CFRP Retrofit of Concrete Columns

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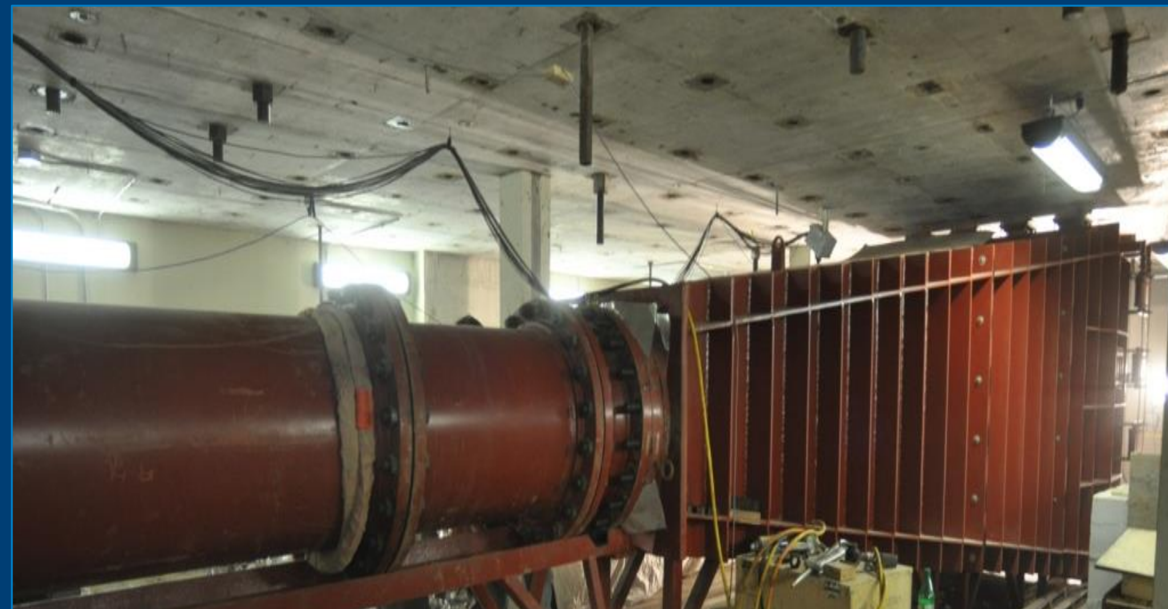
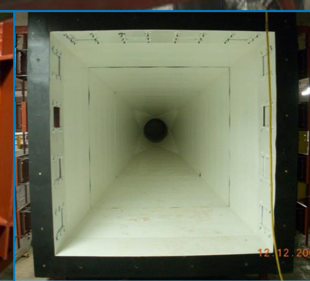
Overview

- Shock tube testing of concrete columns
- Response of columns with and without seismic detailing
- Retrofit of columns with FRP for ductility and for strength
- FRP bond under high strain rates

