames.
- Inelastic behavior of MSB braced frames.
- Inelastic characteristics of MSB braced frames.

MSB Braced Frames:



Floor Plan of MS Building



4-Storey MS Braced frame

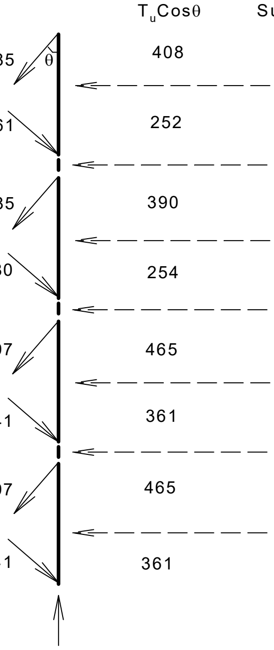
Design:

- Initial design of frame members based on strength and stiffness criteria for specified imposed gravity and earthquake actions.
- Modification of frame member sections according to ductility design requirements and capacity design procedures.

Ductility provision is based on the assumption that braces reach their ultimate strength and all other members and components must resist the resulting induced forces.

Western Engineering CHARACTERISTICS OF MSB BRACED FRAMES

Cumulative Brace Loads:



LOADS IN kN

C_u or T_u	$C_u Sin\theta$ or $T_u Cos\theta$	Direct Summation	SRSS
585	408		
		408	408
361	252		
		660	
585	390		
		1050	1050
380	254		
		1304	
697	465		
		1769	1337
541	361		
		2130	
697	465		
		2595	1640
541	361		

Sample Calculation of SRSS

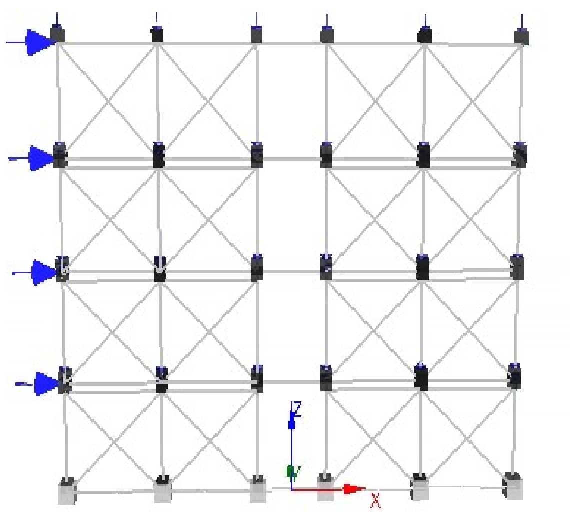
$465 + 254 + (390^2 + 252^2 + 408^2)^{1/2} = 1337\text{kN}$

4-storey MSB Members:

Frame Member	Story / Floor #	Strength Design	Ductility Design (column design by SRSS approach)	Ductility Design (column design by DS approach)
Braces	4	HS 76X76X5	HS 76X76X6	HS 76X76X6
	3	HS 76X76X5	HS 76X76X6	HS 76X76X6
	2	HS 89X89X6	HS 89X89X6	HS 89X89X6
	1	HS 89X89X6	HS 89X89X6	HS 89X89X6
Columns	4	HS 76X76X5	HS 102X102X6	HS 102X102X6
	3	HS 178X178X5	HS 178X178X6	HS 178X178X6
	2	HS 178X178X5	HS 203X203X6	HS 203X203X10
	1	HS 178X178X6	HS 203X203X8	HS 254X254X10
Beams	Roof	W100X19	W100X19	W100X19
	Floor 4	W100X19	W100X19	W100X19
	Floor 3	W100X19	W100X19	W100X19
	Floor 2	W100X19	W100X19	W100X19
	Floor 1	W100X19	W100X19	W100X19
	Ceiling	W100X19	W100X19	W100X19

