Reducing Seismic Residual Deformations in Civil Structures using Superelastic Shape Memory Alloys

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Western Engineering

Western
UNIVERSITY · CANADA

London

- **Population**: about 400,000
- Approximately 2 hours driving distance from Toronto, ON and Detroit, MI

Western University

- **Founded**: 1878
- **Faculties**: 12
- **Land Area:** 1,200 acres (82 Buildings)
- **Undergrads:** 25,000 Student
- **Grads:** 5,000 Student
- **Faculty:** 1,500 Professor

Western Engineering

- **Founded**: 1954
- **Departments**:
  - Chemical and Biochemical Engineering.
  - Civil and Environmental Engineering.
  - Electrical and Computer Engineering
  - Mechanical and Materials Engineering.
- **Undergrads:** 1,600 Student
- **Grads:** 750 Student
- **Faculty:** 100 Professor
- Students can graduate with Dual Degrees (Engineering and Business, Law, Music, etc.)

Western Engineering

Civil and Environmental Engineering

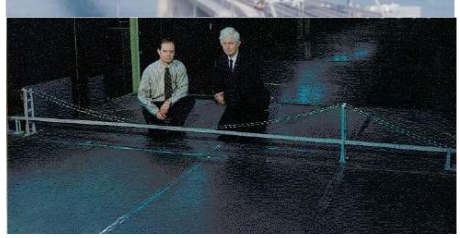
- Environmental & Water Resources Engineering
- Geotechnical & Geoenvironmental Engineering
- **Natural Disaster Mitigation**
- **Structures and Infrastructure**
- **Wind Engineering** & Environmental Fluid Mechanics

WIND ENGINEERING AT WESTERN

1960-present : 5 decades of wind engineering research & consulting

1000+ world-wide projects

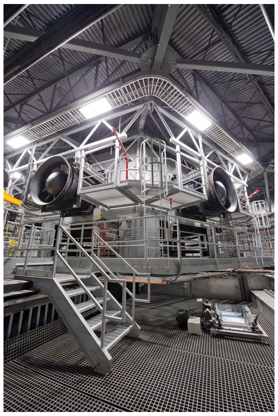
Shanghai Grand Center, China



The Tsing Ma Bridge, Hong Kong

WindEEE Dome

- $35M+ investment
- World's first 3D wind chamber
- Large scale 25 m in diameter
- Capable of testing urban infrastructure, power facilities, solar panels, wind farms, etc.
- 60 fans installed to manipulate inflow & boundary layer conditions to reproduce large-scale wind systems.



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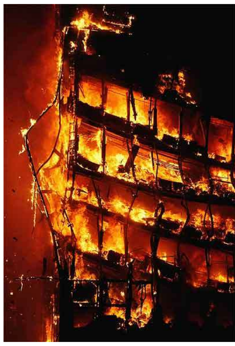
Insurance Research Lab for Better Homes

Dr. Maged A. Youssef, P.Eng.

Professor, E-mail: youssef@uwo.ca



Structural Fire Engineering
Concrete Structures

Shape Memory Alloy Bars
Earthquake Engineering

Prefabricated Structures
(Precast or Modular)

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Reducing Seismic Residual Deformations in Civil Structures using Superelastic Shape Memory Alloys

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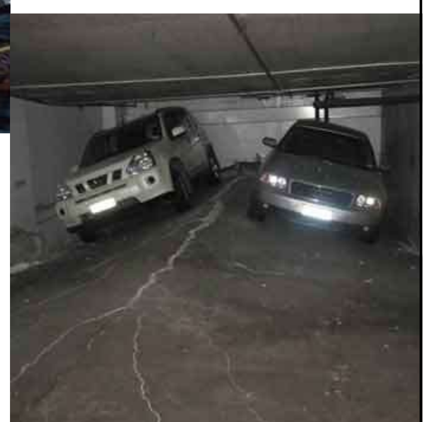
Design Philosophy

- Buildings are seismically designed for safety.
- Economy is achieved by allowing steel to yield dissipating the seismic energy.
- Permanent residual deformations are expected following a strong seismic activity.
- Design for wind loads is currently being revised to follow the seismic approach.



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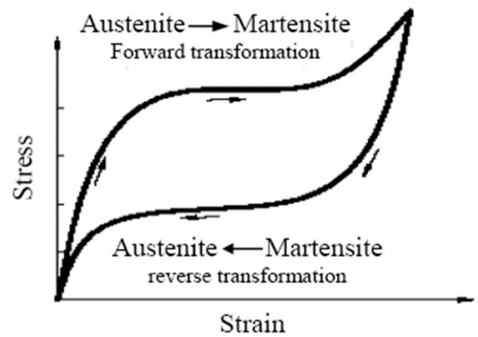
SHAPE MEMORY ALLOY (SMA)

SMAs are unique materials that can recover from large strains upon Stress Removal (Superelasticity) or Heating (Shape Memory Effect)



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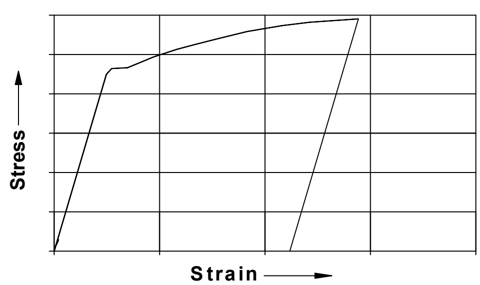


Conventional Steel

Advantages:

Higher initial Modulus

Higher Energy Dissipation

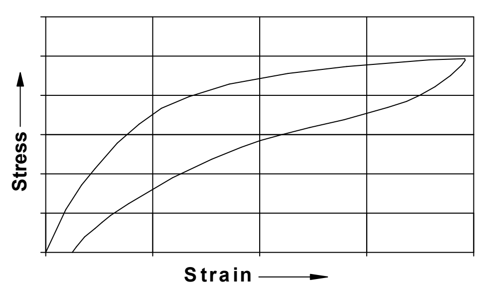
Lower cost

Machinable

Superelastic NiTi SMA

Advantage:

Close to zero residual strains



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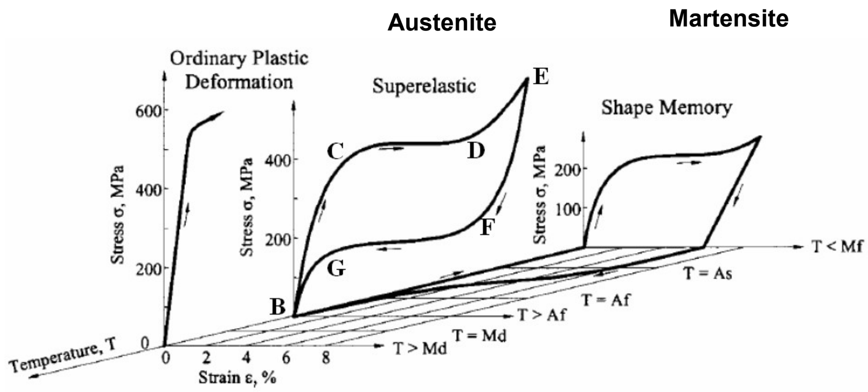
3D stress-strain-temperature relationship of NiTi SMA



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RESEARCH OBJECTIVES

Use SE SMA at specific locations to:

- restore original shape after earthquake.
- reduce seismic permanent (residual) deformation.
- have a sustainable structure that requires minimum amount of repairing.

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NiTi SMA Research at Western

- Design Issues.
- RC Beam-Column Joints.
- RC Frames.
- RC Walls.
- Steel Frames.
- Modular Steel Structures.