Shock Tube Testing Facility



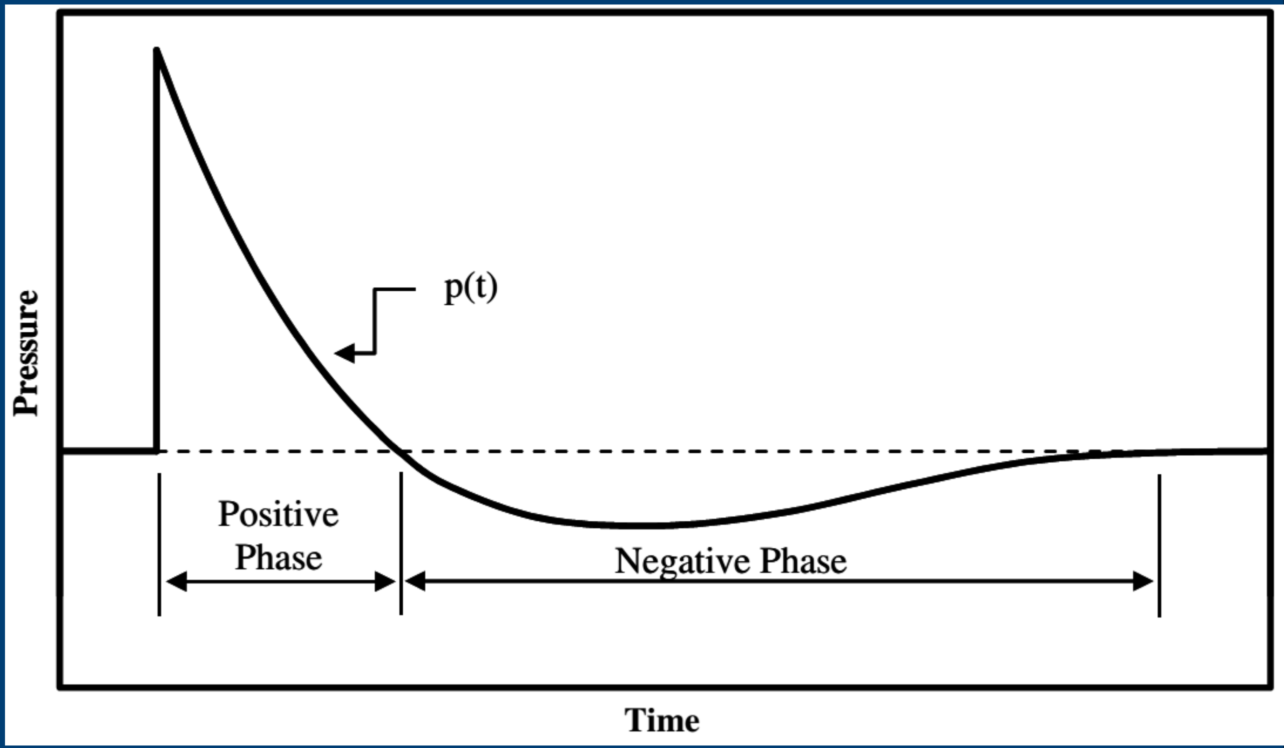


Explosive Simulation

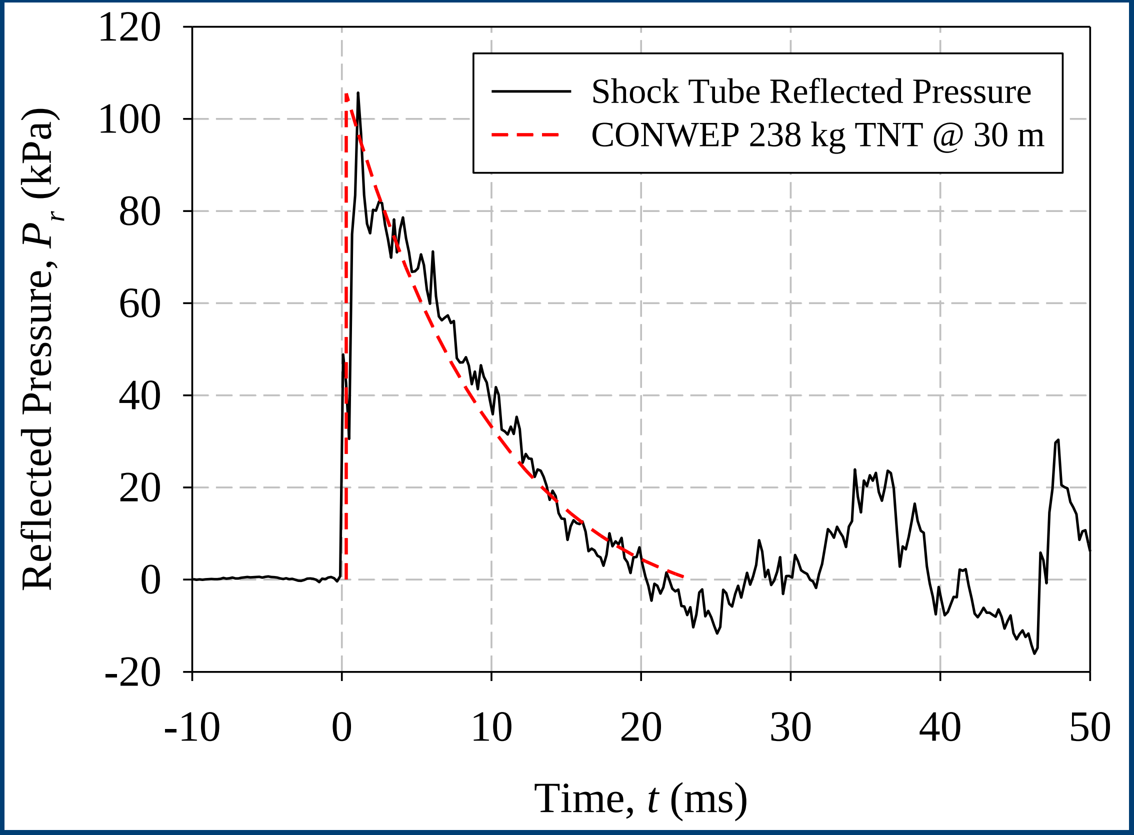
Shock Waves

Properties

- Instantaneous rise to maximum
- Exponential decay
- Short duration



Shock Tube Induced Shock Waves



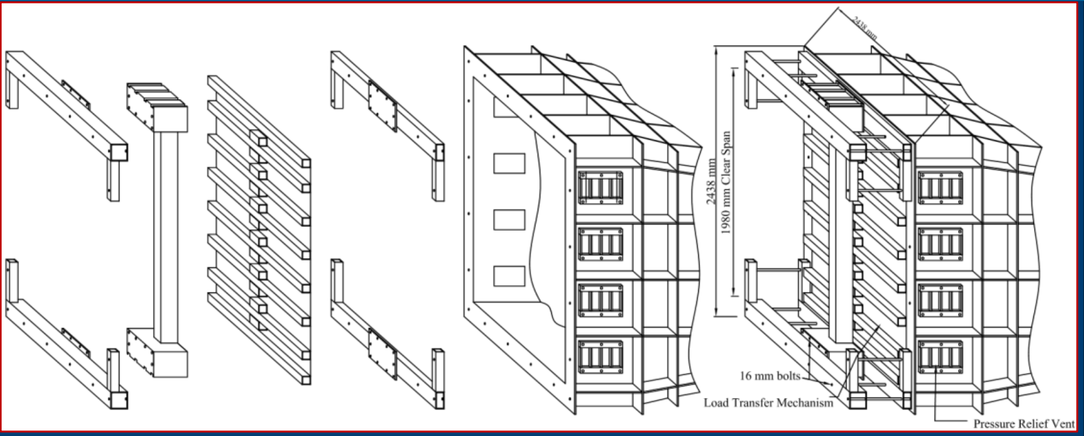
Pressure vs Time

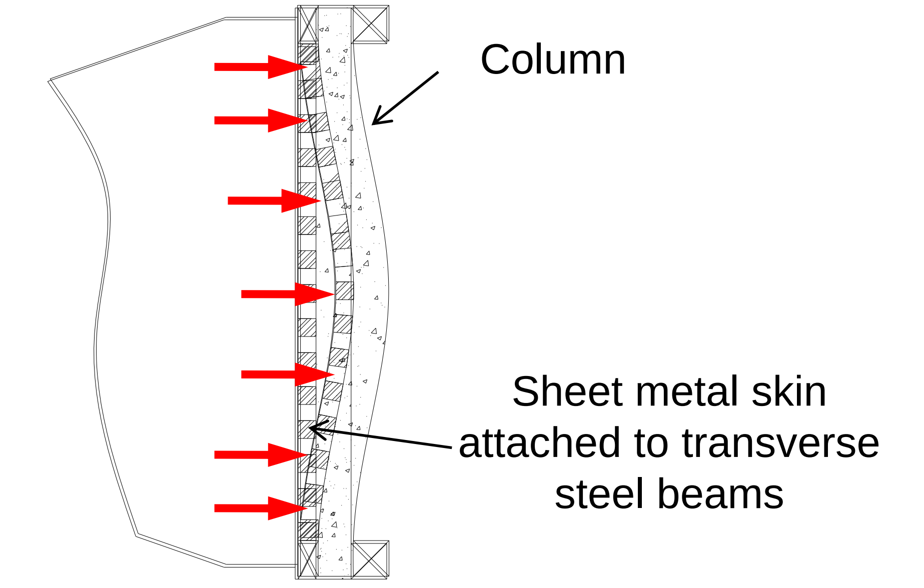
- Near instantaneous rise time
- Exponential decay over very short duration