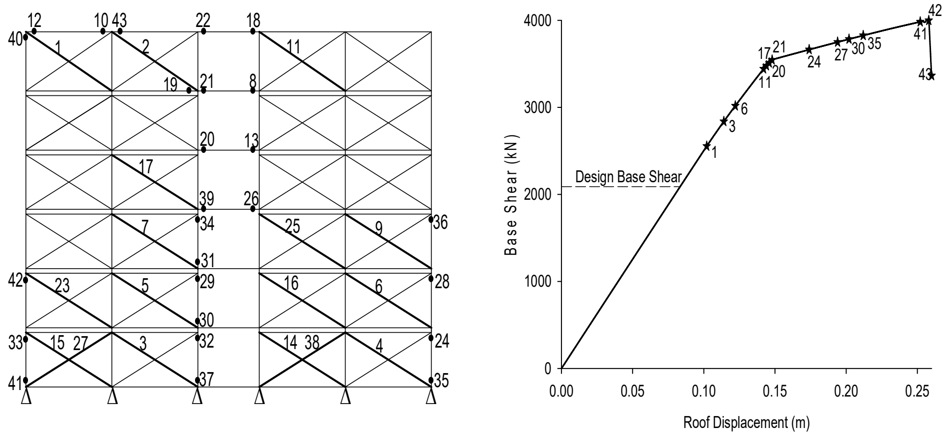
Western Engineering CHARACTERISTICS OF MSB BRACED FRAMES

Model of a Braced Frame:



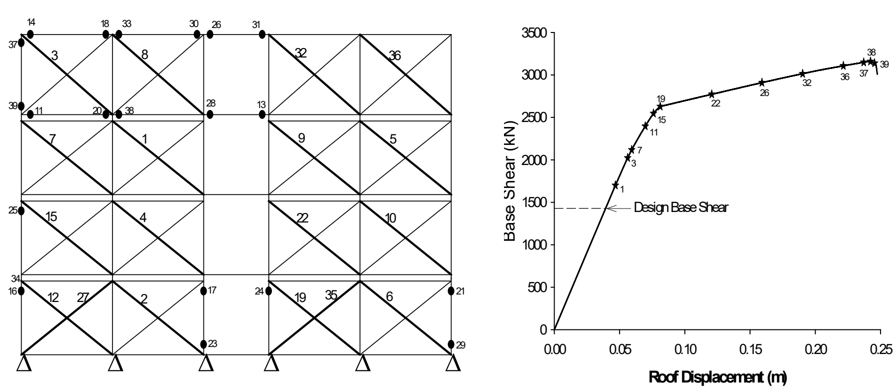
Western Engineering CHARACTERISTICS OF MSB BRACED FRAMES

Yielding/Buckling Sequence (6):



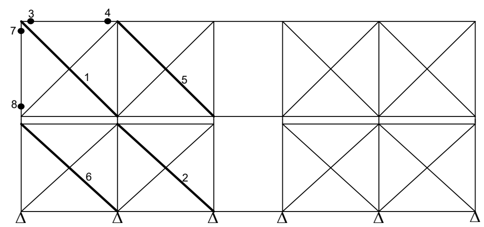
SRSS Approach

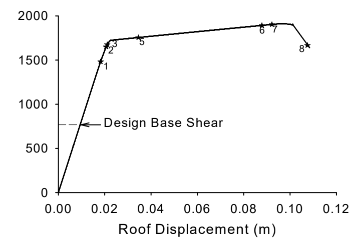
Yielding/Buckling Sequence (4):



SRSS Approach

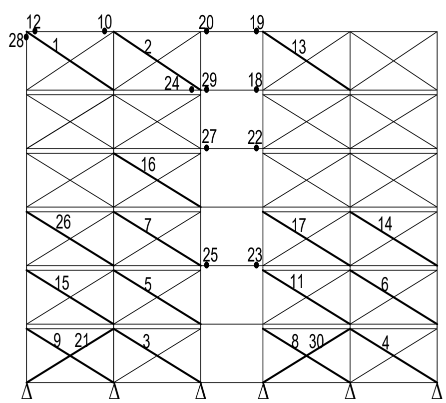
Yielding/Buckling Sequence (2):