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Design Issues

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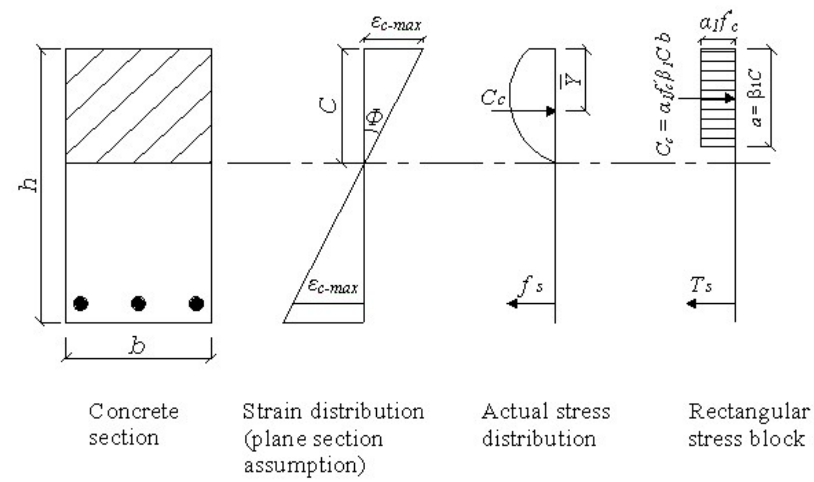
STRESS BLOCK PARAMETERS



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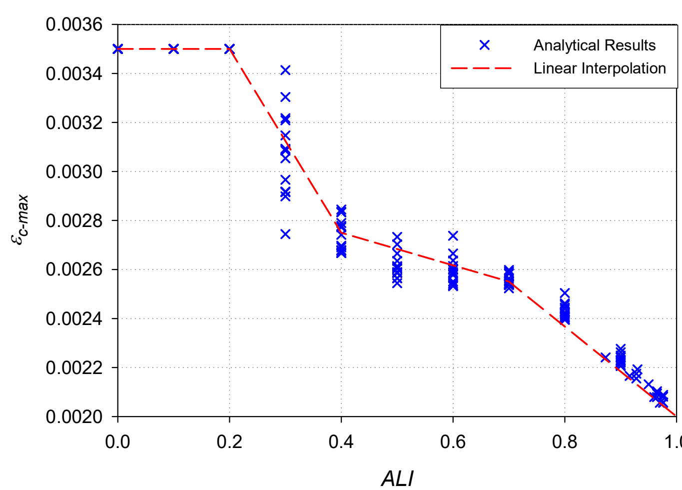
ε_c AT FAILURE



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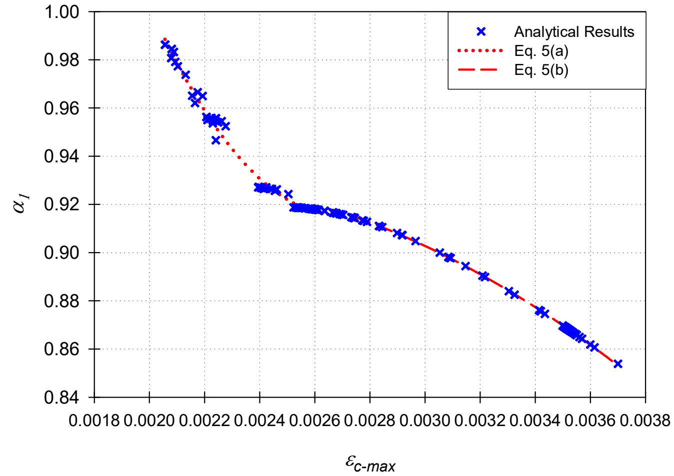
STRESS BLOCK PARAMETER



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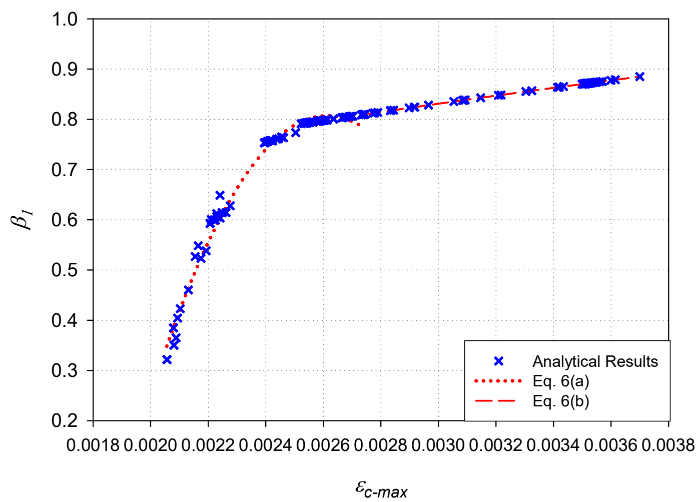
STRESS BLOCK PARAMETER



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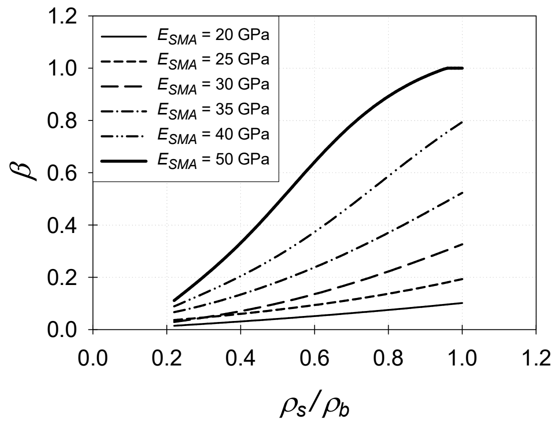
DEFLECTION OF SMA RC BEAMS

$$I_e = \left(\frac{M_{cr}}{M_a}\right)^3 \beta\, I_g + \left[1 - \left(\frac{M_{cr}}{M_a}\right)^3\right] I_{cr} \qquad \le I_g$$



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RC Beam-Column Joints

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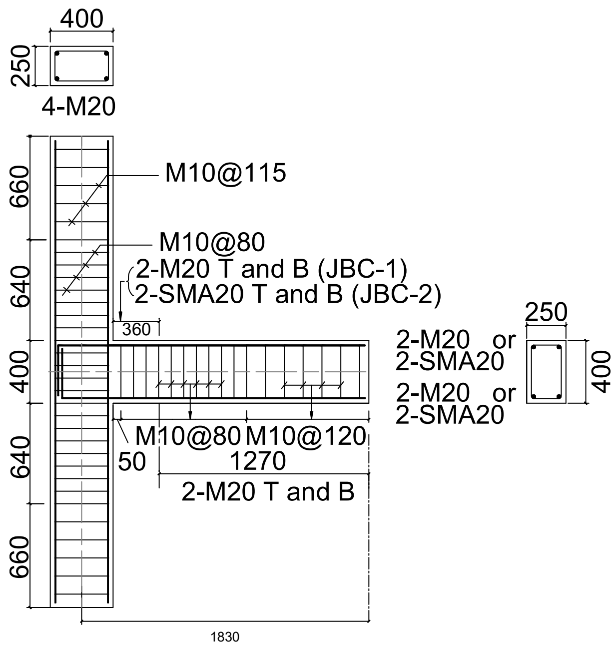
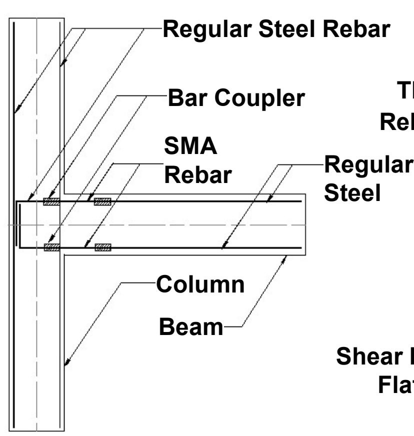
Two large scale beam-column joints:

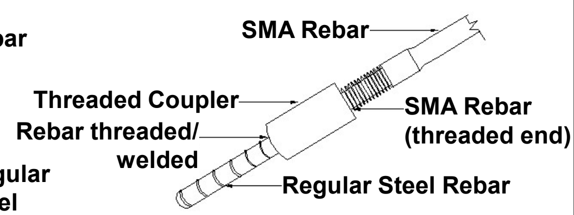
– Specimen-1 steel reinforced,

– Specimen-2 SE SMA reinforced

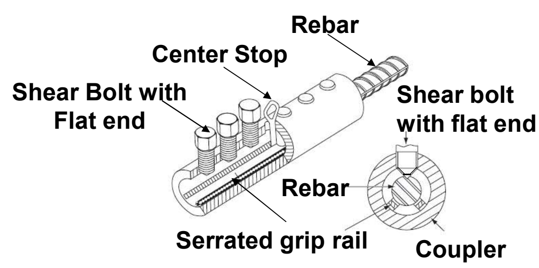




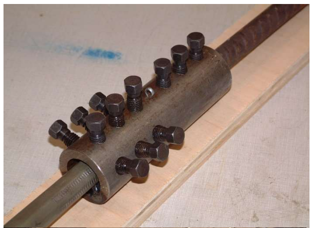
Specimen 2

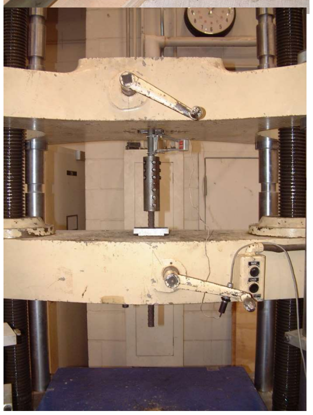


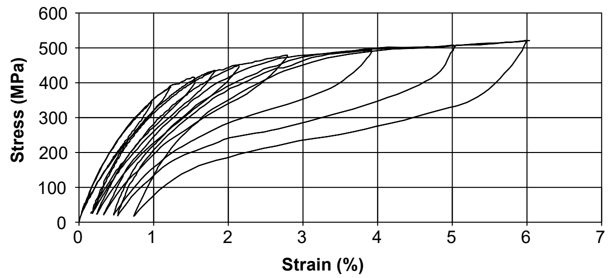
Threaded Coupler



Bar Lock Coupler



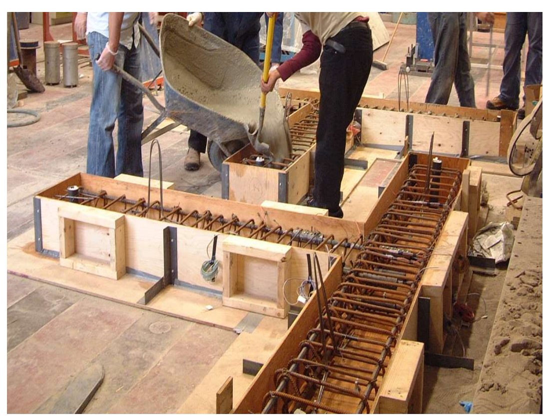




Test Results Indicate

- –Yield strength 401 MPa
- –Young’s Modulus 62,500 MPa
- –Ultimate Strength > 850 MPa
- –Superelastic strain range 6%
- –Residual strain 0.7%

Test Samples



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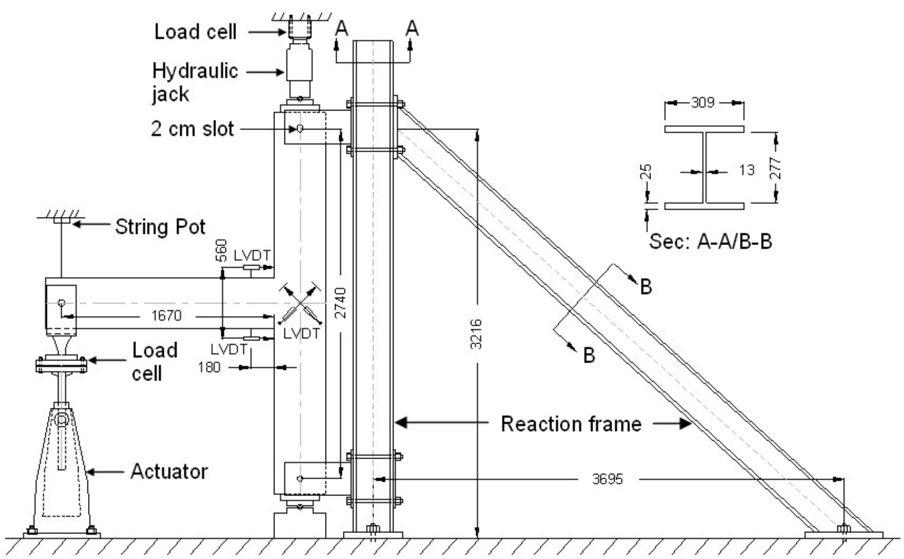
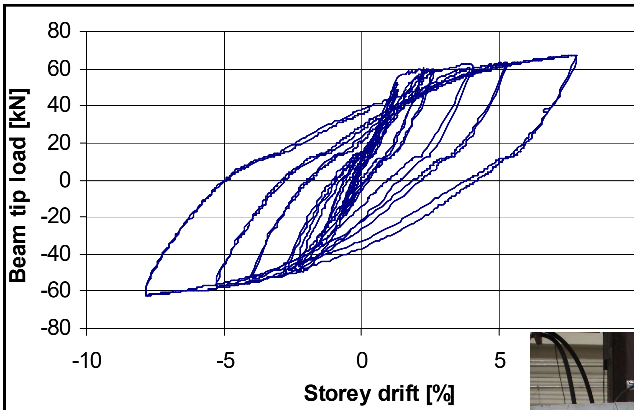
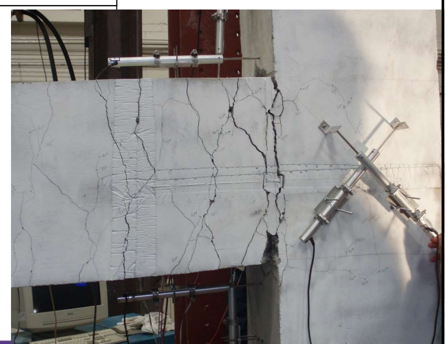
Test Setup

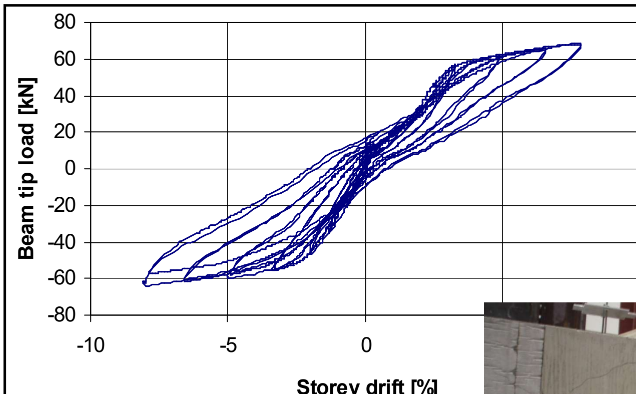

Load cell
Hydraulic jack
2 cm slot
String Pot
560
LVDT
1670
LVDT
2740
Load cell
LVDT
180
Actuator
A
A
309
25
13
277
Sec: A-A/B-B
B
B
3216
Reaction frame
3695

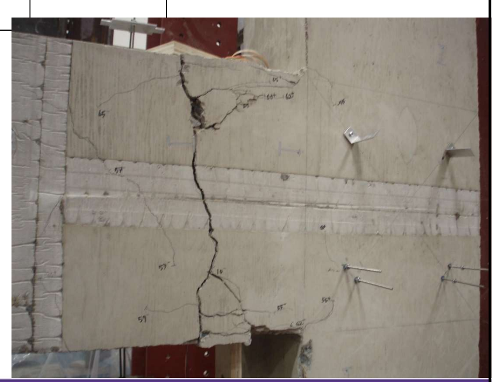




Steel RC Joint

Western Engineering





SMA RC Joint

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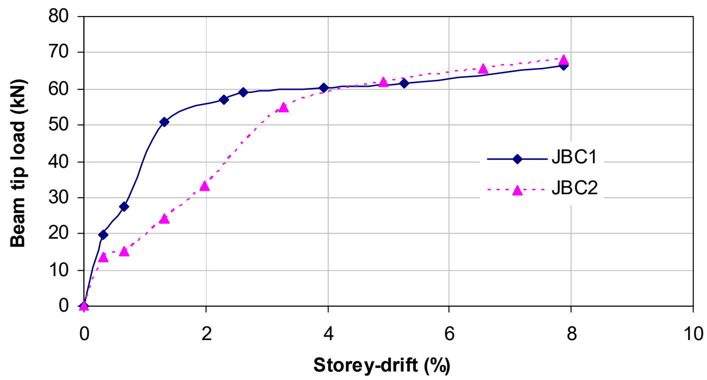
Load-storey drift envelope