Load Transferring Device

Converting Pressure to Load

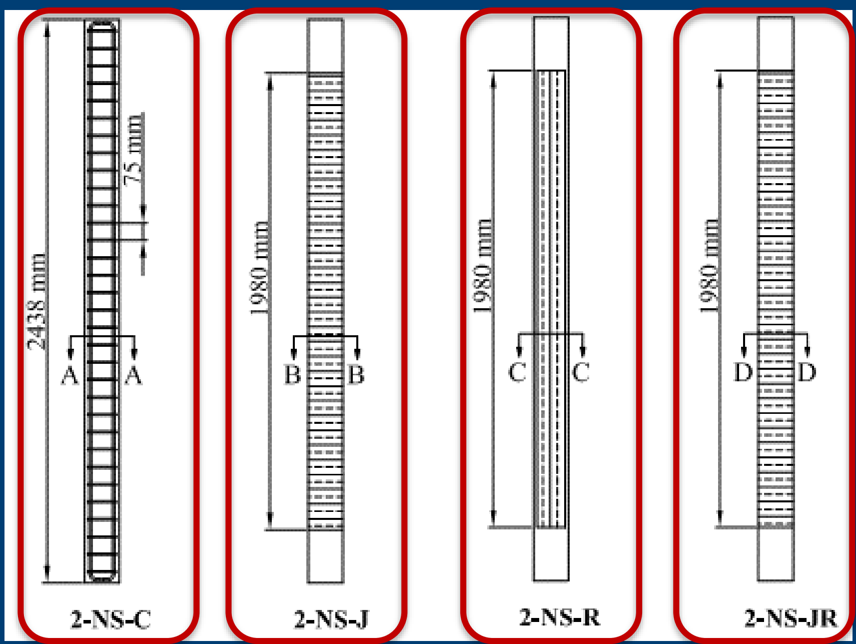
- Collect pressure
- Transfer to column as a UDL
- Increase mass of system
- Increase tributary loaded area
- Reduce venting and ‘wrap around’

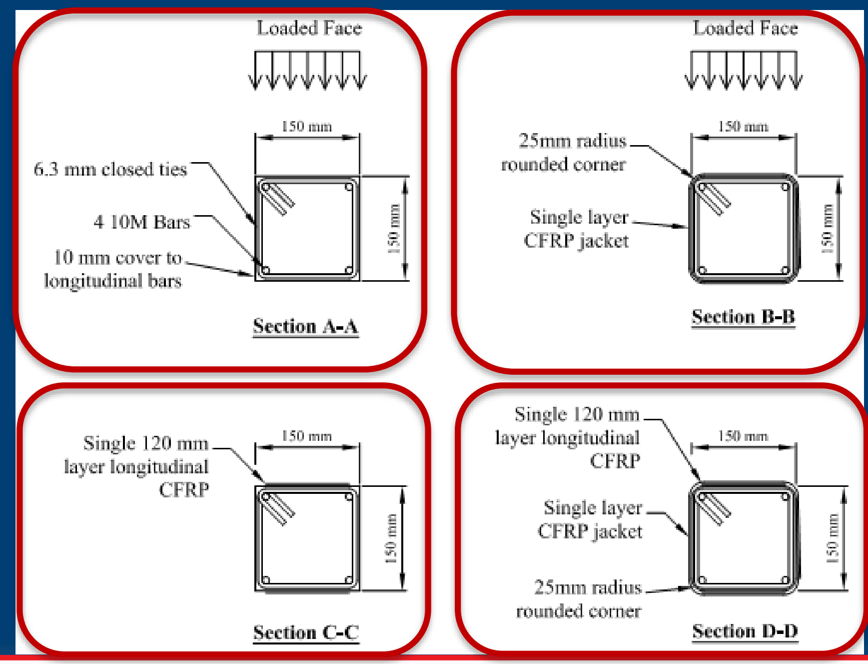




Group 2 Columns – Non-Seismic Detailing

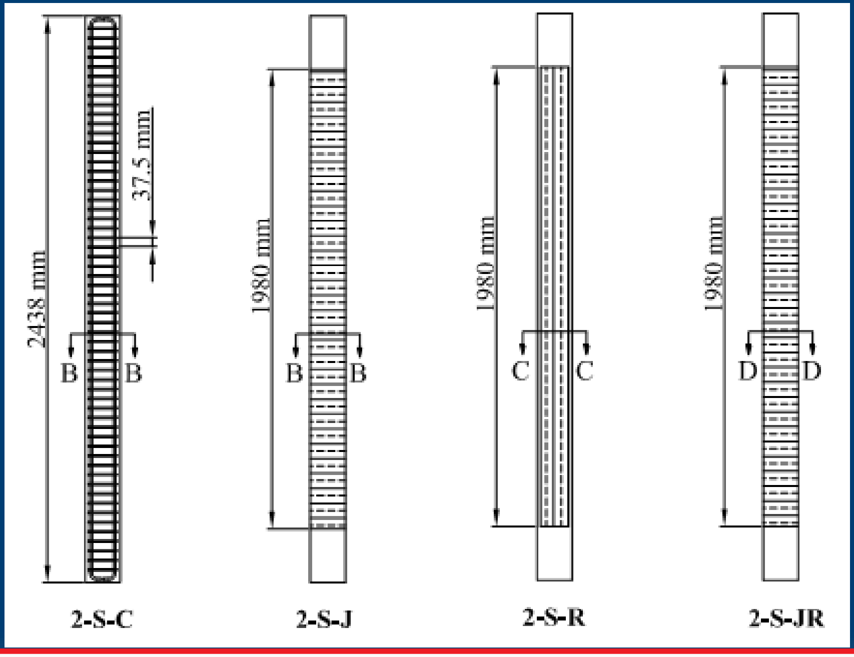
- Control Column – 2-NS-C
- CFRP Jacketed Column – 2-NS-J
- Longitudinal CFRP Column – 2-NS-R
- Longitudinal and Jacketed CFRP – 2-NS-JR

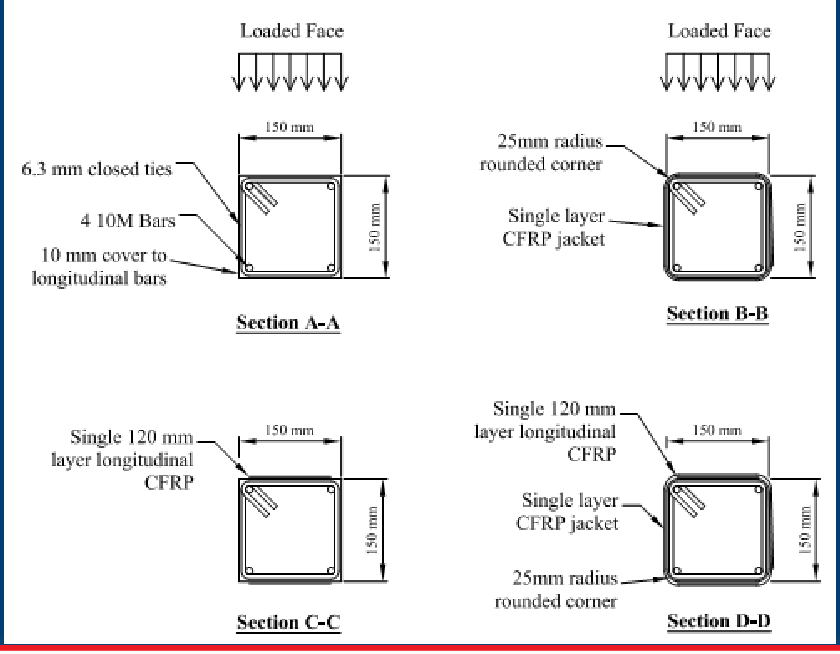




Group 2 Columns – Seismic Detailing

- Control Column – 2-S-C
- CFRP Jacketed Column – 2-S-J
- Longitudinal CFRP Column – 2-S-R
- Longitudinal and Jacketed CFRP – 2-S-JR