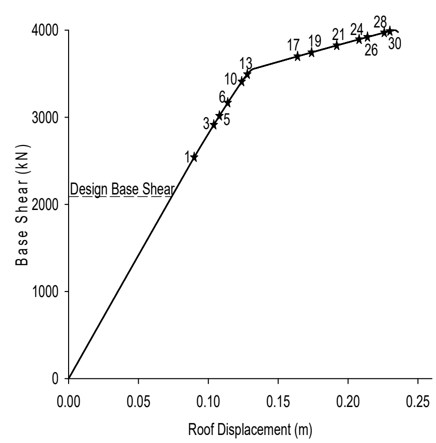




SRSS Approach

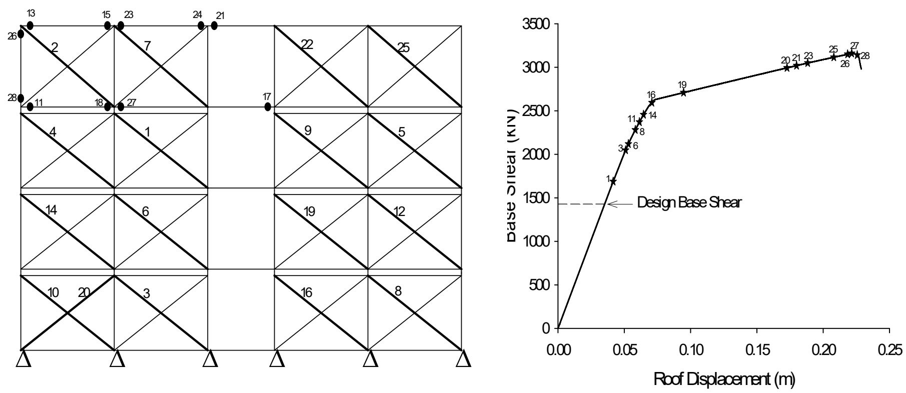
Yielding/Buckling Sequence (6):





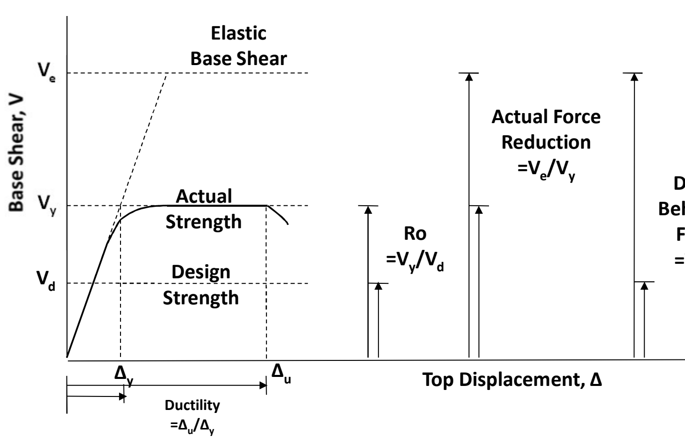
DS Approach

Yielding/Buckling Sequence (4):



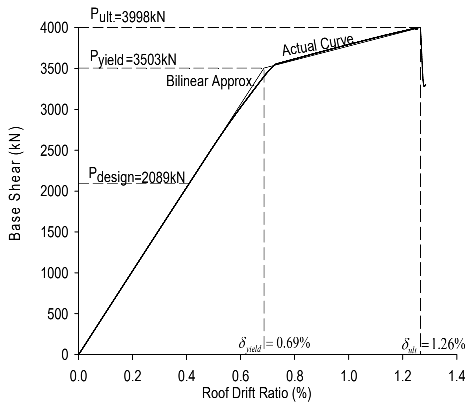
DS Approach

Seismic Overstrength:

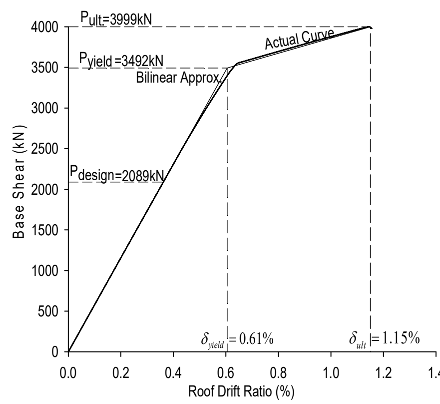


Typical structural response envelope

SRSS VERSUS DS (6-storey):