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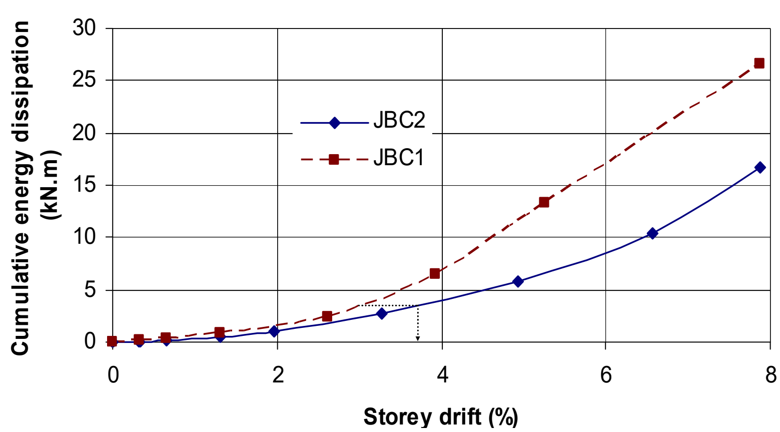
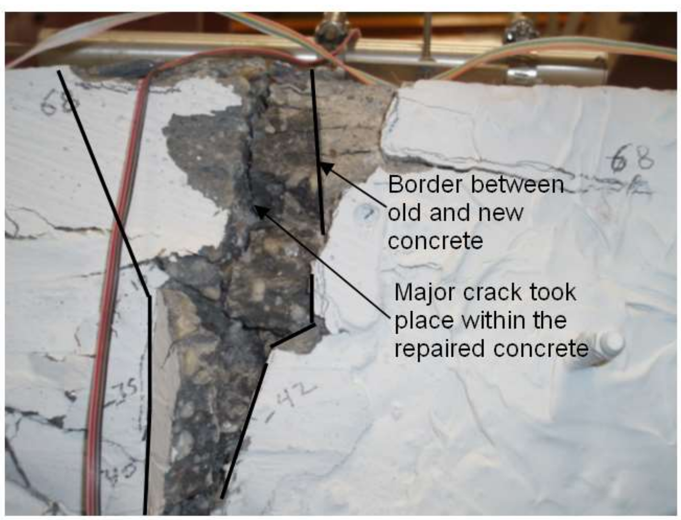
Cumulative Energy Dissipation



Western Engineering

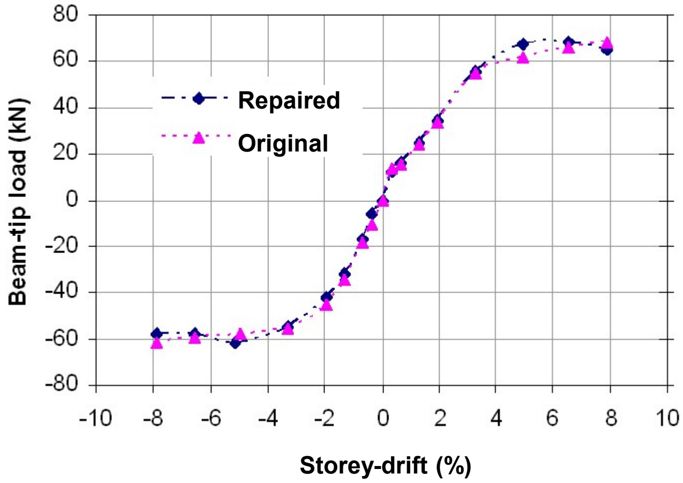
Repairing of Damaged Specimen



Bonding between old and new concrete

Western Engineering

Load-storey drift envelope



Western Engineering

Cumulative energy dissipation

Western Engineering

Comparison between Steel and SMA RC BCJs

- A steel RC BCJ was tested with similar reinforcement arrangement and dimensions
- The specimen subjected to similar drifts experienced irrecoverable damage
- The steel RC specimen was not repairable
- SE SMA RC specimen was serviceable even after similar drift
- Required minimum amount of repairing

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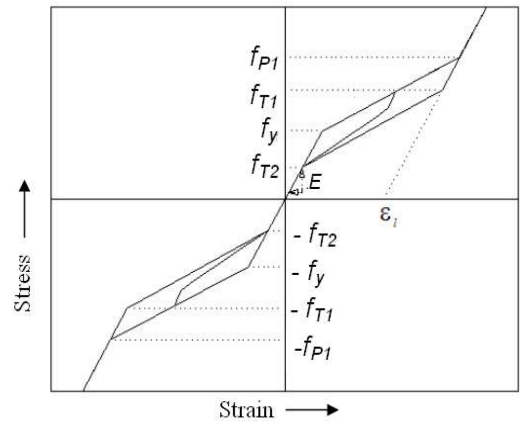
RC Frames

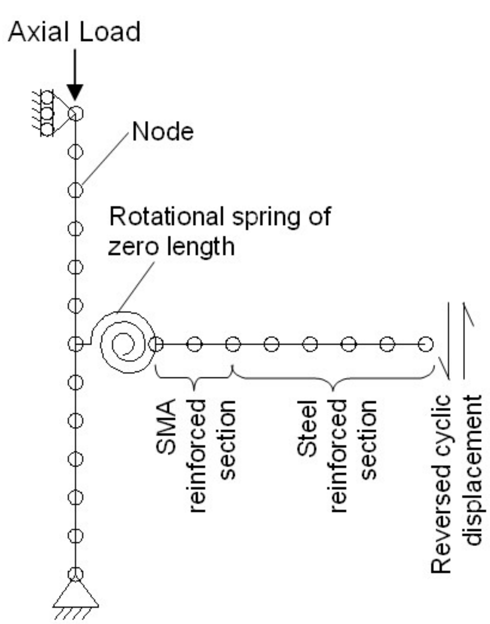
Western Engineering

Finite Element

- Fibre modeling approach
- SMA model (Auricchio and Sacco 1997)



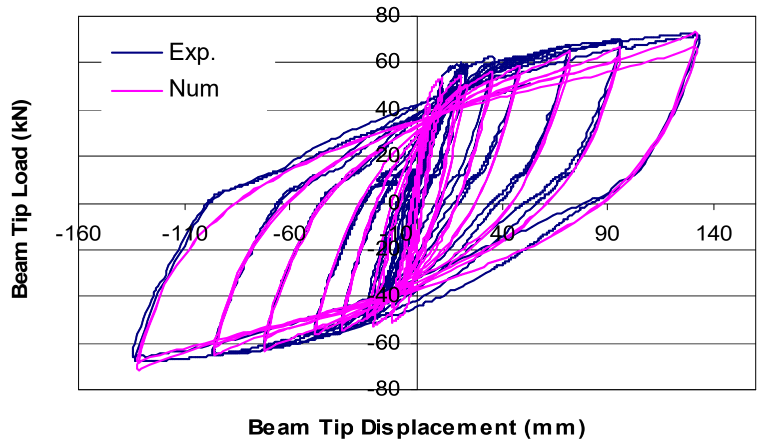
Western Engineering



Finite Element

Western Engineering

Validation



Specimen-1: Steel-RC Joint (JBC-1)

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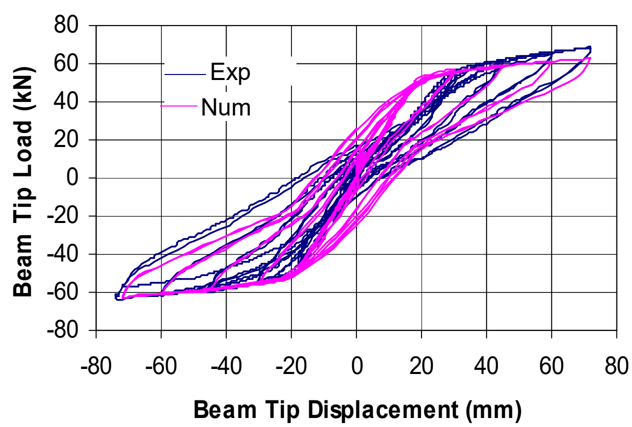

Specimen-2: SE SMA-RC Joint (JBC-2)

