Seismic Design of Shape Memory Alloy Reinforced Concrete Bridge Pier

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Outline

- Current seismic design philosophy
- Performance based seismic design (PBSD)
- PBSD for new materials
- PBSD Example on SMA-RC Pier
- Conclusion

Current Seismic Design Philosophy

Collapse Prevention

“Failure”

Current Seismic Design Philosophy

Successive residual strain accumulation causes large permanent deformation

“Failure”

Current Seismic Design Philosophy

"Success -- ?"

Current Seismic Design Philosophy

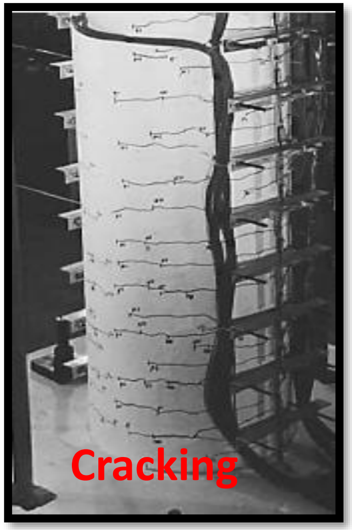
- ☐ May result in bridge closures
    - Excessive column damage
    - Excessive lateral deflection
    - Limited access; may or may not allow even emergency response vehicles
- ☐ Extensive Repairs
    - Patching of spalled concrete
    - Shoring of spans
    - Replacement
    - Disrupts traffic
    - Major economic loss

Improved Seismic Design

- Minimize residual drift
- Minimize repair need
- Keep bridges operational
- Reduce damage to plastic hinges
- Keep an energy dissipating system

Performance Based Design…..

Performance Based Seismic Design


Cracking


Yielding

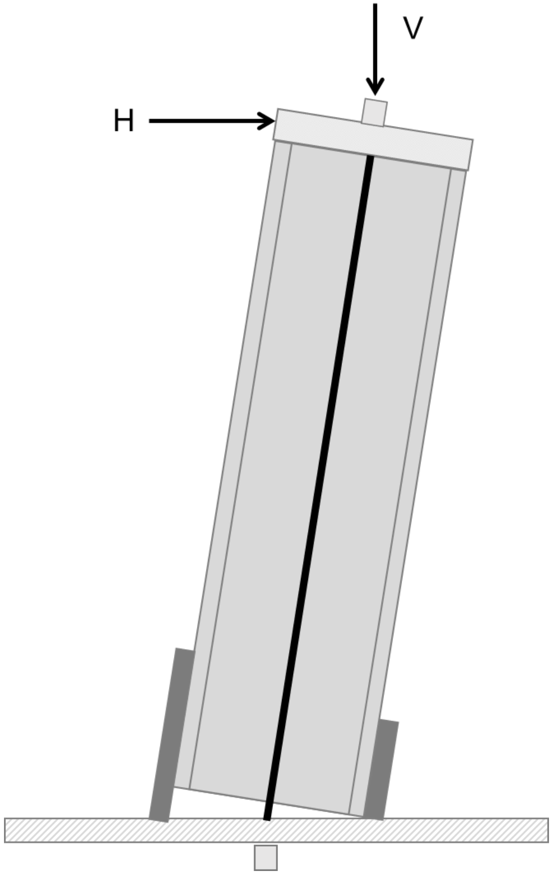

Spalling

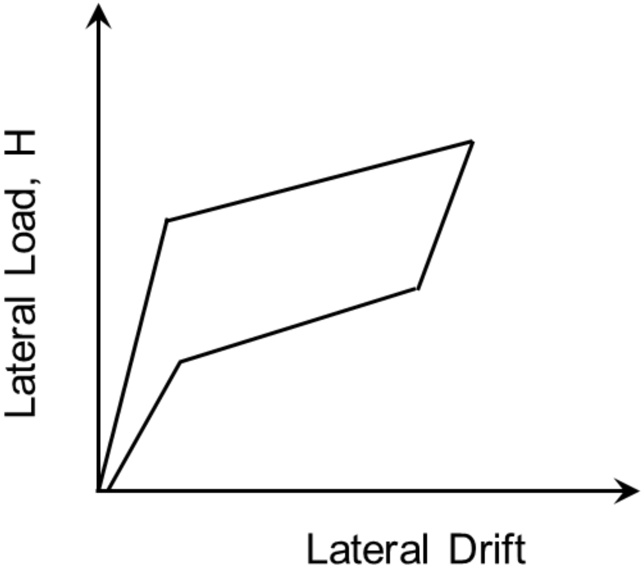

Crushing

Hose et al. 2000

Is it enough to protect our investments?
If not, what can we do?

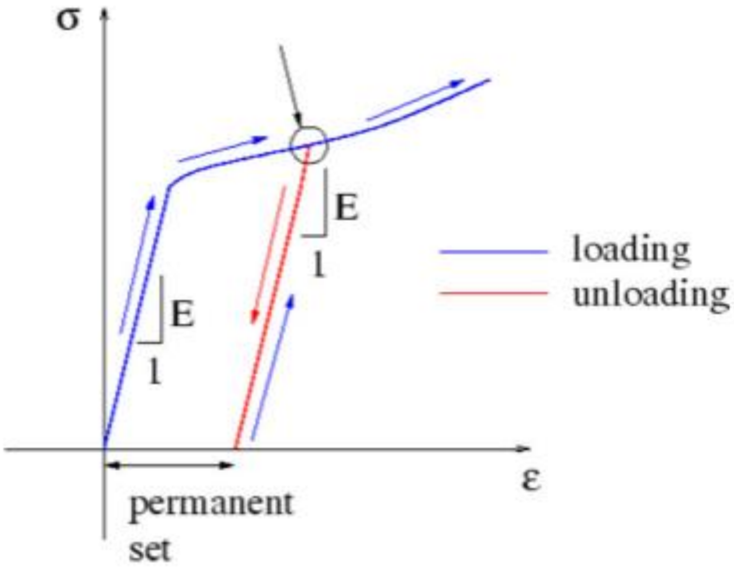
Rocking bridge pier



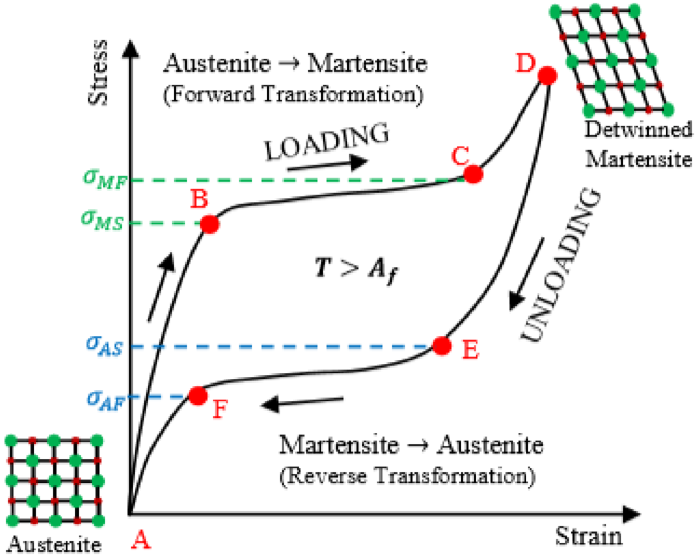


Innovative Materials

Superelastic Shape Memory Alloy (SMA)