Details of Columns Tested

Group	Name	Cross Section Width	Cross Section Height	Longitudinal Reinforcement Ratio	Spacing of Transverse Reinforcement	f'_c	F_y	P/P_o	Retrofit Details
		mm	mm	%	mm	MPa	MPa	%	
1	1-NS-C	150	100	2.67	50	58	483	35.6	-
	1-S-C	150	100	2.67	25	58	483	35.6	-
	1-NS-J	150	100	2.67	50	56.2	483	36.7	FRP Jacket
	1-S-J	150	100	2.67	25	56.2	483	36.7	FRP Jacket
2	2-NS-C	150	150	1.78	75	69.6	483	25.1	-
	2-S-C	150	150	1.78	37.5	69.6	483	25.1	-
	2-NS-J	150	150	1.78	75	69.6	483	25.1	FRP Jacket
	2-S-J	150	150	1.78	37.5	69.6	483	25.1	FRP Jacket
	2-NS-R	150	150	1.78	75	69.6	483	25.1	FRP Reinforcement
	2-S-R	150	150	1.78	37.5	69.6	483	25.1	FRP Reinforcement
	2-NS-JR	150	150	1.78	75	69.6	483	25.1	FRP Jacket and Reinforcement
	2-S-JR	150	150	1.78	37.5	69.6	483	25.1	FRP Jacket and Reinforcement
3	3-NS-C	150	150	1.78	75	49.5	497	31.3	-
	3-NS-W	150	150	1.78	150	49.5	497	34.7	Prestressed Steel Jacket
	3-NS-CB	150	150	1.78	75	49.5	497	34.7	Compression Brace
	3-NS-TB1	150	150	1.78	75	49.5	497	34.7	Tension Brace
	3-NS-TB2	150	150	1.78	75	49.5	497	34.7	Tension Brace
	3-NS-TB3	150	150	1.78	75	49.5	497	11.6	Tension Brace

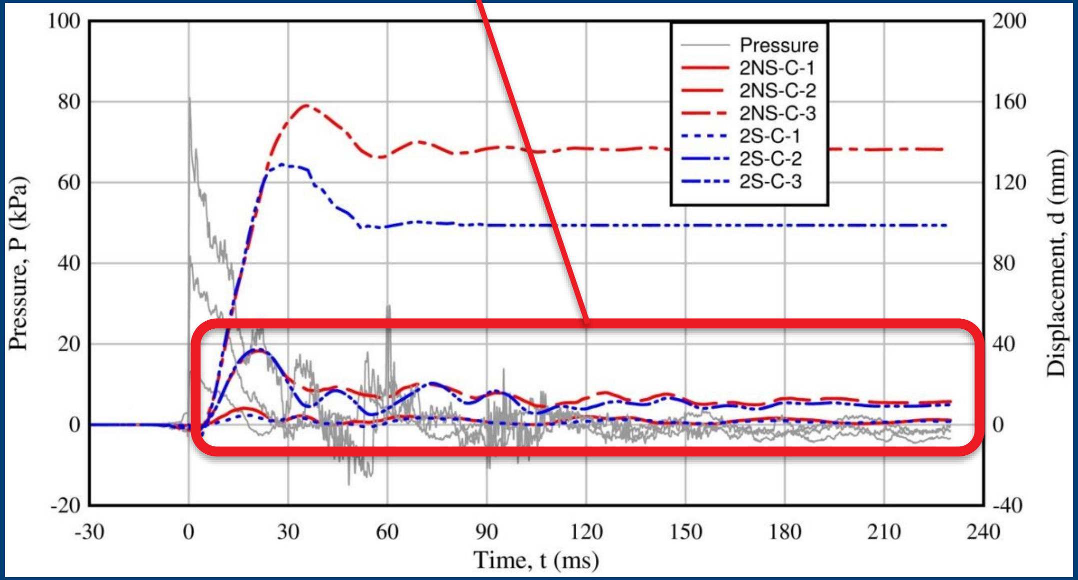
Control Columns

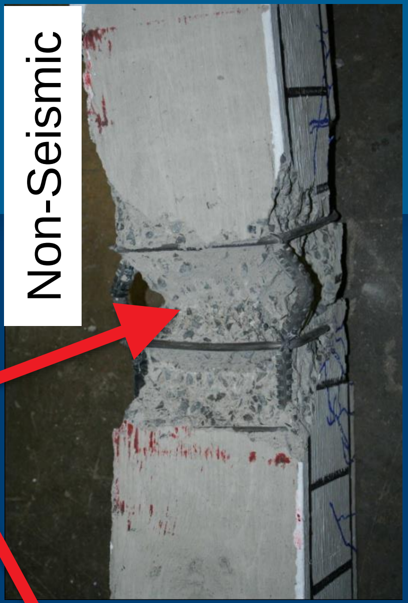
Non-Seismic Column

Seismic Column

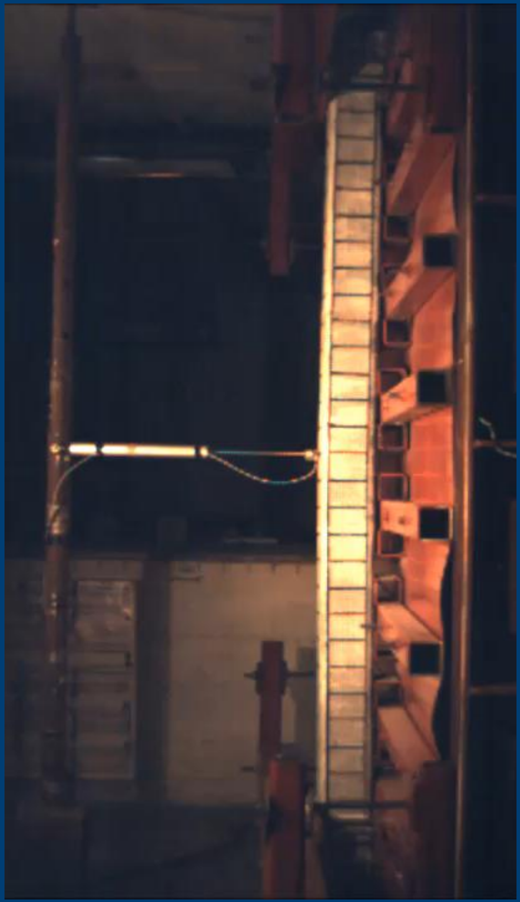
Control Columns

- Similar response in elastic tests
- Bar buckling prevention with seismic detailing
- Minimal core concrete loss with seismic