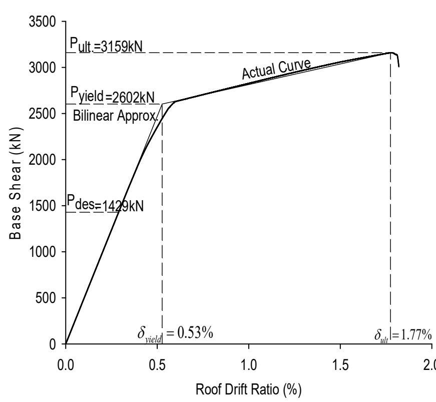
SRSS approach



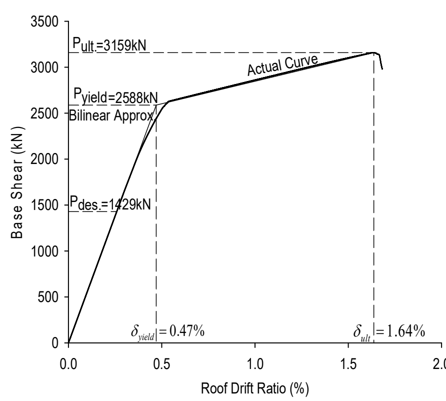
DS approach

Western Engineering CHARACTERISTICS OF MSB BRACED FRAMES

SRSS VERSUS DS (4-Storey):



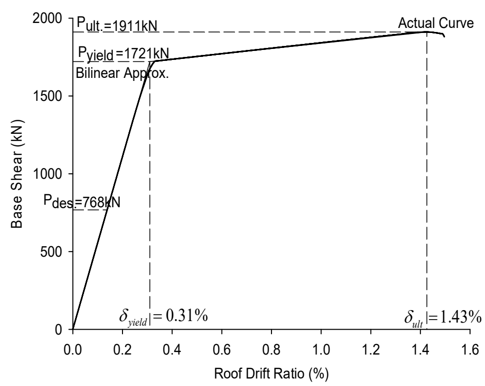
SRSS approach



DS approach

Western Engineering CHARACTERISTICS OF MSB BRACED FRAMES

SRSS VERSUS DS (2-Storey):



Overstrength and Ductility:

Number of Stories	Overstrength Factor, R_0		Structural Ductility, μ	
	SRSS Approach	DS Approach	SRSS Approach	DS Approach
6	1.91	1.91	1.84	1.89
4	2.20	2.20	3.30	3.48
2	2.49		4.62	

Discussion:

- The use of SRSS approach in the determination of brace induced column actions in capacity design of braced frames may not be conservative for MSB braced frames due to the system's unique detailing requirements.
- Beams in unbraced bays may govern capacity design of beams and care must be taken when assigning such beams with sections obtained from the design of beams in brace bays.

SEISMIC DEMANDS & CAPACITIES OF MSB BRACED FRAMES

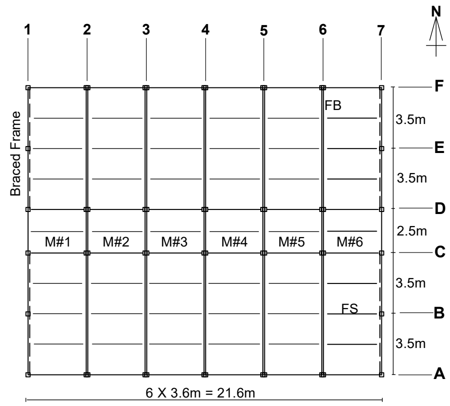
Outline:

- Introduction
- Selection & design of braced frames of a typical MSB
- Selection of ground motion records & analysis characteristics
- Modeling and analysis of MSB braced frames
- Inelastic behaviour of MSB braced frames
- Seismic Inelastic demands and capacities of MSB braced frames

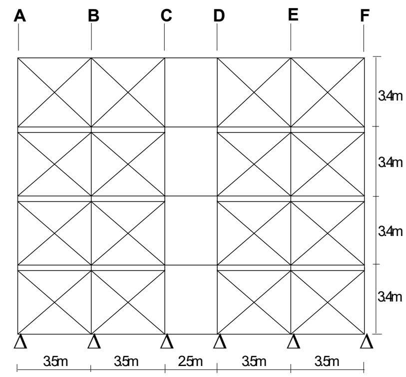
Introduction:

- Dynamic inelastic analysis is the preferred choice for assessing seismic capacity of building structures
- Structural seismic vulnerability is affected by inelastic characteristics such as energy dissipation and strength degradation
- Uncertainties and randomness pose a serious challenge in the analysis procedure
- Inelastic drift provides an assessment of potential seismic damage

MSB Braced Frames:



Floor Plan of MS Dormitory



4-Storey MS Braced frame

Western Engineering Seismic Vulnerability Assessment of MSBs

Analysis Characteristics:

- Seismic inelastic demands are determined using incremental dynamic analysis procedure
- Simple stepping algorithm for scaling ground motion records to target spectral acceleration
- Intensity measure (IM) parameter used is the spectral acceleration at 5% damping, $Sa(T_1,5\%)$
- Engineering demand parameters (EDP) used were maximum peak inter-storey drift ratio, θ_{max}, and peak roof drift ratio, θ_{roof}.