Steel

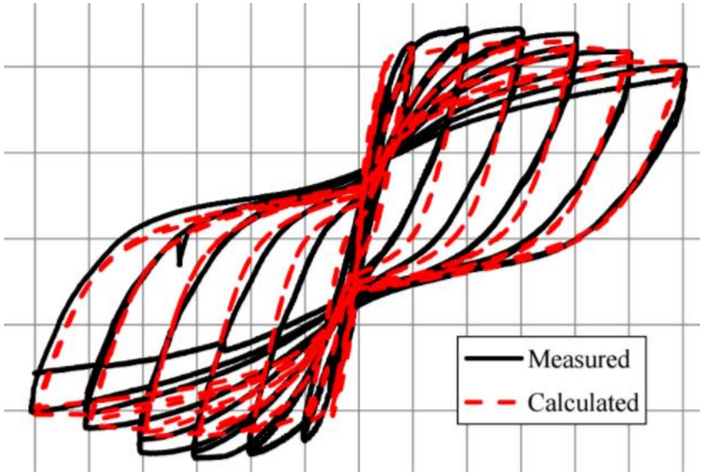


SMA

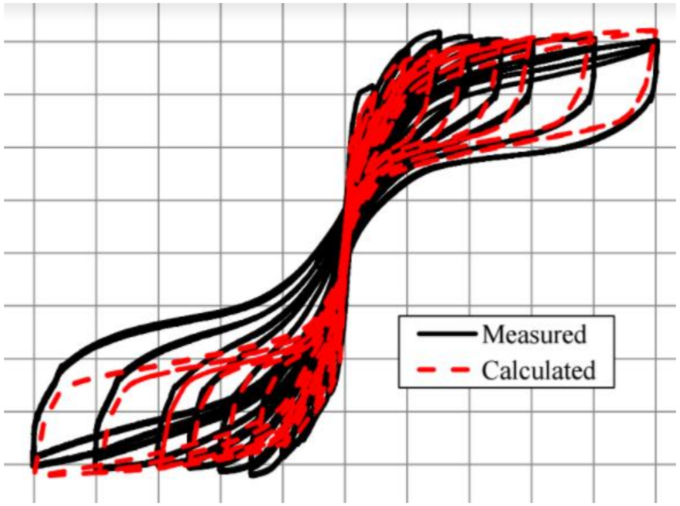
Innovative Materials

Reinforced Concrete Columns

- ➢Reduced residual deformation

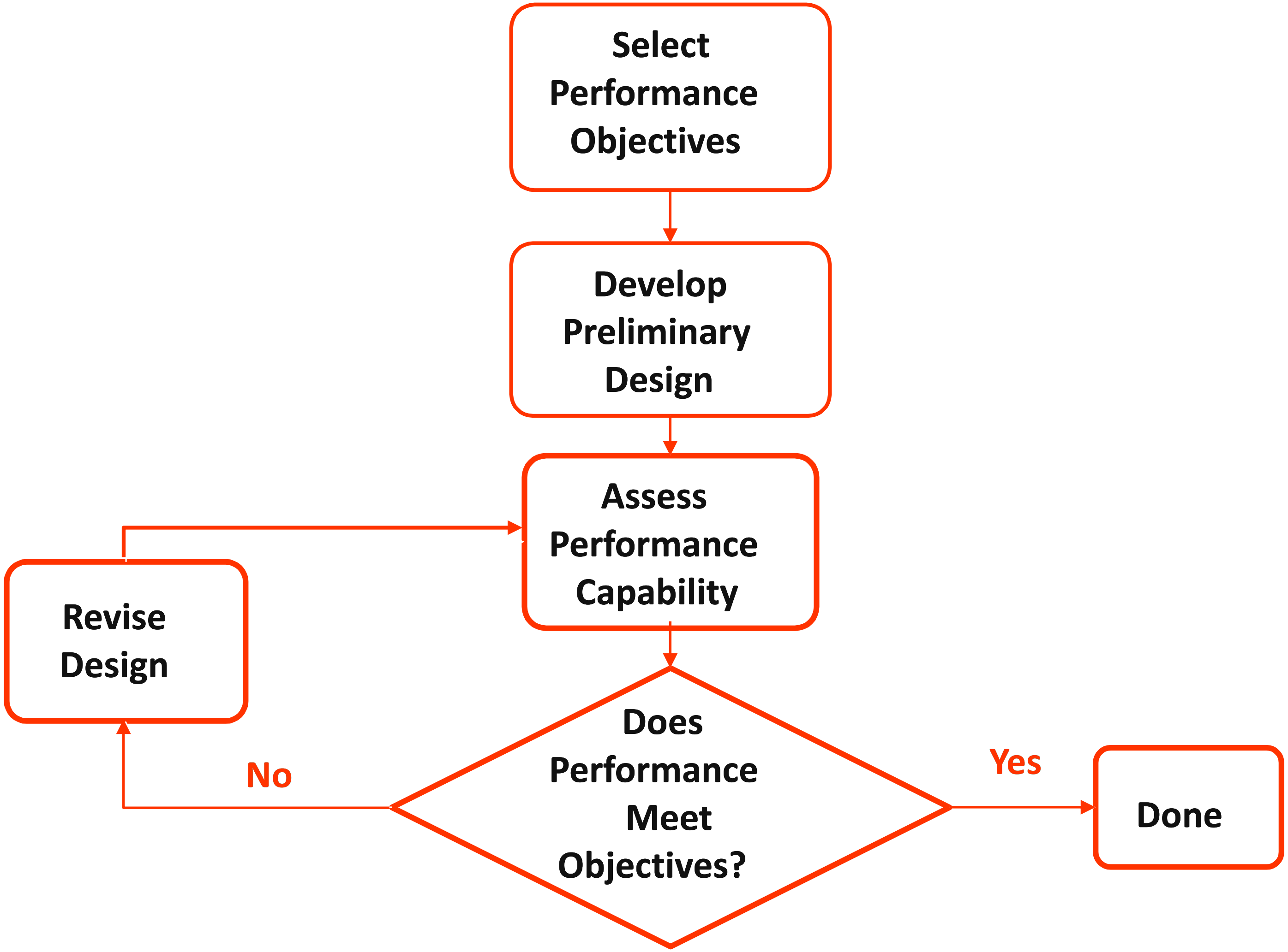


Steel RC Column

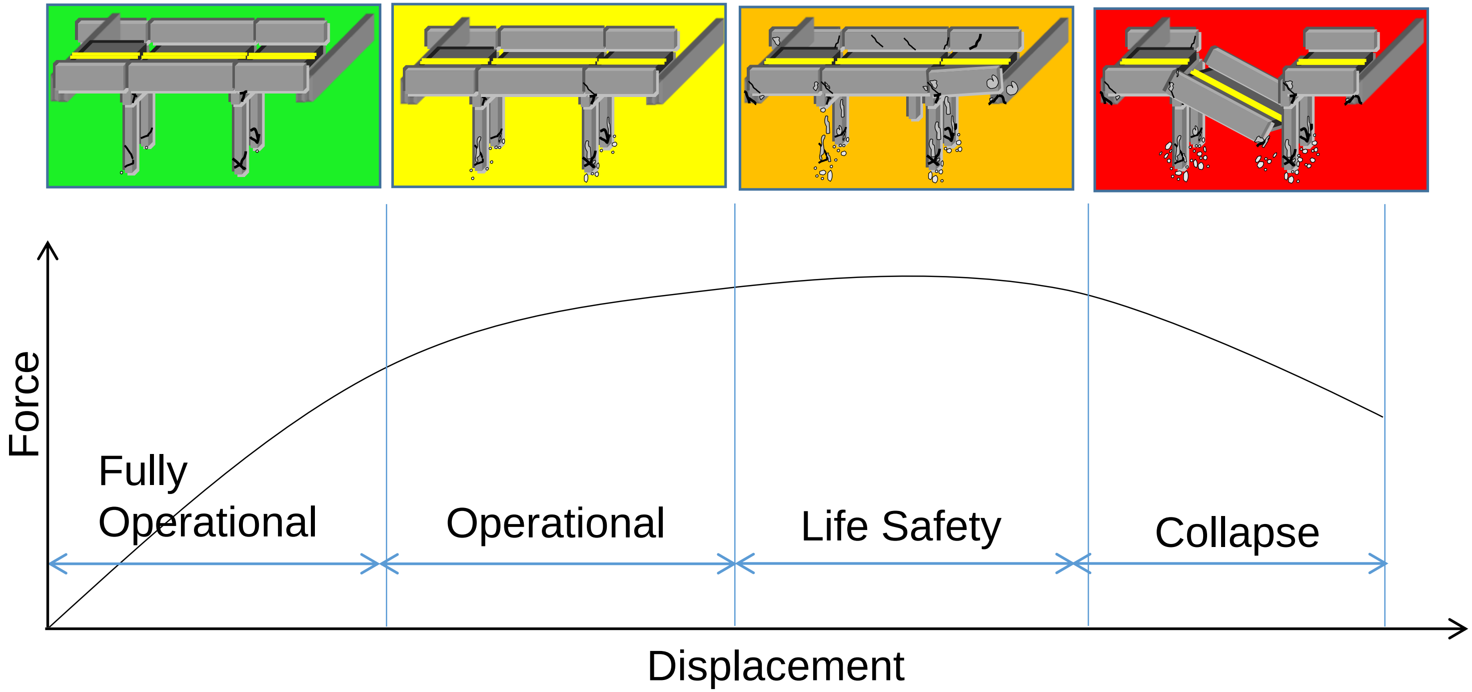


SMA RC Column

Performance Based Design of SMA-RC Pier



Performance-based Damage States



Damage State Development

Selection of Shape Memory Alloy

Design of bridge piers with different SMA

Moment-curvature analysis of different SMA-RC section

Selection of suitable ground motions

IDA of different SMA-RC bridge pier

Capture the different performance limits for each EQ at different intensity

Develop the dynamic pushover curves for each EQ and compute the median, 5 percentile and 95 percentile curves