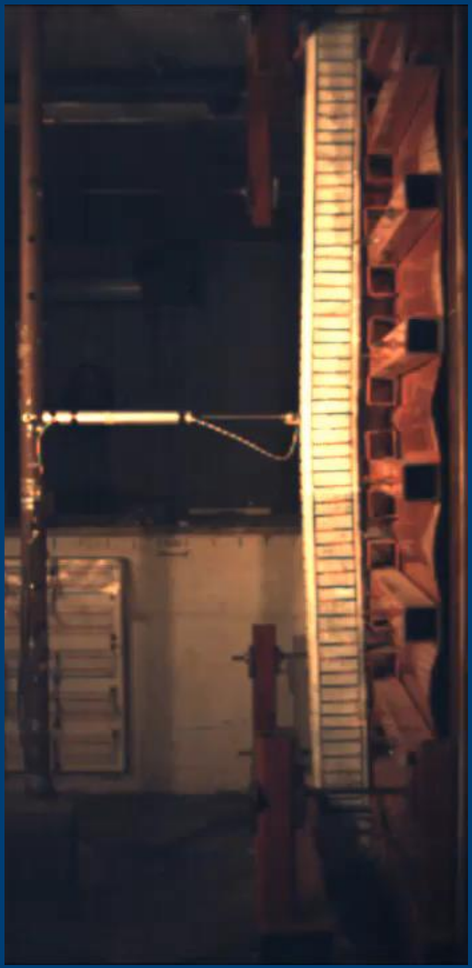
FRP Jacketed Columns

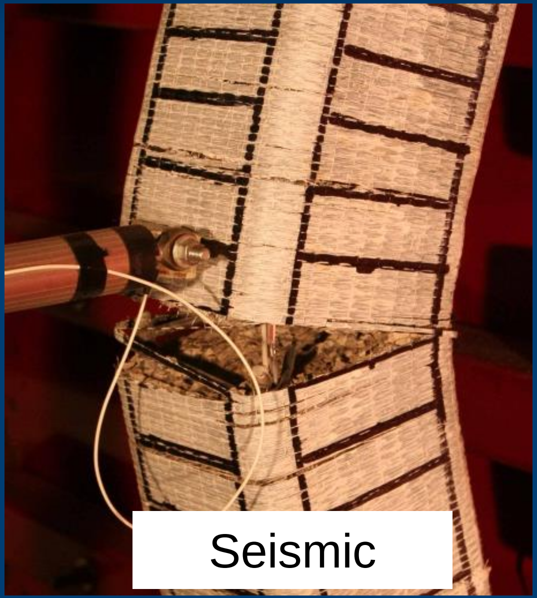


Non-Seismic Column

Seismic Column

Jacketed Columns High Pressure Test

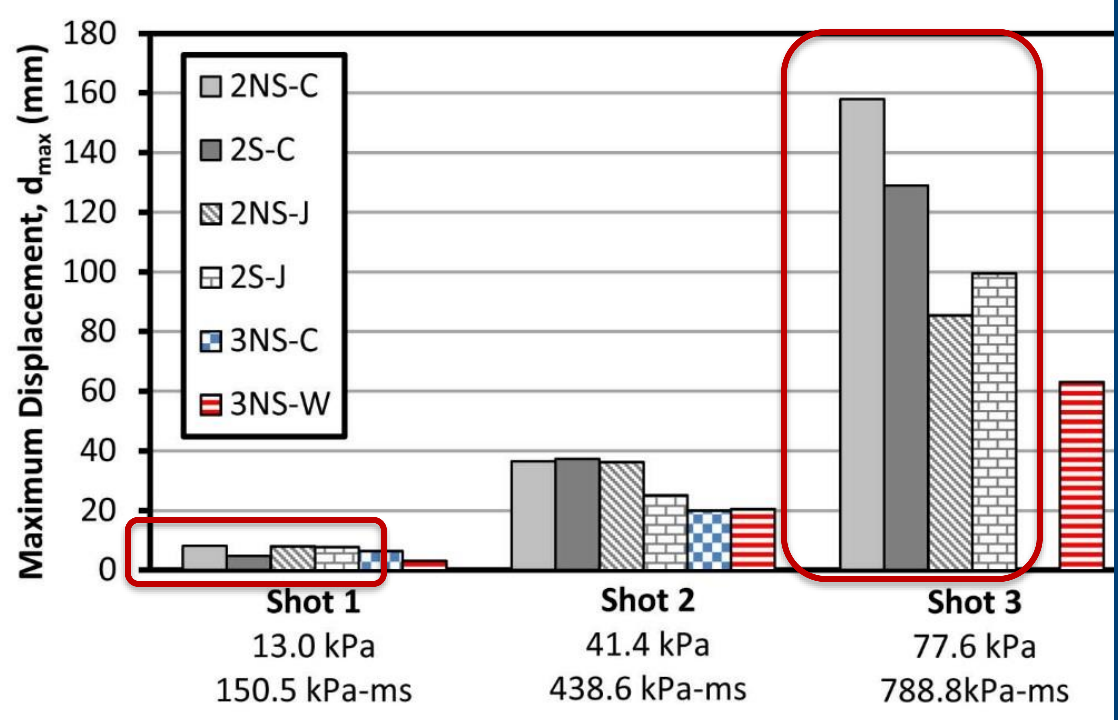




- Buckling and concrete compression failure prevented
- Failure due to rebar rupture

Maximum Displacement of Jacketed Columns

- No real change in elastic response
- Moderate reduction in maximum displacement for high damage