Western Engineering Seismic Vulnerability Assessment of MSBs

Earthquake Records:

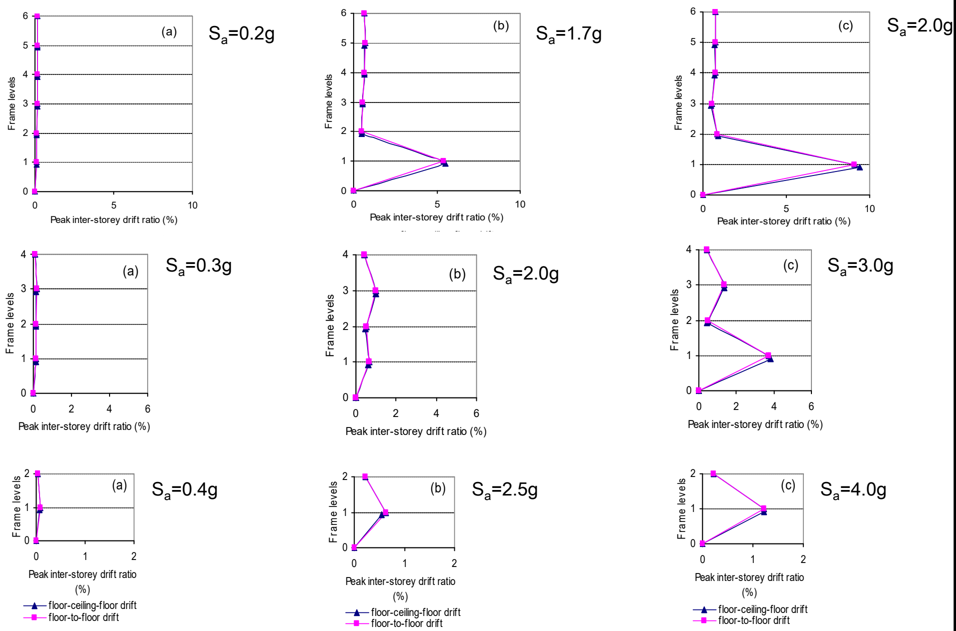
No.	Event	Year	Record station	Φ[1]	M*[2]	R*[3] (km)	PGA (g)
1	Imperial Valley	1979	Plaster City	45	6.5	31.7	0.042
2	Imperial Valley	1979	Plaster City	135	6.5	31.7	0.057
3	Imperial Valley	1979	Westmoreland Fire Sta.	90	6.5	15.1	0.074
4	Imperial Valley	1979	Westmoreland Fire Sta.	180	6.5	15.1	0.11
5	Imperial Valley	1979	El Centro Array #13	140	6.5	21.9	0.117
6	Imperial Valley	1979	El Centro Array #13	230	6.5	21.9	0.139
7	Loma Prieta	1989	Agnews State Hospital	90	6.9	28.2	0.159
8	Loma Prieta	1989	Coyote Lake Dam	285	6.5	22.3	0.179
9	Superstition Hill	1987	Wildlife Liquefaction Array	90	6.7	24.4	0.18
10	Superstition Hill	1987	Wildlife Liquefaction Array	360	6.7	24.4	0.2
11	Loma Prieta	1989	Sunnyvale Colton Ave	270	6.9	28.8	0.207
12	Loma Prieta	1989	Sunnyvale Colton Ave	360	6.9	28.8	0.209
13	Loma Prieta	1989	Anderson Dam	270	6.9	21.4	0.244
14	Imperial Valley	1979	Chihuahua	282	6.5	28.7	0.254
15	Loma Prieta	1989	Hollister Diff. Array	165	6.9	25.8	0.269
16	Loma Prieta	1989	Hollister Diff. Array	255	6.9	25.8	0.279
17	Imperial Valley	1979	Cucapah	85	6.9	23.6	0.309
18	Loma Prieta	1989	WAHO	0	6.9	16.9	0.37
19	Loma Prieta	1989	Holister South &Pine	0	6.9	28.8	0.371
20	Loma Prieta	1989	WAHO	90	6.9	16.9	0.638