Obtain the drift limit at different performance levels and determine the suitable distribution

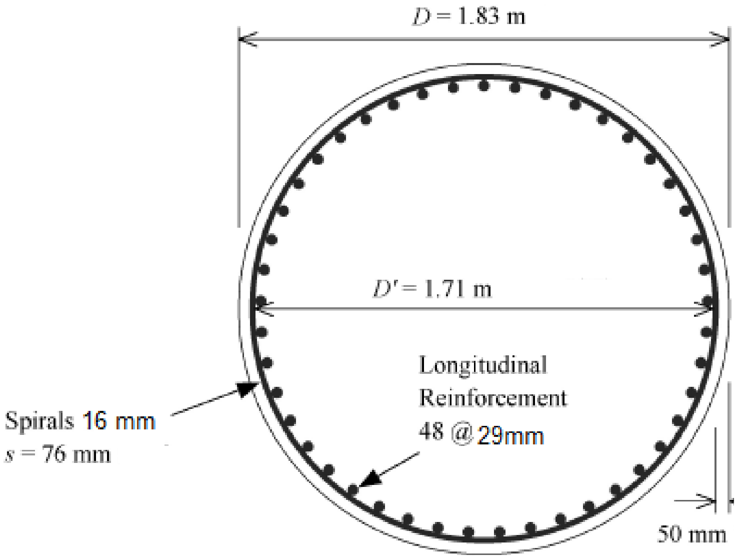
Define drift limits at different performance levels for different SMAs

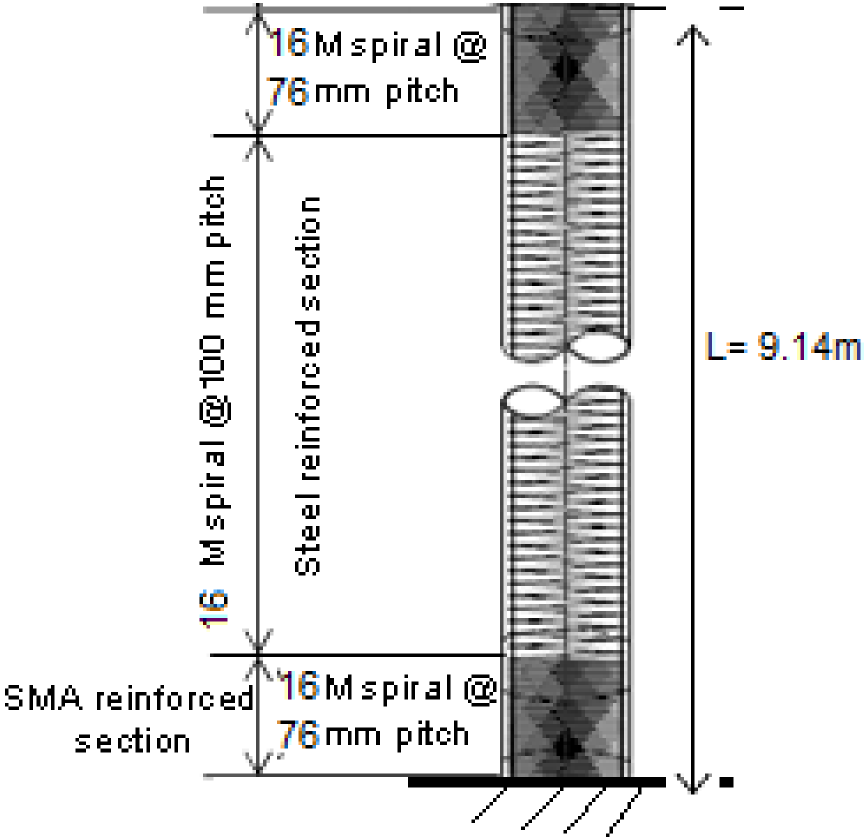
Properties of Different SMAs

	Alloy	εs (%)	E (GPa)	fy (MPa)	f_{p1} (MPa)	f_{T1} (MPa)	f_{T2} (MPa)	Ref
SMA-1	$NiTi_{45}$	6	62.5	401.0	510	370	130	Alam et al. 2008
SMA-2	$NiTi_{45}$	8	68	435.0	535.0	335	170	Ghassemieh et al. 2012
SMA-3	FeNCATB	13.5	46.9	750	1200	300	200	Tanaka et al. 2010
SMA-4	CuAlMn	9	28	210.0	275.0	200	150	Shrestha et al. 2013
SMA-5	FeMnAlNi	6.13	98.4	320.00	442.5	210.8	122	Omori et al. 2011

f_y (austenite to martensite starting stress); f_{P1}(austenite to martensite finishing stress); f_{T1}(martensite to austenite starting stress); f_{T2}(martensite to austenite finishing stress) , ε_s (superelastic plateau strain length); and E (modulus of elasticity).

Design and Geometry of Bridge Piers

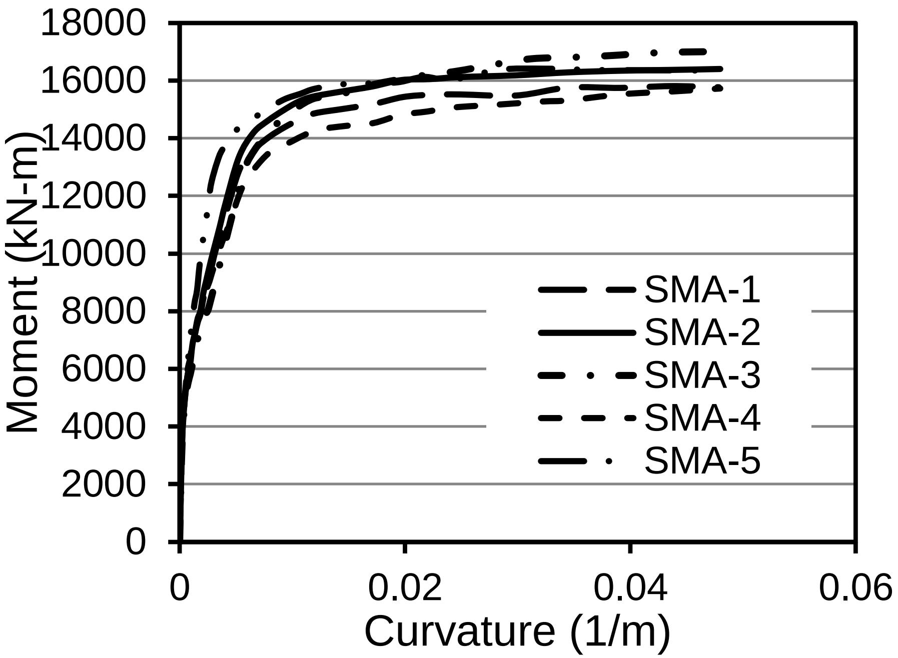


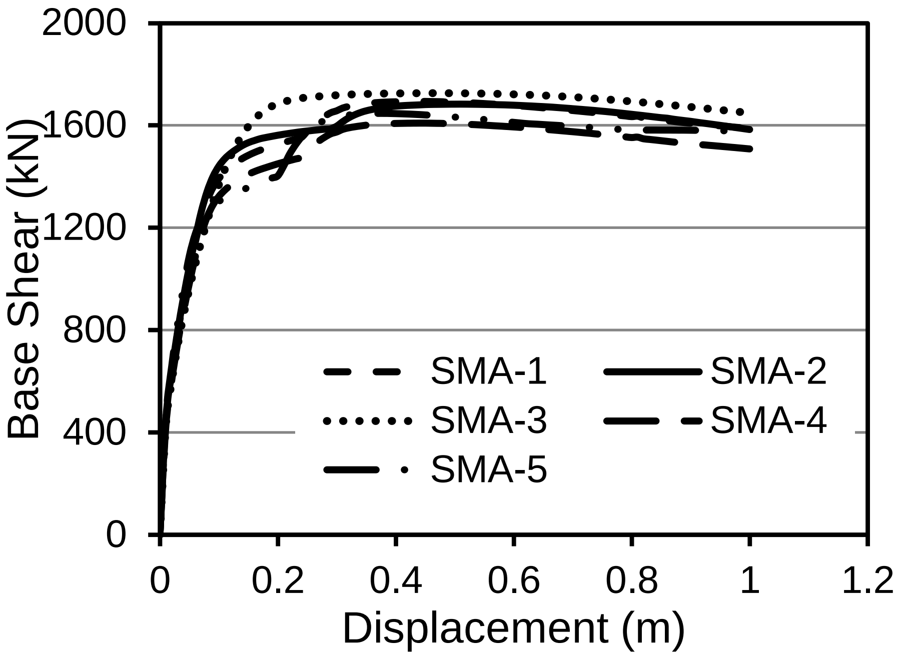


Bridge Pier Configuration

Pier	Longitudinal Rebar	ρ_l (%)	Spiral	ρ_s (%)
SMA-RC-1	48-28M	1.12	15M @76 mm	0.70
SMA-RC-2	48-28M	1.12	15M @76mm	0.70
SMA-RC-3	48-20M	1.20	15M @76 mm	0.70
SMA-RC-4	48-35M	1.75	15M @76 mm	0.70
SMA-RC-5	48-32M	1.46	15M @76mm	0.70