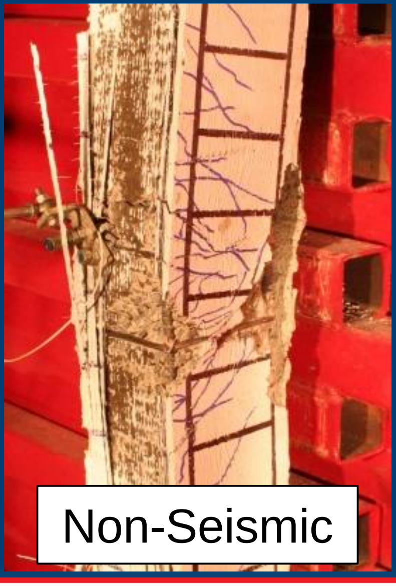


Longitudinal FRP Reinforced Columns

Non-Seismic

Seismic

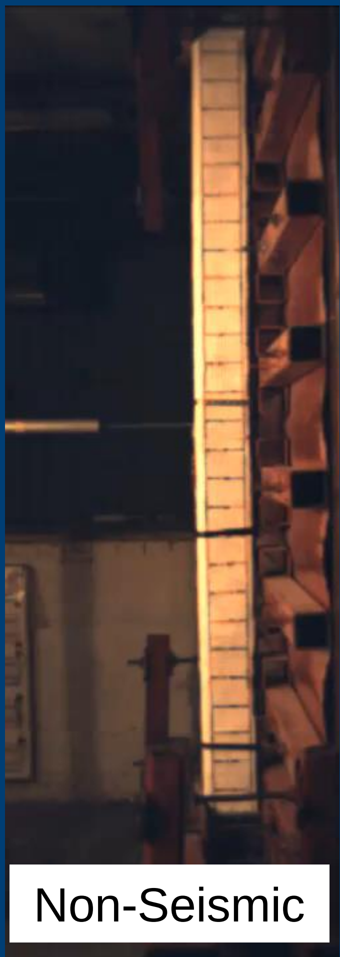
- Brittle failure mode of FRP debonding
- Post-debond damage to columns similar to control columns

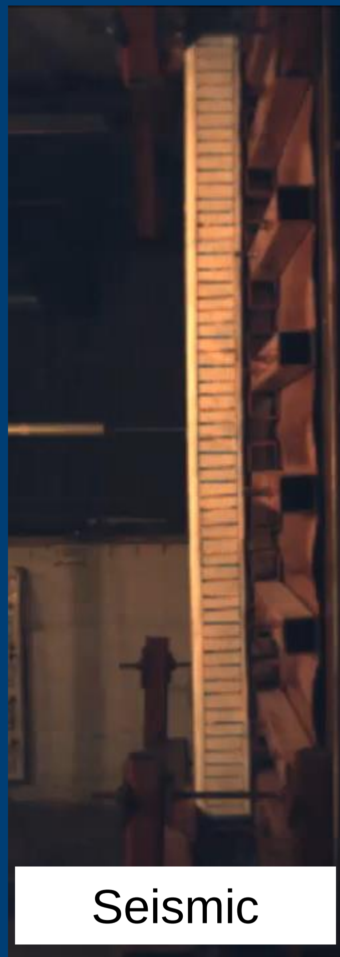


Non-Seismic

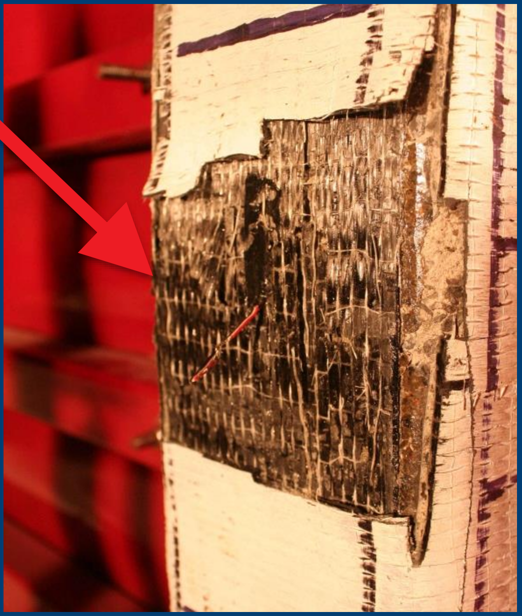
Seismic

Longitudinal and Jacketed FRP Columns

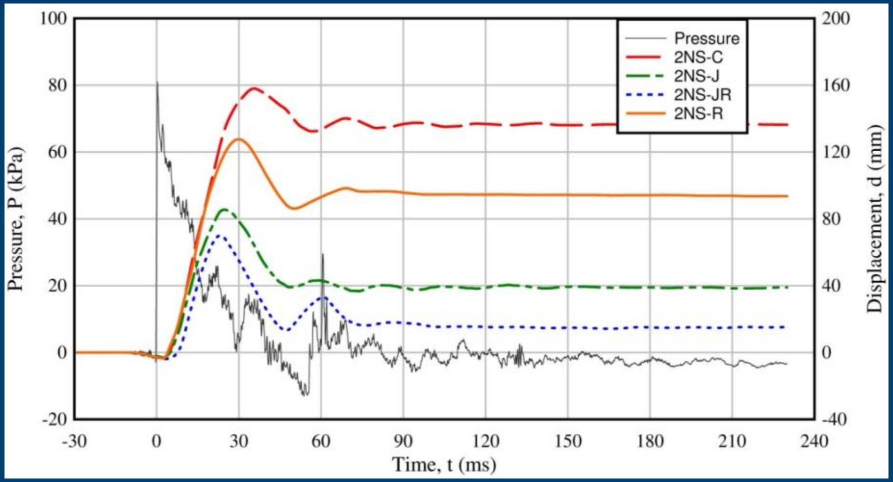




- Limited deflection
- Bar buckling and concrete compression failure prevented
- Longitudinal FRP rupture



Summary of FRP Performance



- The combination of longitudinal strengthening and FRP jacketing showed the best performance
- However, this is not the end of the story

Performance

- 2NS-JR
- 2NS-J
- 2NS-R
- 2NS-C

BEST

WORST

A Canadian Blast Retrofit Perspective

CSA Group

S850-12

Design and assessment of buildings subjected to blast loads

CSA STANDARDS

S806-12

Design and construction of building structures with fibre-reinforced polymers

The use of FRP to retrofit reinforced concrete columns in Canada

Standard Levels of Protection (LOP)

- LOPs are selected based on design objectives
- LOPs are achieved by limiting member response

Table 4.1
LOP damage description for building elements
(See Clauses 4.3.3, 4.3.4, 4.4.1.1, and A.4.5)

LOP	Building perform-ance (Clause 4.4.2)	Building component damage levels				
		Components (Clause 4.4.3)			Glazing* (Clause 4.4.4.2)	Doors† (Clause 4.4.4.3)
		Primary structural	Secondary structural	Non-structural‡		
Very Low (VL)	Collapse prevention	Heavy	Hazardous		Low hazard rating	Failure
Low (L)	Life safety	Moderate	Heavy		Very low hazard rating	Category IV
Medium (M)	Immediate occupancy	Superficial	Moderate		Minimal hazard rating	Category III
High (H)	Operational	Superficial			No break	Category I or II

Columns should be on the higher end of LOP

Response Limits

- Flexure members design based on displacement levels (support rotation)
- Column design based on ductility capacity
- Higher ductility allowed for seismic columns

Table 4.3
Response limits for reinforced concrete*
(See Clauses 4.5.2, 9.1.9, and A.4.5 and Table 4.8.)