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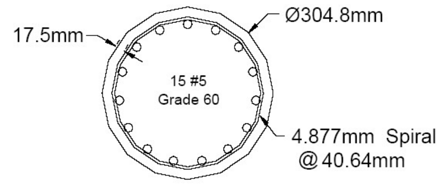
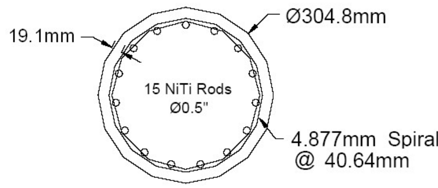
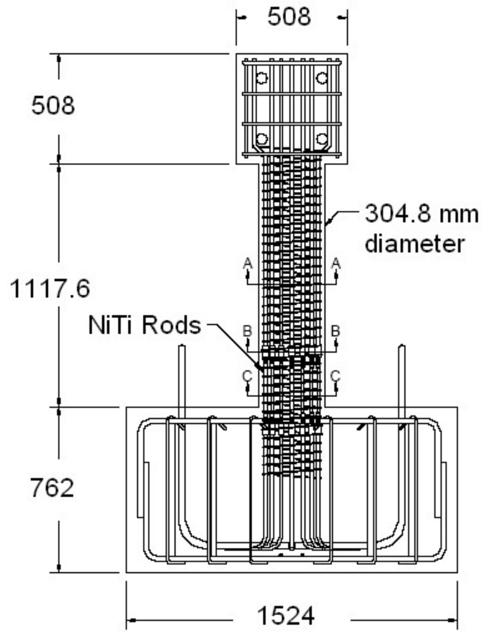
SMA-RC Column



Sec: A-A



Sec: C-C



University of Nevada, Reno

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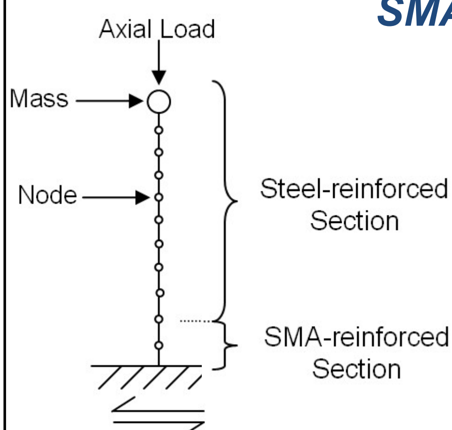
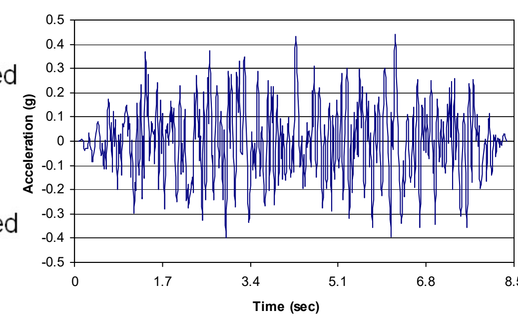
SMA-RC Column



FE Model of SMA-RC Bridge Pier



Acceleration-time history

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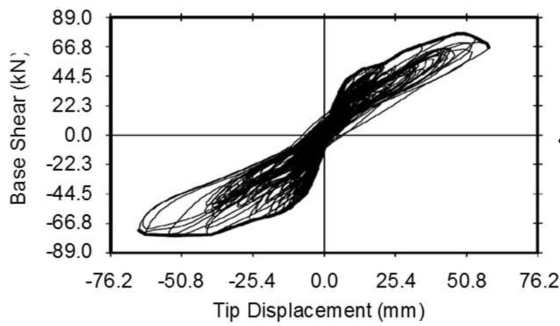
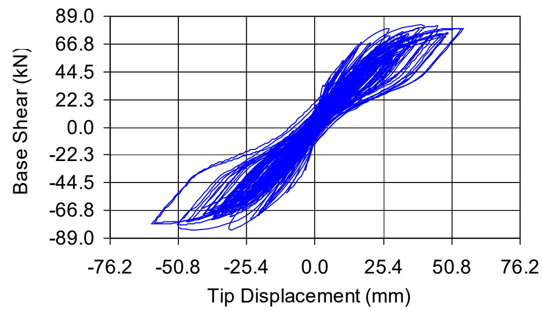
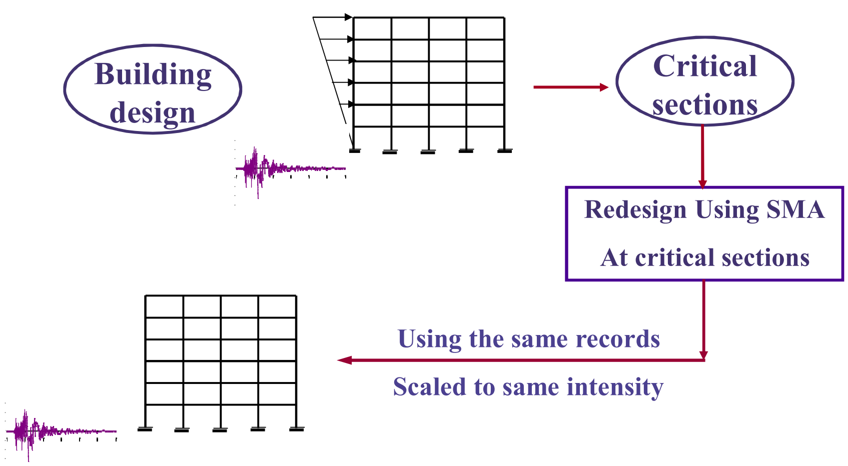


Experimental Results

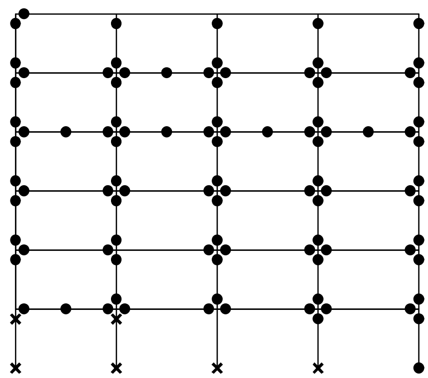
Numerical Results



Procedure for Frame Analysis

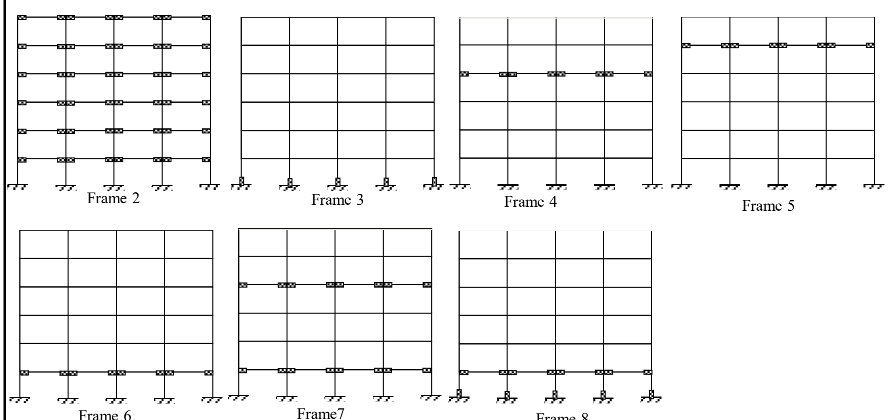


DAMAGE SCHEME AT COLLAPSE



Whittier (Steel RC Building)

SMA Frames



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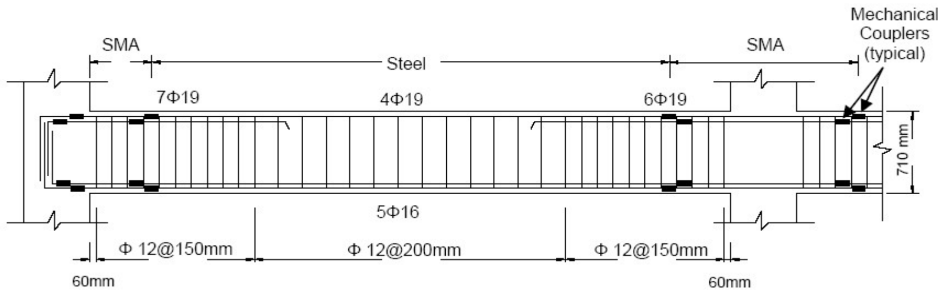
Reinforcement details of a typical SMA RC beam