Capacity Curves

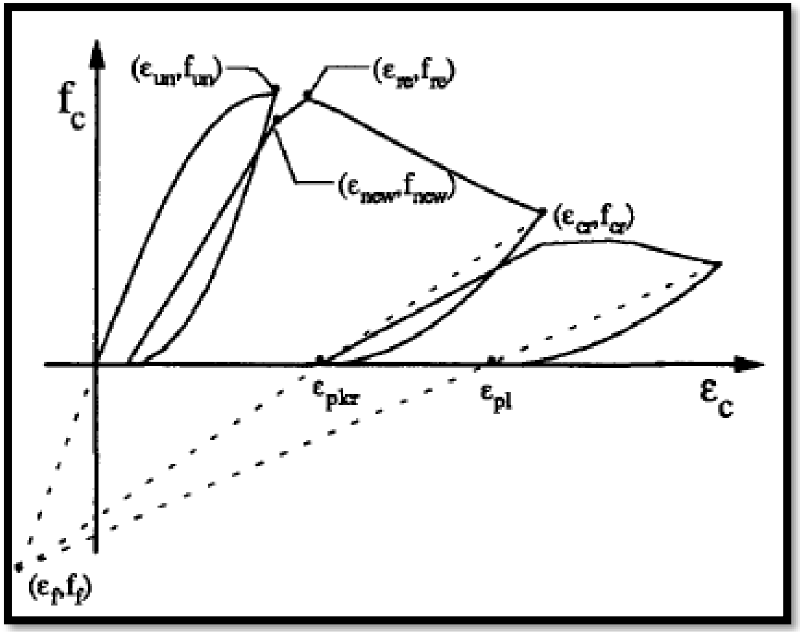




Finite Element Modeling

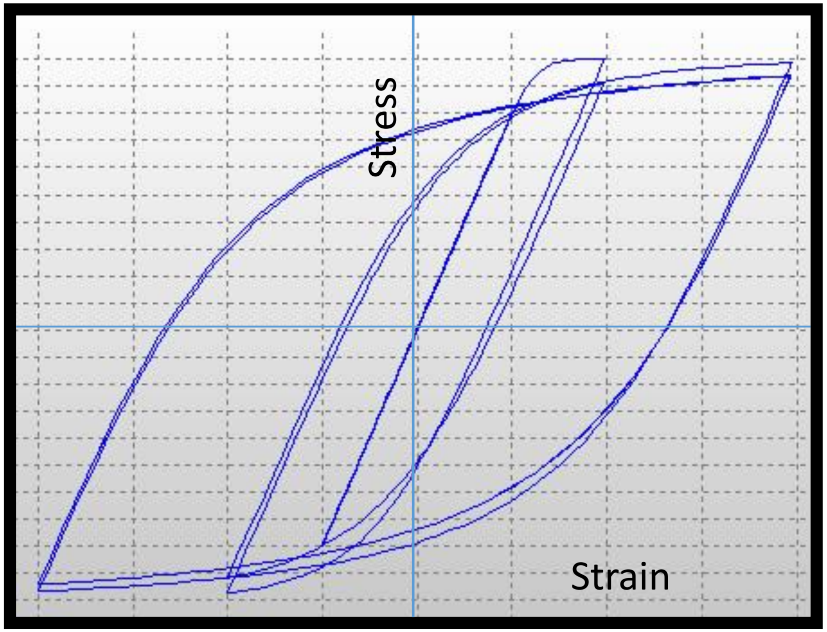
Concrete Model

Mander et al. [1988] & Martinez-Rueda and Elnashai [1997]



Steel Model

Menegotto and Pinto,1973



SeismoStruct

Validation with Experimental Result

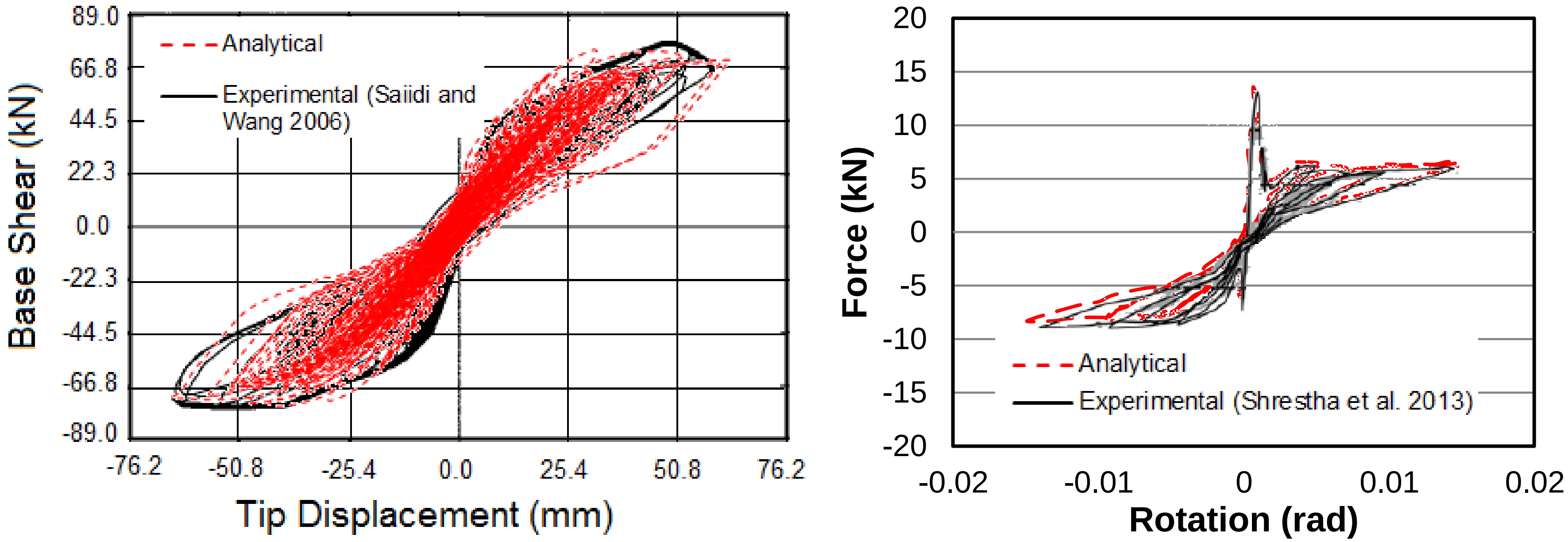
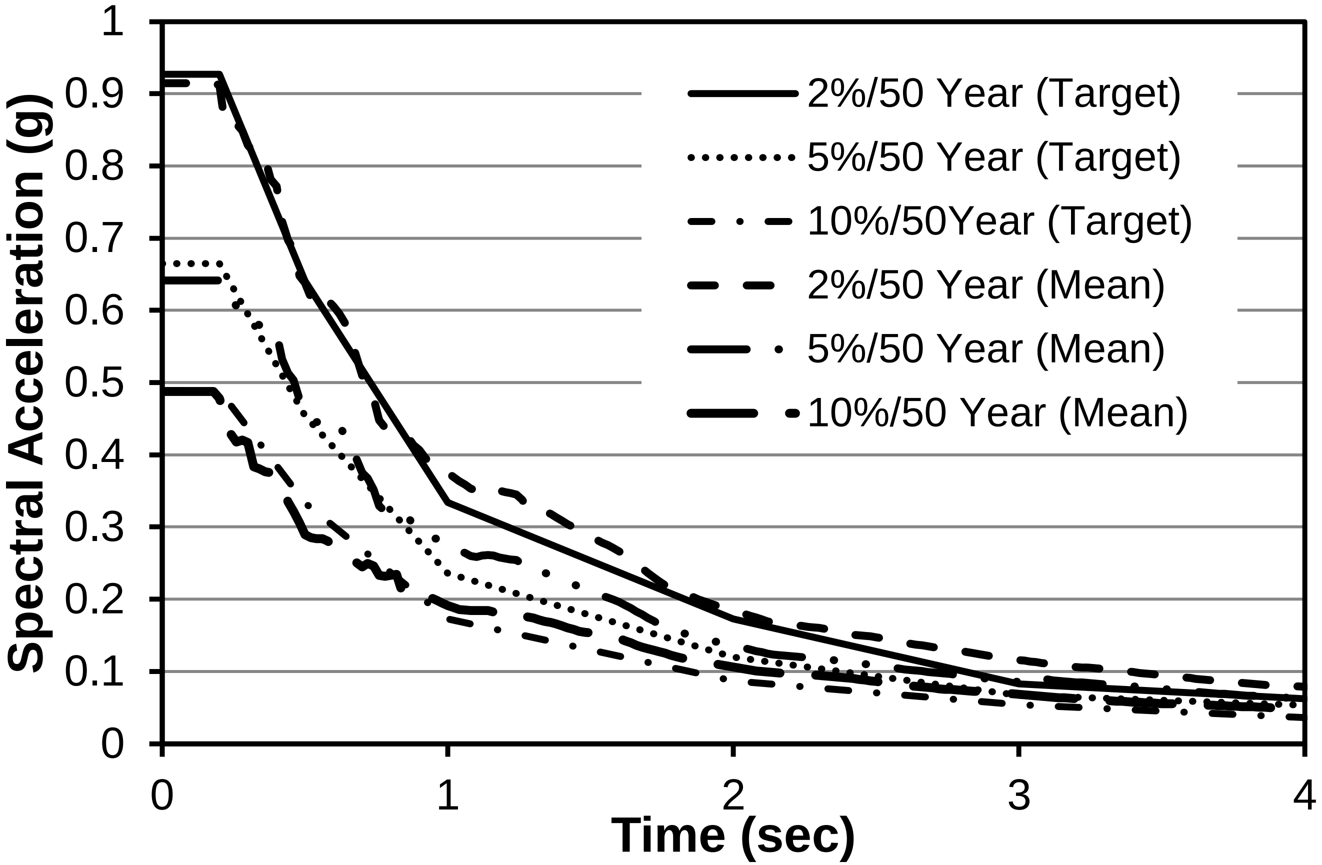