[1] Component, [2] Moment Magnitudes, [3] Closest Distances to Fault Rupture

Source: PEER Strong Motion Database, http://peer.berkeley.edu/svbin

Dynamic characteristics of selected MSB braced frames:

Dynamic characteristics		MSB Braced frame		
		2-storey	4-storey	6-storey
Period (sec)	NBCC design	0.21	0.35	0.48
	1st mode	0.20	0.42	0.61
	2nd mode	0.08	0.16	0.21
Mass participation factor (%)	1st mode	94	81	77
	2nd mode	5	15	17



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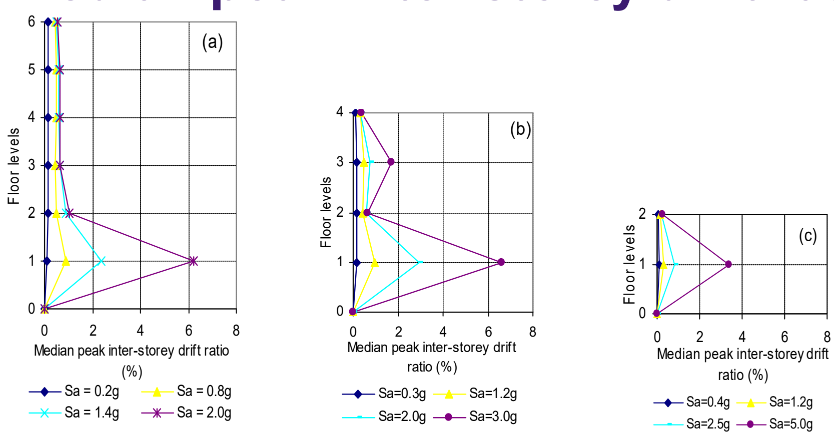
Median peak inter-storey drift ratios:



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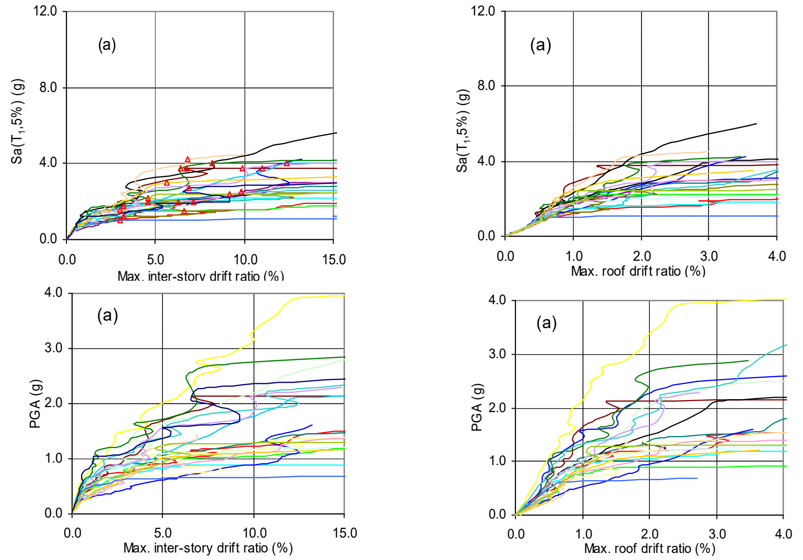
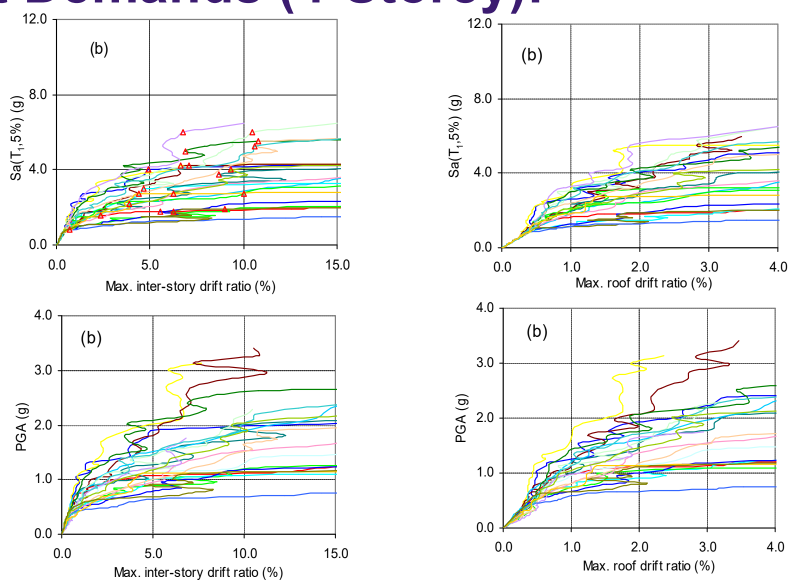
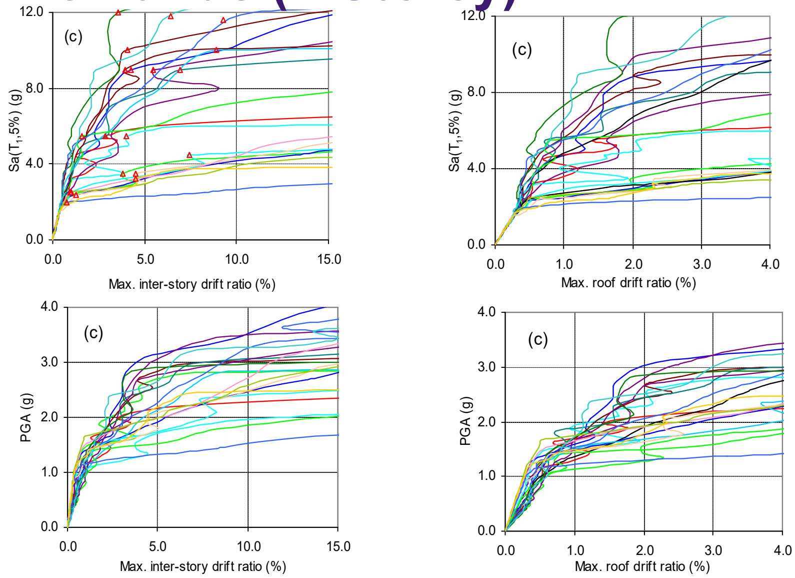
Drift Demands (6-Storey):



Drift Demands (4-Storey):



Drift Demands (2-Storey):



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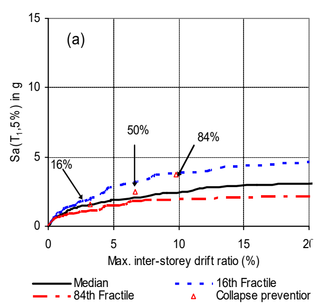
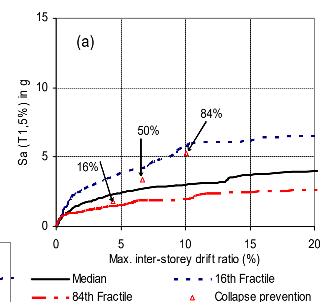
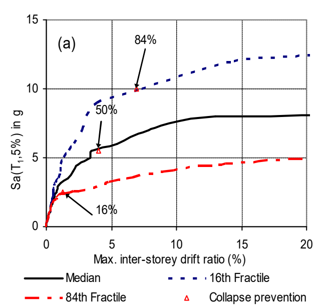
Drift fractile capacities



6-storey



4-storey



2-storey

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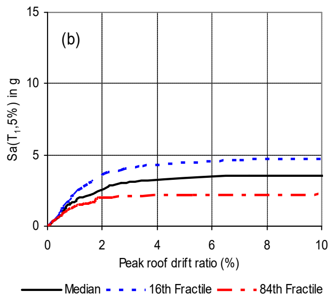
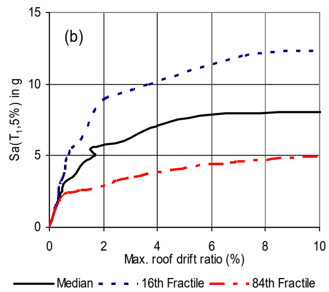
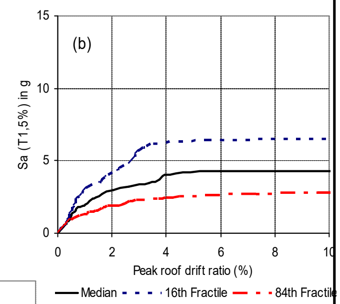
Drift fractile capacities