Element type		B1		B2		B3		B4	
		μ_{max}	θ_{max}	μ_{max}	θ_{max}	μ_{max}	θ_{max}	μ_{max}	θ_{max}
Flexure	Single-reinforced slab or beam†	1	—	—	2°	—	5°	—	10°
	Double-reinforced slab or beam without shear reinforcement‡§	1	—	—	2°	—	5°	—	10°
	Double-reinforced slab or beam with shear reinforcement‡	1	—	—	4°	—	6°	—	10°
	With tension membrane**	1	—	—	6°	—	12°		20°

Table 4.3 (Concluded)

Element type		B1		B2		B3		B4	
		μ_{max}	θ_{max}	μ_{max}	θ_{max}	μ_{max}	θ_{max}	μ_{max}	θ_{max}
Combined flexure and axial compres-sion	Single-reinforced beam-column†	1	—	—	2°	—	2°	—	2°
	Double-reinforced beam-column without shear reinforcement‡§	1	—	—	2°	—	2°	—	2°
	Double-reinforced beam-column with shear reinforcement‡	1	—	—	4°	—	4°	—	4°
	Wall or seismic column††	0.9	—	1	—	2	—	3	—
	Nonseismic column††	0.7	—	0.8	—	0.9	—	1	—

Response Limits with FRP

- Higher ductility capacities for FRP confined columns than seismic columns
- FRP strengthening limits not currently defined

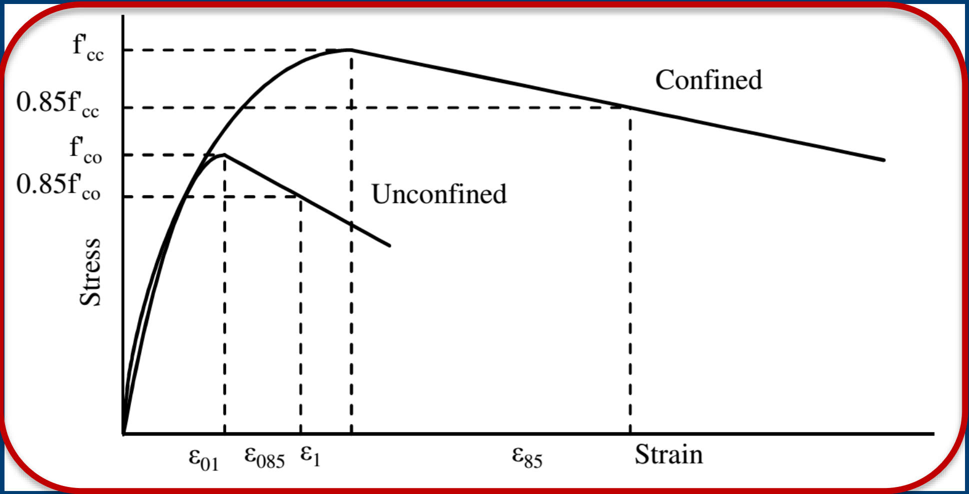
Table 4.9
Response limits for FRP composites*
(See Clauses 4.5.2, 9.1.9, and A.4.5.)

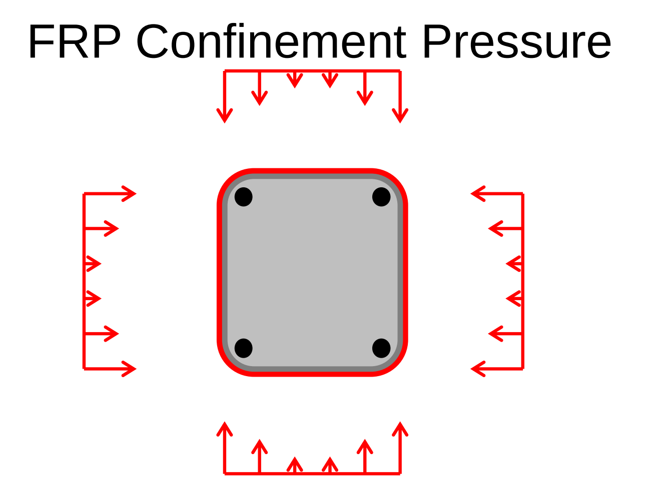
Element type	B1		B2		B3		B4	
	μ_{max}	θ_{max}	μ_{max}	θ_{max}	μ_{max}	θ_{max}	μ_{max}	θ_{max}
FRP confined columns	1	—	3	—	6	—	6	—
FRP strengthened elements	No response limits are provided in this Standard†							

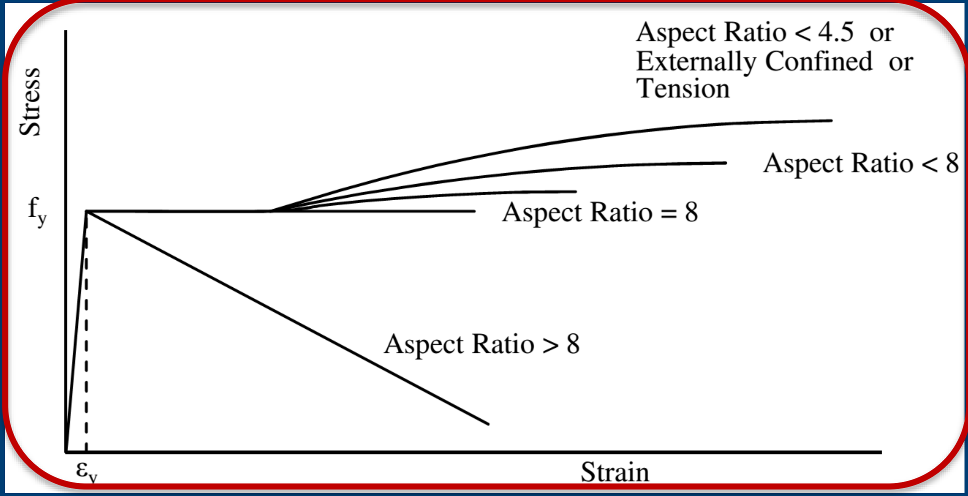
* *Where a dash (—) is shown, the corresponding parameter is not applicable as a response limit.*
† *1.0 may be used for all μ_{max} response limits until further information becomes available.*