Fig. Comparison of experimental and numerical results (a) SMA-RC (SMA-1) bridge pier (Saiidi and Wang 2006). (b) SMA-RC (SMA-4) beam (Shrestha et al. 2013).

Different Hazard Levels



Proposed Damage State Framework

Damage Parameter	Damage State	Functional Level	Description
Cracking	DS-1	Immediate	Onset of hairline cracks
Yielding	DS-2	Limited	Theoretical first yield of longitudinal rebar
Spalling	DS-3	Service disruption	Onset of concrete spalling
Core Crushing	DS-4	Life safety	Crushing of core concrete

Maximum Drift Damage States

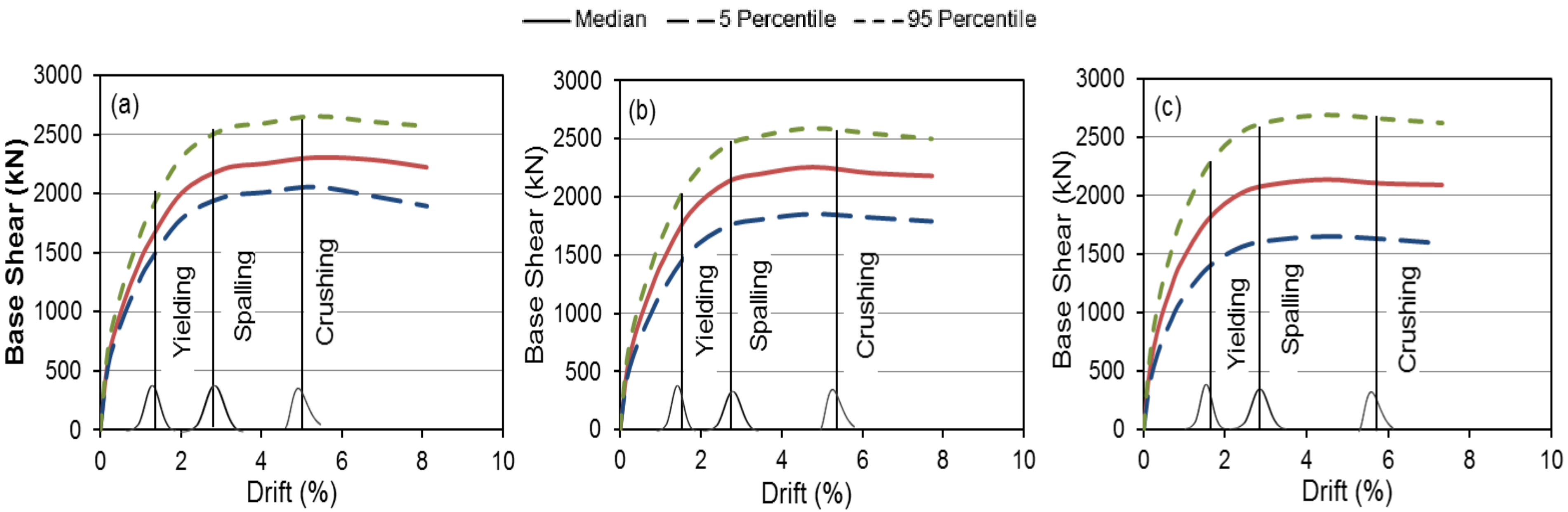


Figure . Dynamic pushover response and different damage states with distribution for SMA-RC-1 for (a) 2% in 50 years (b) 5% in 50 years and (c) 10% in 50 years probability of exceedance

Damage States of SMA-RC Bridge Pier

		SMA-1			SMA-2			SMA-3			SMA-4			SMA-5			Distribution
Damage Parameter	Damage State	Drift (%)			Drift (%)			Drift (%)			Drift (%)			Drift (%)			
		Probability of Exceedance															
		2% 50	5% 50	10% 50	2% 50	5% 50	10% 50	2% 50	5% 50	10% 50	2% 50	5% 50	10% 50	2% 50	5% 50	10% 50	
Cracking	DS-1	0.28	0.28	0.28	0.30	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	Uniform
Yielding	DS-2	1.68	1.76	1.86	1.66	1.72	1.80	2.28	2.42	2.58	1.74	1.83	1.95	1.10	1.16	1.21	Lognormal
Spalling	DS-3	2.66	2.79	2.88	2.69	2.77	2.87	1.64	1.72	1.80	2.52	2.61	2.68	1.97	2.02	2.10	Normal
Crushing	DS-4	5.05	5.68	5.94	5.51	5.91	6.05	7.65	7.81	7.94	5.56	5.63	5.72	4.73	4.79	4.84	Gamma

Maximum Drift Damage States

Damage Parameter	Damage State	Functional Level	Maximum Drift (%)		
			Probability of Exceedance		
			10% in 50	5% in 50	2 % in 50
Cracking	DS-1	Fully Operational	0.28	0.28	0.28
Yielding	DS-2	Operational	1.86	1.76	1.68
Spalling	DS-3	Life safety	2.88	2.79	2.66
Crushing	DS-4	Collapse Prevention	5.94	5.68	5.05

Residual Drift Damage States

Damage State	Functional Level	Description
Slight (DS=1)	Fully Operational	No structural realignment is necessary
Moderate (DS=2)	Operational	Minor structural repairing is necessary
Extensive (DS=3)	Life safety	Major structural realignment is required
Collapse (DS=4)	Collapse	Structure in danger of collapse from earthquake aftershocks