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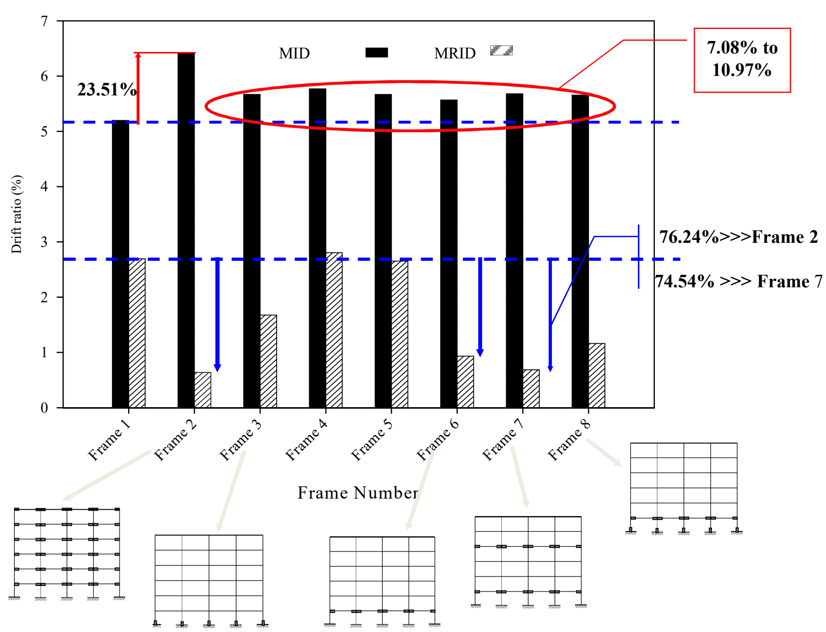

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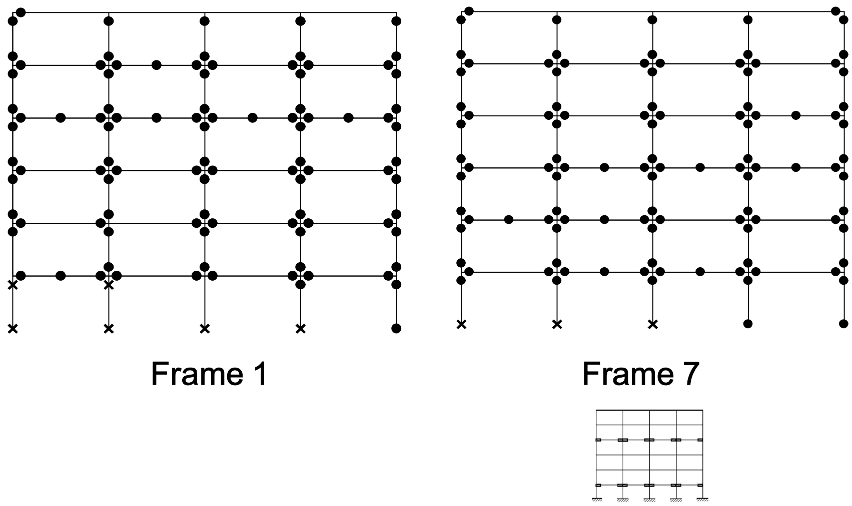
Damage Schemes (Whittier record)



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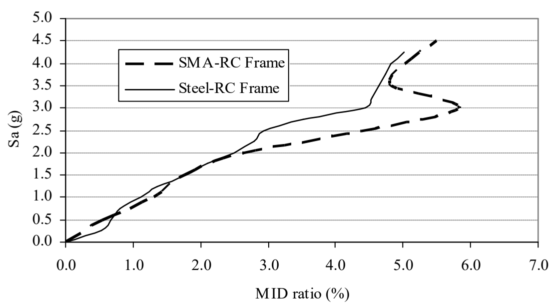

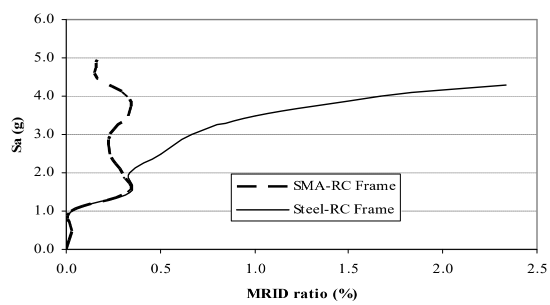

Drift values during Whittier record

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Spectral Acceleration at Collapse

Earthquake record	Steel Frame	SMA Frame
	Sa at collapse (g)	Sa at collapse (g)
Northridge	2.60	3.10
Imperial Valley	1.15	1.28
Loma Prieta	4.28	5.75
Whittier	5.00	5.25
San Fernando	8.15	8.90

The percentage of Sa increase is varying from 5.0% to 34.3%

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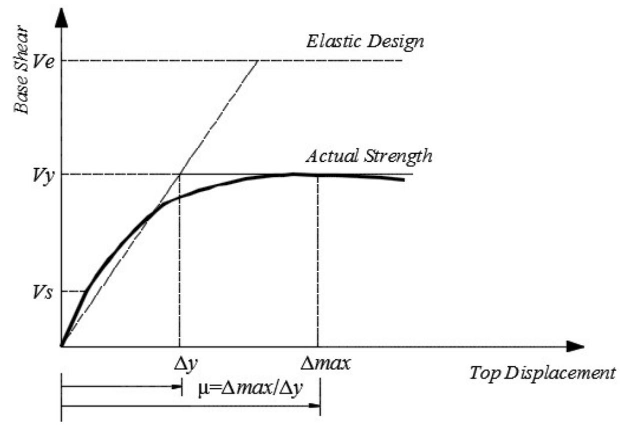
RC Walls

Western Engineering



$$\mu = \frac{\Delta_{max}}{\Delta_y} \qquad R = \Omega R_\mu$$

$$\Omega = \frac{V_y}{V_s} \qquad R_\mu = \begin{cases} \mu & T > 0.5\ sec \\ \sqrt{2\mu - 1} & T < 0.5 sec \end{cases}$$

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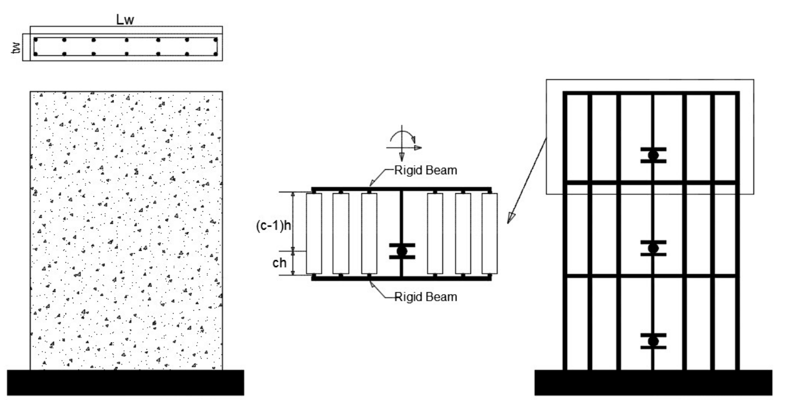
ANALYTICAL MODELING



RC WALL

Shear-Flexural Multi-Vertical Line Element Model (SFI-MVLEM)

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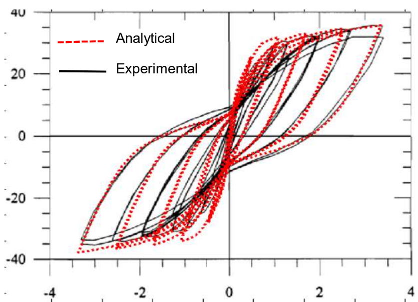
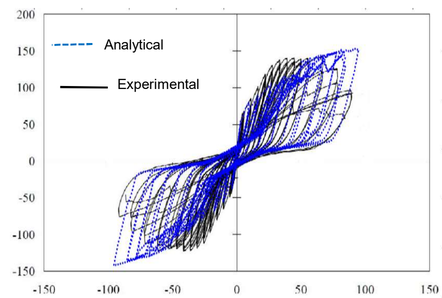
VALIDATION



Wallace (2004)



Abdulridha (2012)

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Examined Walls

Aspect Ratio	Wall Thickness	Axial Load %	Transverse RFT %	Web RFT %	Boundary RFT %
6.0	150, 200, 230	2, 7.5, 10	0.25, 0.5, 1	0.5, 0.6, 0.75, 1	0.5, 1.0, 1.5
3.0	150, 200, 230	2, 7.5, 10	0.25, 0.5, 1	0.5, 0.6, 0.75, 1	0.5, 1.0, 1.5
1.5	150, 200, 230	2, 7.5, 10	0.25, 0.5, 1	0.5, 0.6, 0.75, 1	0.5, 1.0, 1.5