6-storey



2-storey



4-storey

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Drift fractile capacities

Fractile capacities in terms of intensity measure, $S_a(T_1,5\%)$

MSB frame	Design level intensity, $Sa(T_1)$ in g	Fractile S_a capacity (g) based on collapse prevention level			Standard Dev. of median capacity	S_a capacity (g) based on NBCC drift limit
		16%	50%	84%		
2-storey	0.96	2.50	5.50	10.00	0.61	4.00
4-storey	0.85	1.80	3.30	5.25	0.53	1.75
6-storey	0.75	1.60	2.45	3.75	0.44	1.25

Fractile capacities in terms of maximum drift, θ_{max}

MSB frame	Fractile θ_{max} capacities (%)			Standard Dev. of capacities
	16%	50%	84%	
2-storey	1.2	4.0	6.9	0.76
4-storey	4.4	6.7	10.0	0.63
6-storey	3.2	6.7	9.8	0.43

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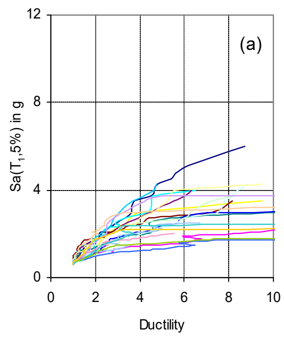
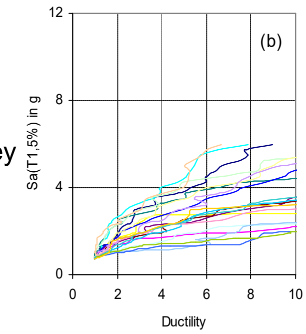
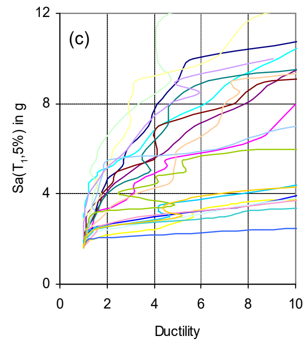
Ductility demands



6-storey

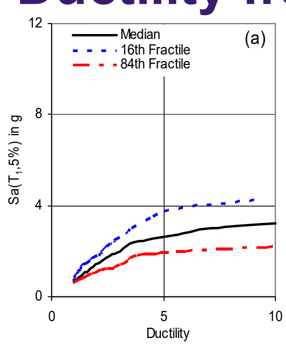
4-storey





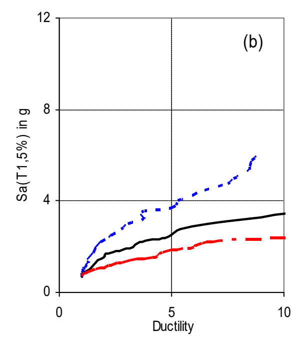
2-storey

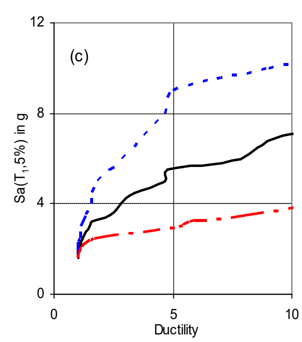
Ductility fractile capacities



6-storey

4-storey





2-storey

Ductility capacities

MSB frame	Ductility capacity based on NBCC drift limit median capacity in Sa	Ductility capacity based on collapse prevention level median capacity in Sa
2-storey	2.80	4.80
4-storey	2.40	4.50
6-storey	1.80	3.90

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Journal Papers

Experimental evaluation of the seismic performance of modular steel-braced frames
Engineering Structures 31 (7), 1435-1446, 2009

Seismic overstrength in braced frames of Modular Steel Buildings
Journal of Earthquake Engineering 13 (1), 1-21, 2009

Effect of directly welded stringer-to-beam connections on the analysis and design of modular steel building floors
Advances in Structural Engineering 12 (3), 373-383, 2009

Seismic Vulnerability Assessment of Modular Steel Buildings
Journal of Earthquake Engineering 13 (8), 1065-1088, 2009

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