Residual Drift Damage States

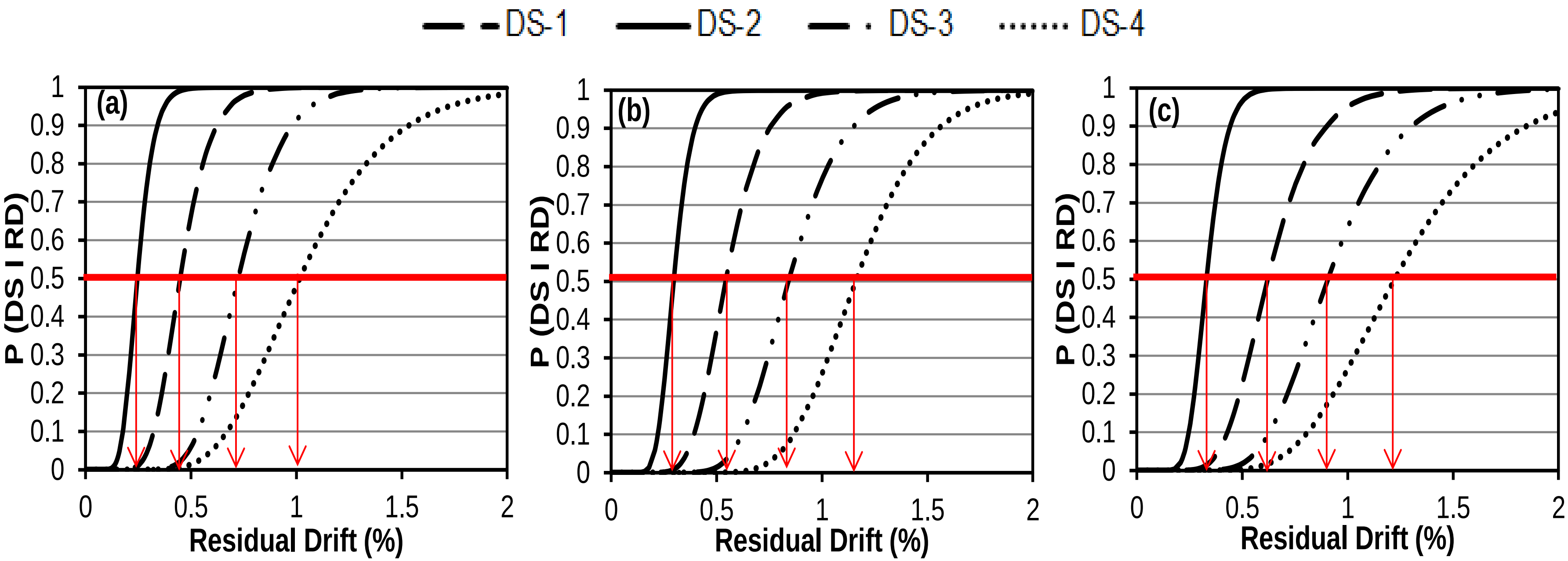


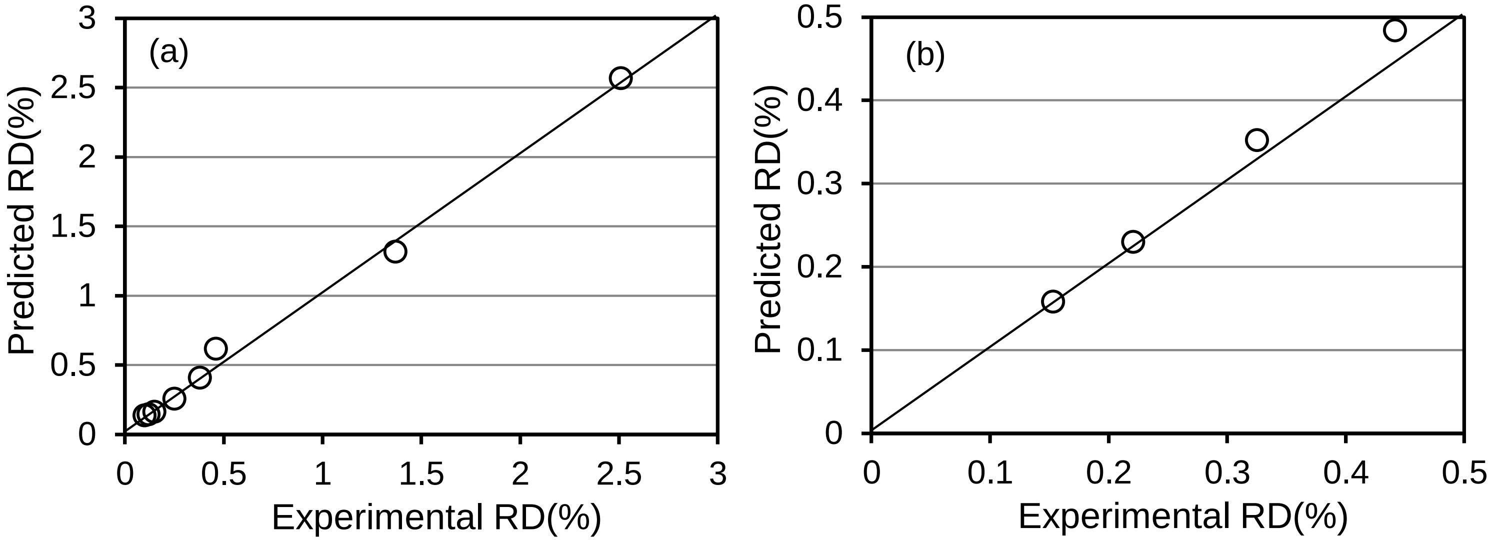
Figure. Fragility curves in terms of residual drift at (a) 10% in 50 years (b) 5% in 50 years and (c) 2% in 50 years probability of exceedance

Residual Drift Damage States

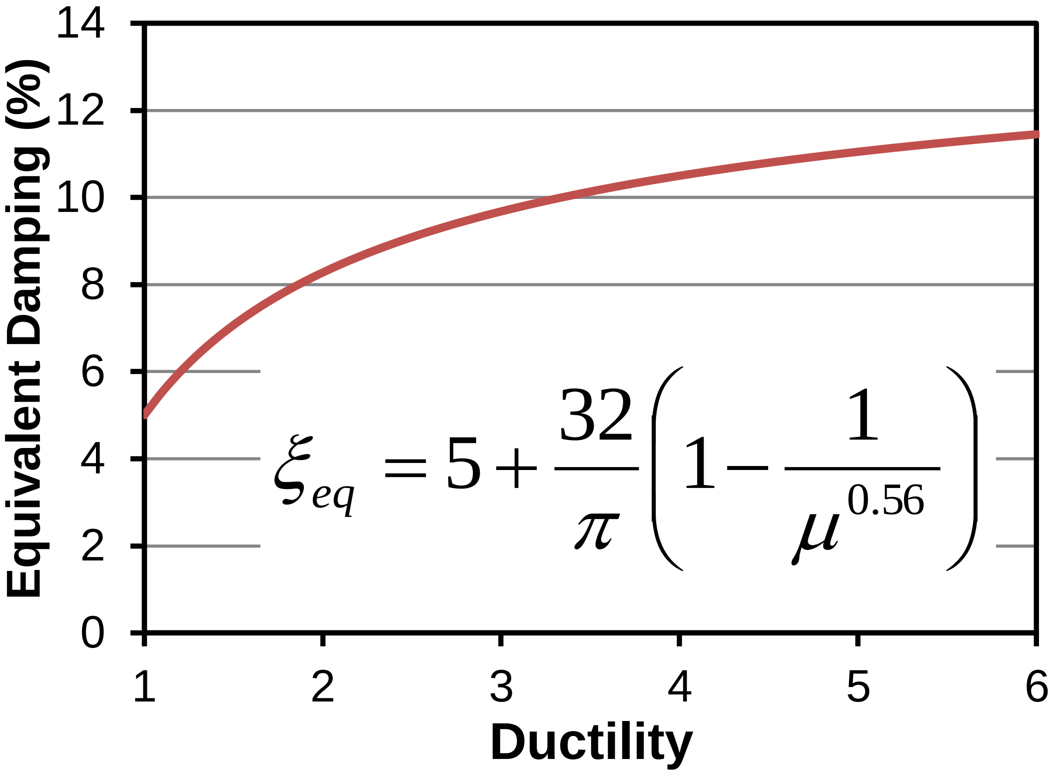
Damage State	Functional Level	Description	Residual Drift, R_Δ (%)		
			Probability of Exceedance		
			10% in 50	5% in 50	2 % in 50
Slight (DS=1)	Fully Operational	No structural realignment is necessary	0.24	0.28	0.33
Moderate (DS=2)	Operational	Minor structural repairing is necessary	0.48	0.55	0.62
Extensive (DS=3)	Life safety	Major structural realignment is required	0.73	0.82	0.87
Collapse (DS=4)	Collapse	Structure in danger of collapse from earthquake aftershocks	1.04	1.16	1.22

Prediction of Residual Drift

$$RD = 0.5\left(\frac{\varepsilon_s}{100}MD^2\right) - \left(\frac{\varepsilon_s}{100}MD\right) + \left(\frac{1}{\varepsilon_s}\right)$$