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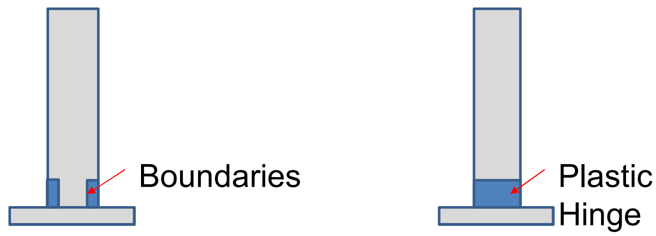
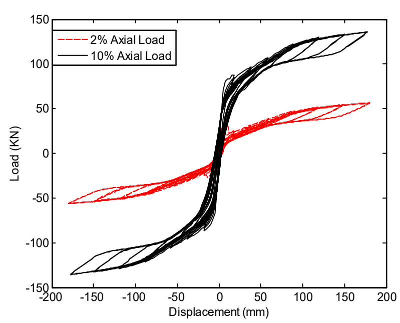
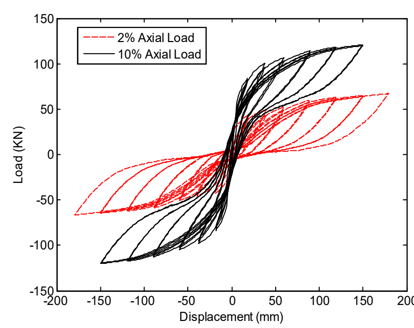
SMA LOCATIONS



Typical Cyclic behaviour

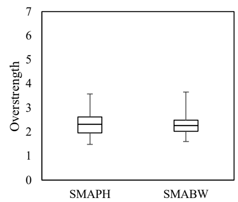


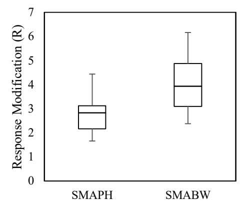
SMA at Plastic Hinge



SMA at Boundaries

Response Modification and Overstrength Factors





Seismic Design Parameters	SMAPH	SMABW	COV_{SMAPH}	COV_{SMABW}
Response Modification Factor R	3.0	4.0	0.22	0.26
Overstrength Factor Ω	2.25	2.25	0.21	0.18

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Steel Frames

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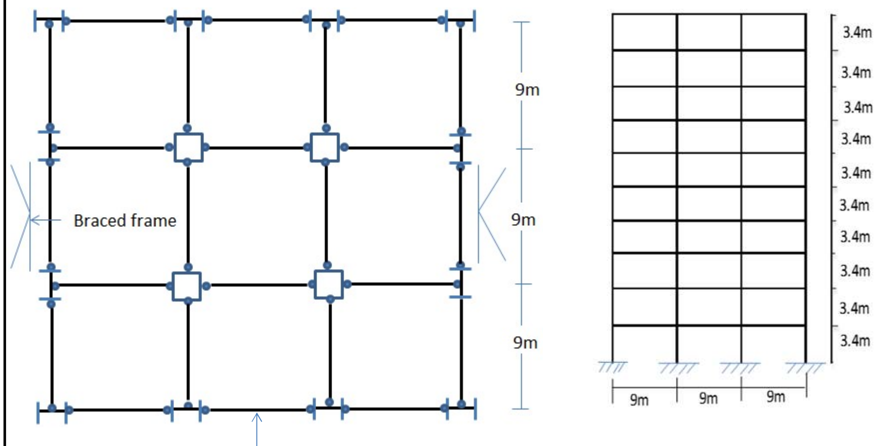
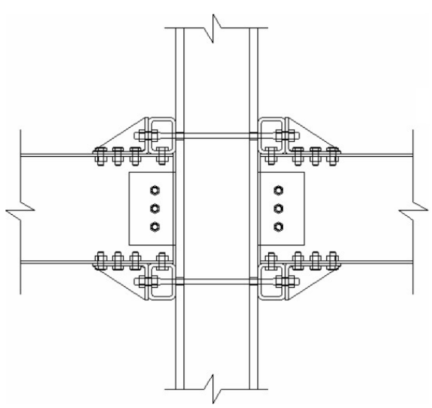
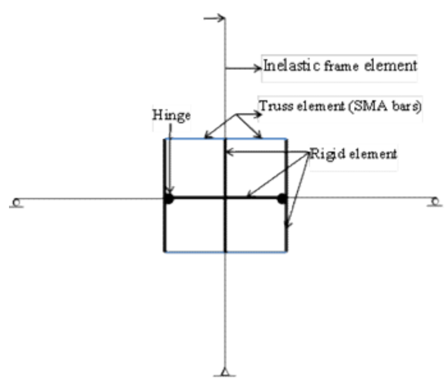
Case study



Finite element model of super-elastic SMA connection

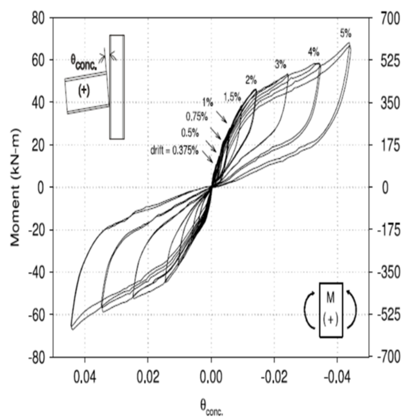


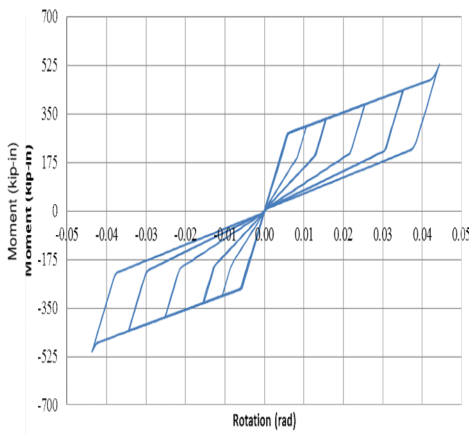
SMA connection [Speicher et. al.,2011]



FE model

Experimental Versus Analytical





Experimental **Analytical**

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MID and MRID of SMRF

Ground motion	Sa(T1,5%) at collapse	Frame 1	
		MID (%)	MRID (%)
Imperial	(0.341g)	2.97 (2nd storey)	0.67 (2nd floor)
Northridge	(0.489g)	3.17 (3rd storey)	0.41 (1st floor)
Loma	(0.619g)	5.02 (7th storey)	0.56 (8th storey)
San Fernando	(0.476g)	3.48 (6th storey)	1.21 (4th storey)
Tabas	(0.445g)	2.75 (3rd storey)	0.29 (2nd storey)

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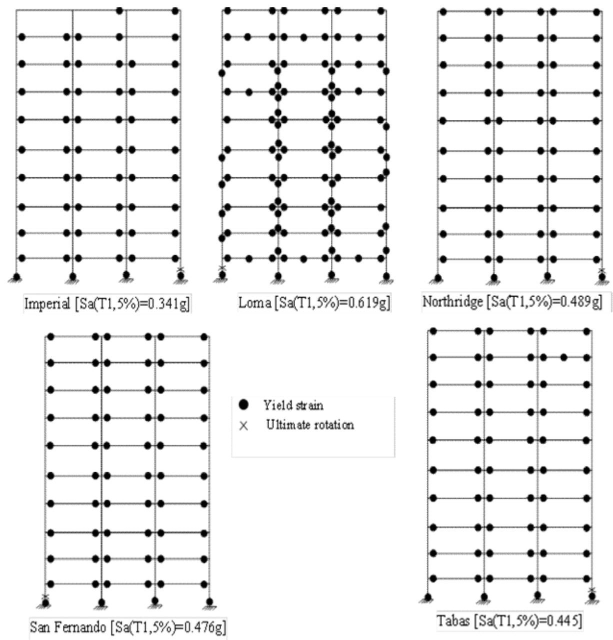
Damage distribution of SMRF (Frame 1)