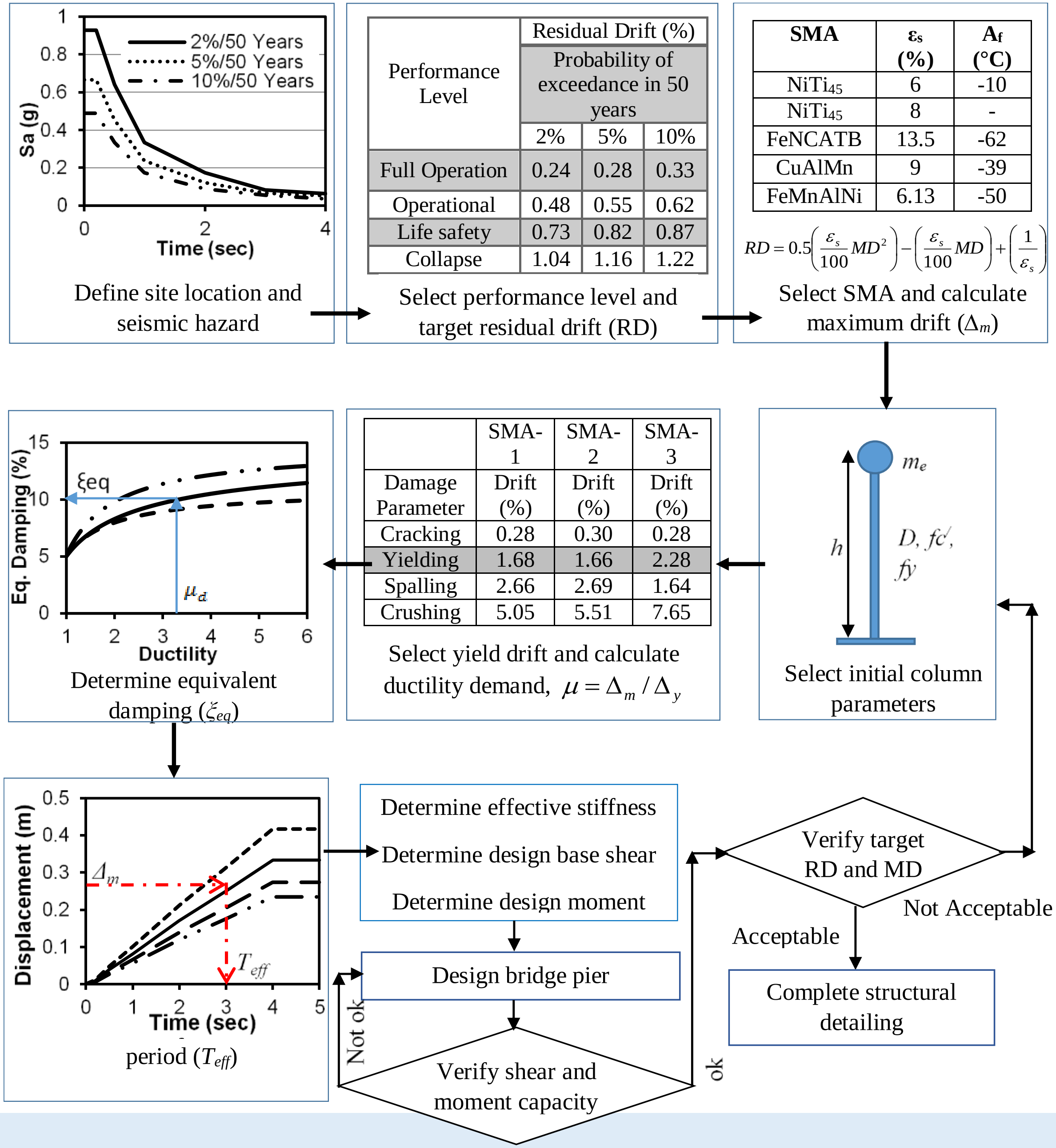


μ-ξ Relationship of SMA-RC Pier



$$\xi_{eq} = 5 + \frac{32}{\pi}\left(1 - \frac{1}{\mu^{0.56}}\right)$$

PBSD Of SMA-RC Pier



Define site location and seismic hazard

Performance Level	Residual Drift (%)		
	Probability of exceedance in 50 years		
	2%	5%	10%
Full Operation	0.24	0.28	0.33
Operational	0.48	0.55	0.62
Life safety	0.73	0.82	0.87
Collapse	1.04	1.16	1.22

Select performance level and target residual drift (RD)

SMA	ε_s (%)	A_f (°C)
$NiTi_{45}$	6	-10
$NiTi_{45}$	8	-
FeNCATB	13.5	-62
CuAlMn	9	-39
FeMnAlNi	6.13	-50

$$RD = 0.5\left(\frac{\varepsilon_s}{100}MD^2\right) - \left(\frac{\varepsilon_s}{100}MD\right) + \left(\frac{1}{\varepsilon_s}\right)$$

Select SMA and calculate maximum drift (Δ_m)

Select initial column parameters

	SMA-1	SMA-2	SMA-3
Damage Parameter	Drift (%)	Drift (%)	Drift (%)
Cracking	0.28	0.30	0.28
Yielding	1.68	1.66	2.28
Spalling	2.66	2.69	1.64
Crushing	5.05	5.51	7.65

Select yield drift and calculate ductility demand, $\mu = \Delta_m / \Delta_y$

Determine equivalent damping (ξ_{eq})

period (T_{eff})

Determine effective stiffness

Determine design base shear

Determine design moment

Design bridge pier

Verify shear and moment capacity

Not ok

ok

Verify target RD and MD

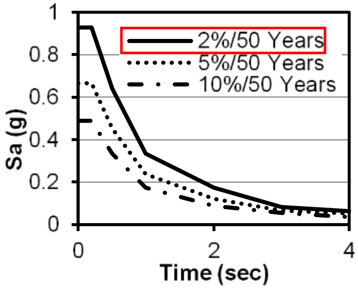
Not Acceptable

Acceptable

Complete structural detailing

Design of SMA-RC Pier

- Location: Vancouver (Soil Class-C)
- Life Line Bridge
- EQ Return Period: 2475 Yr
- Functional Level: Operational
- Damage Level: Moderate
- Target RD =0.6%



Define site location and seismic hazard

Performance Level	Residual Drift (%)		
	Probability of exceedance in 50 years		
	10%	5%	2%
Full Operation	0.24	0.28	0.33
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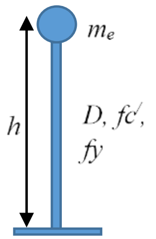
$$RD = 0.5\left(\frac{\varepsilon_s}{100}MD^2\right) - \left(\frac{\varepsilon_s}{100}MD\right) + \left(\frac{1}{\varepsilon_s}\right)$$

Select SMA and calculate maximum drift (Δ_m)

4.92%



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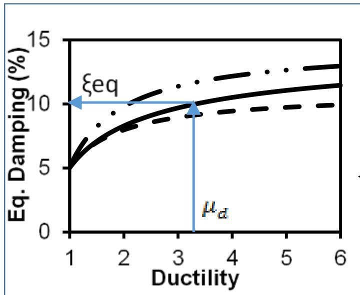
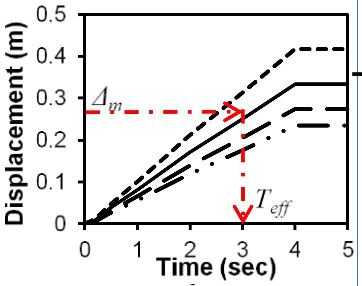
Select yield drift and calculate ductility demand, $\mu = \Delta_m / \Delta_y$ 3



Determine equivalent damping (ξ_{eq})



period (T_{eff})

Determine effective stiffness

Determine design base shear

Determine design moment

Design bridge pier

Verify shear and moment capacity

Not ok

ok

Verify target RD and MD

Not Acceptable

Acceptable

Complete structural detailing

Design of SMA-RC Pier

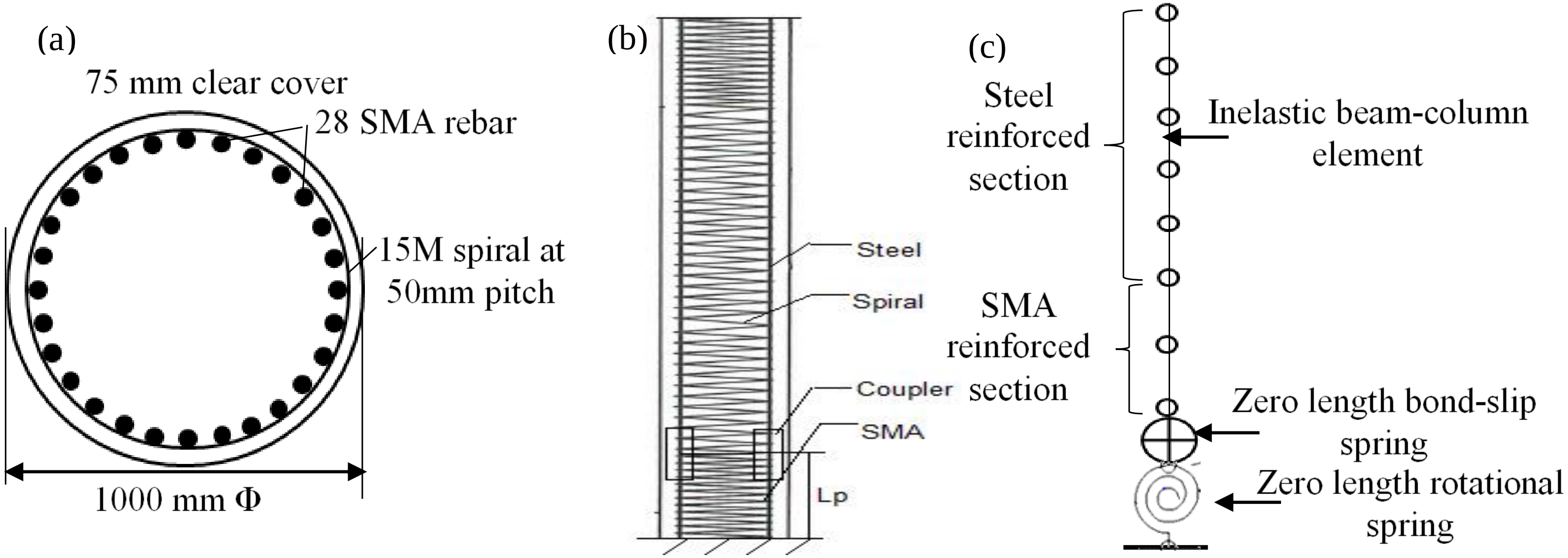
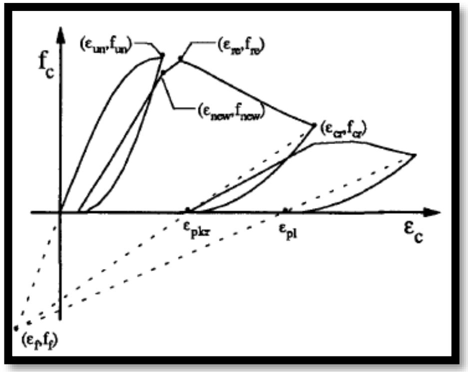


Figure. (a) Cross section, (b) elevation and (c) finite element model of SMA-RC bridge pier

Finite Element Modeling

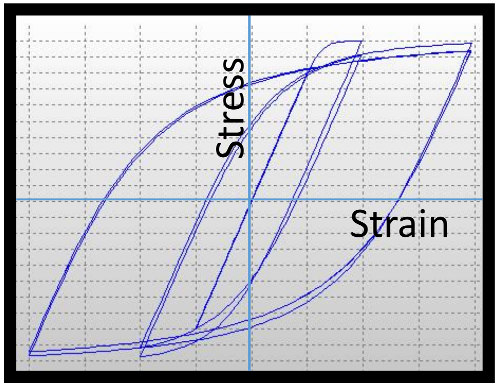
Concrete Model

Mander et al. [1988] & Martinez-Rueda and Elnashai [1997]



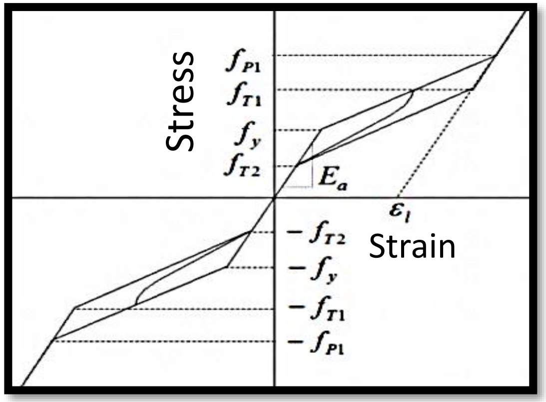
Steel Model

Menegotto and Pinto,1973



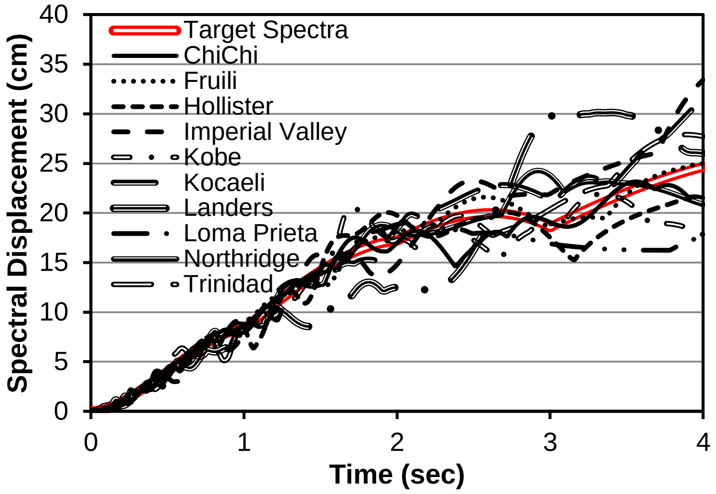
SMA Model

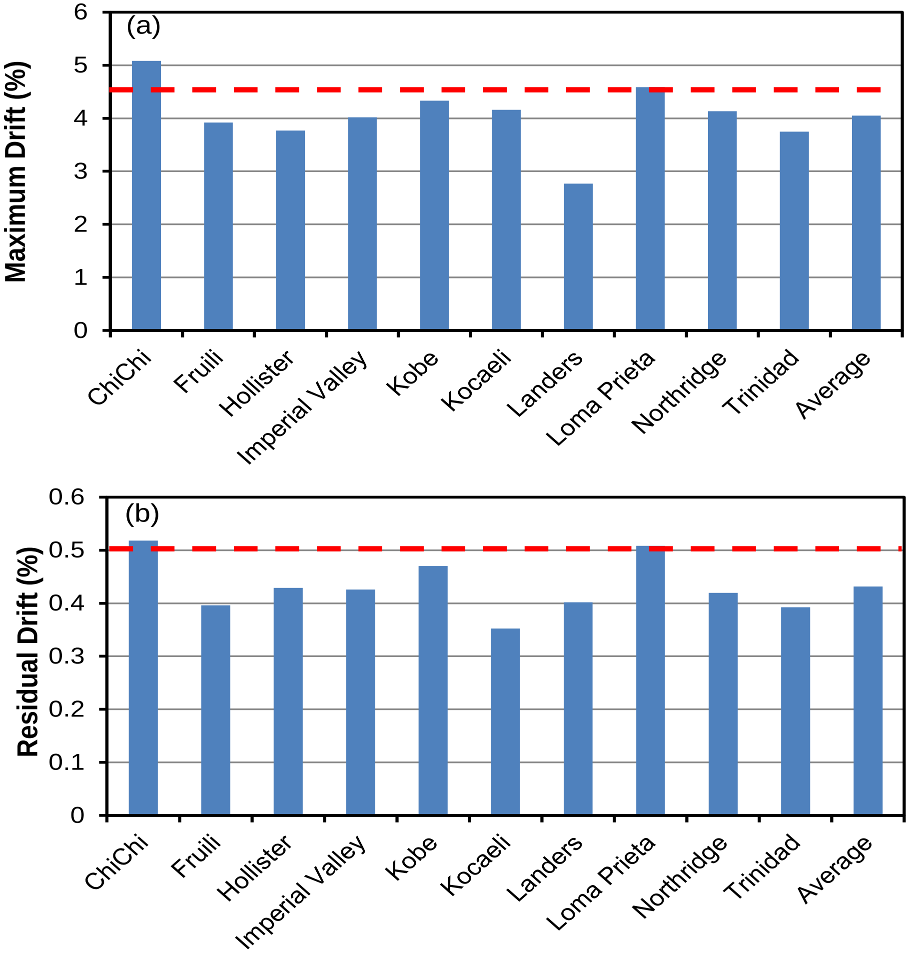
Auricchio and Sacco [1997]



SeismoStruct

Performance Evaluation





Conclusions

- A new residual drift–based design method
- A comprehensive approach for PBSD of SMA-RC bridge piers
- Meets performance expectations
- Lower residual drift
- Less maintenance cost

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NSERC CRSNG

UBC a place of mind THE UNIVERSITY OF BRITISH COLUMBIA

BOURCET ENGINEERING

Fall 2017 — Making Connections

Thanks for your attention

Source:http://www.wsdot.wa.gov/publications/fulltext/Bridge/Shape_Memory.pdf

Q & A

Questions/Comments

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