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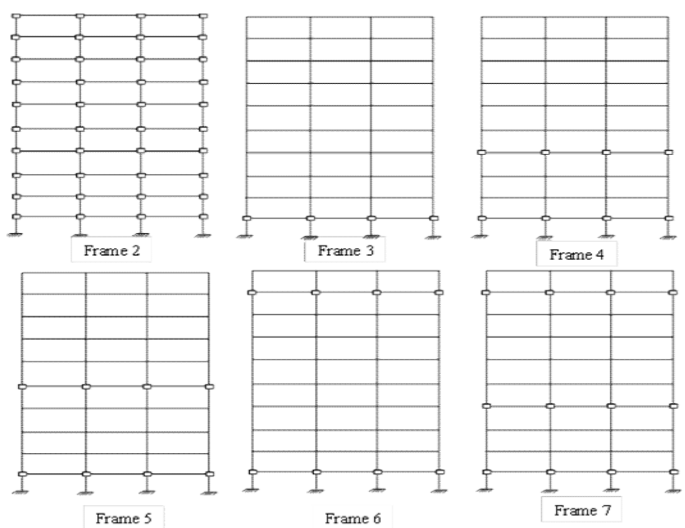
Location of SMA connections



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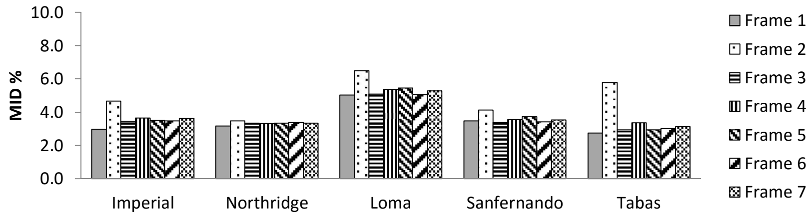

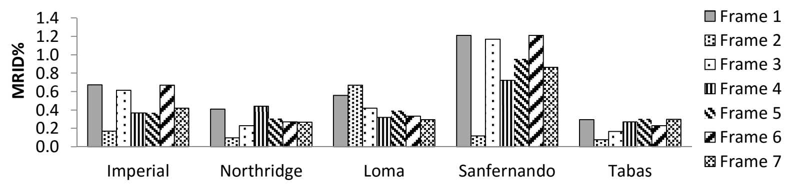

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Change of MID and MRID compared with SMRF

	Imperial		Northridge		Loma		San Fernado		Tabas	
	MID (% change)	MRID(% change)	MID(% change)	MRID	MID(% change)	MRID	MID(% change)	MRID	MID(% change)	MRID(% change)
Frame 2	**56.90**	**-74.74**	**9.78**	**-76.44**	**29.08**	**19.50**	**18.39**	**-90.25**	**110.18**	**-74.42**
Frame 3	16.50	-8.77	5.27	-44.63	1.31	-24.69	-3.16	-3.31	6.55	-43.20
Frame 4	**23.10**	**-45.32**	**4.73**	**7.07**	**7.17**	**-42.93**	**2.01**	**-40.50**	**21.82**	**-8.50**
Frame 5	18.52	-45.32	5.14	-25.37	8.43	-30.23	6.90	-21.24	6.91	3.06
Frame 6	16.84	-0.59	6.62	-34.15	0.60	-40.68	-2.01	0.00	9.93	-21.77
Frame 7	22.22	-37.84	5.50	-35.13	4.96	-47.59	1.28	-28.52	13.65	1.61

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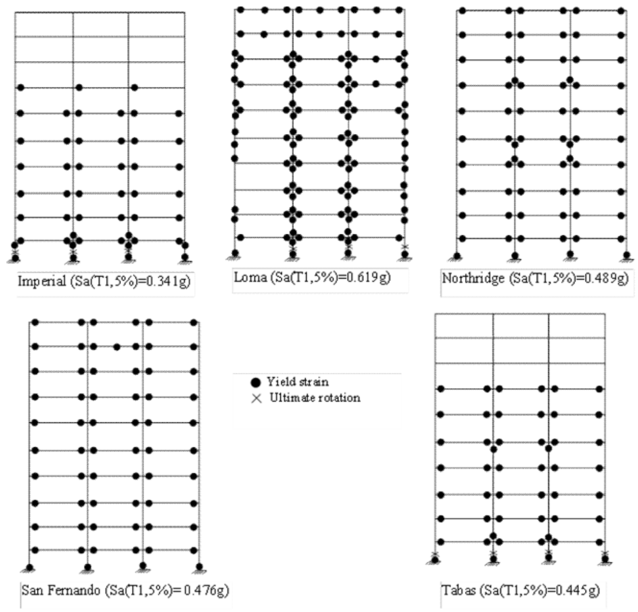
Damage distribution of Frame 2



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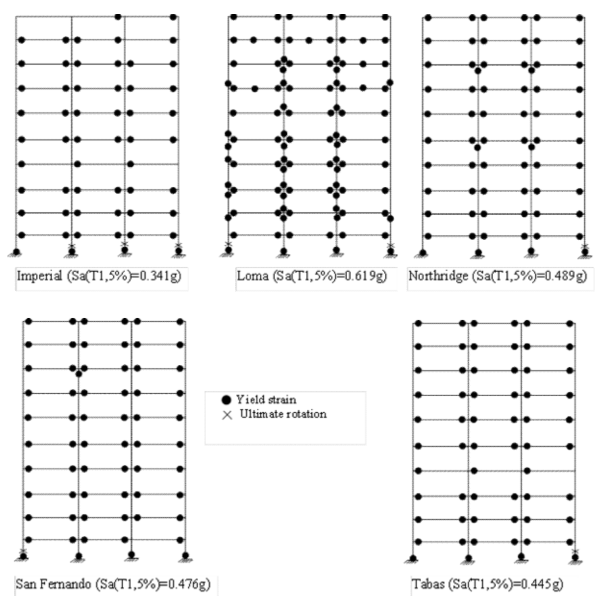
Damage distribution of Frame 4



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Modular Steel Frames

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Modular Steel Structures

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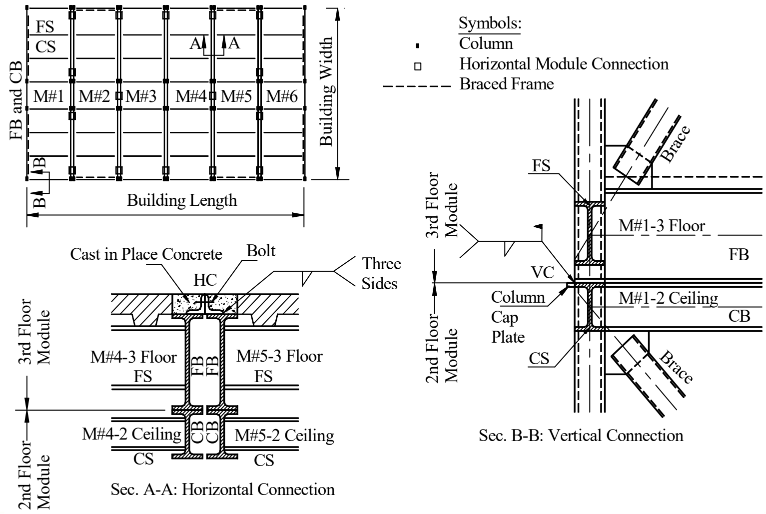
Modular Steel Structures



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2. 2012: Seismic Performance of Concrete Frames Reinforced with Superelastic Shape Memory Alloys, **Smart Structures and Systems**, 9(4): 313-333.
3. 2011: Seismic Behaviour of Repaired Superelastic Shape Memory Alloy Reinforced Concrete Beam-Column Joint, **Smart Structures and Systems**, 7(5): 329-348.
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5. 2010: Development of corrosion-free concrete beam-column joint with adequate seismic energy dissipation, **Engineering Structures**, 32(9): 2518-2528.
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11. 2008: Experimental Investigation on the Seismic Behaviour of Beam-Column Joints Reinforced with Superelastic Shape Memory Alloys, **Journal of Earthquake Engineering**, 12(7): 1205-1222.
12. 2008: Shape Memory Alloy-Based Smart RC Bridge: Overview of State-of-the-Art, **Smart Structures and Systems**, 4(3): 367-389.
13. 2007: Utilizing Shape Memory Alloys to Enhance the Performance and Safety of Civil Infrastructure: a Review", **Canadian Journal of Civil Engineering**, 34(9): 1075-1086.

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