Column Confinement

- Increase in concrete compression strength and ductility
- Prevention of compression reinforcement buckling

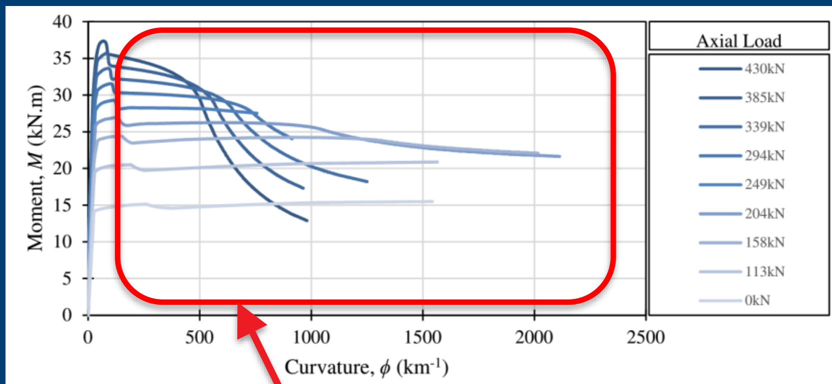


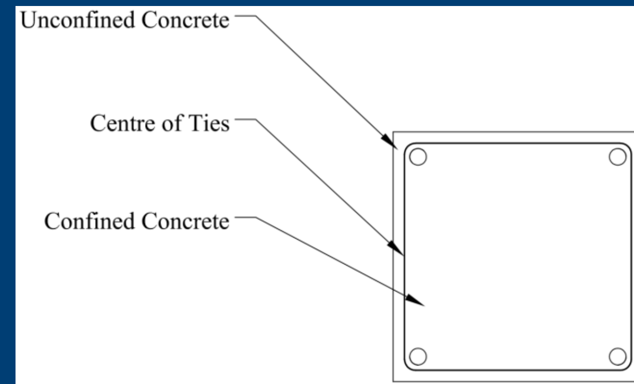




Concrete Confinement

No FRP Jacket

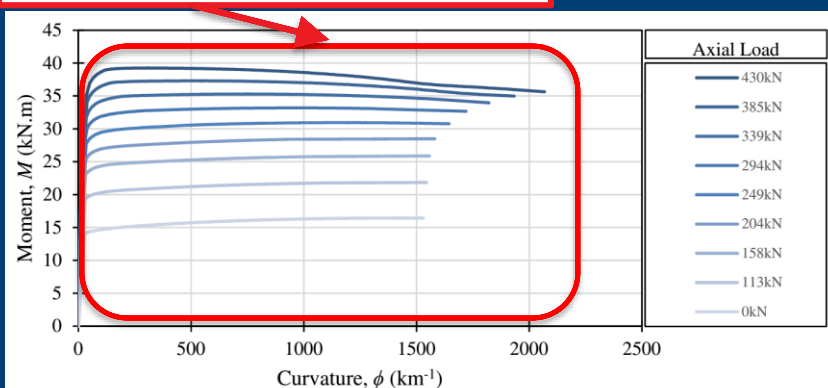


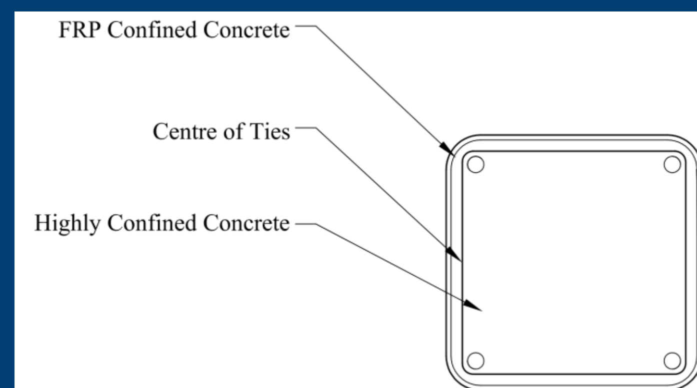


Low Ductility Capacity

High Ductility Capacity

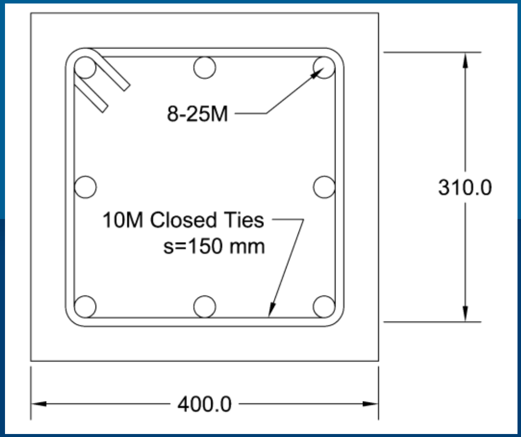
FRP Jacket



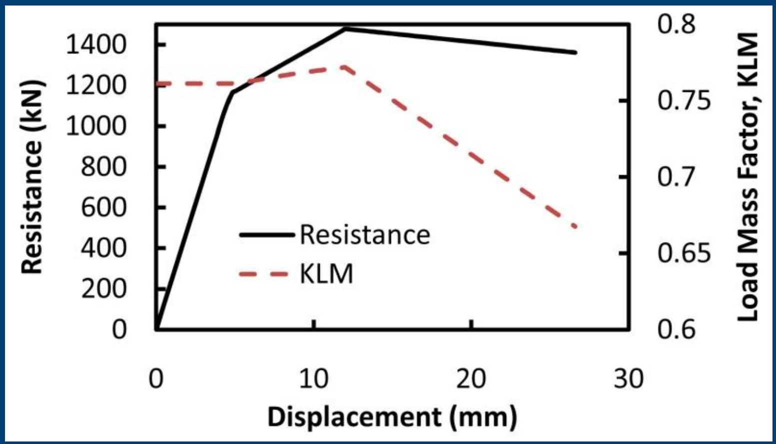


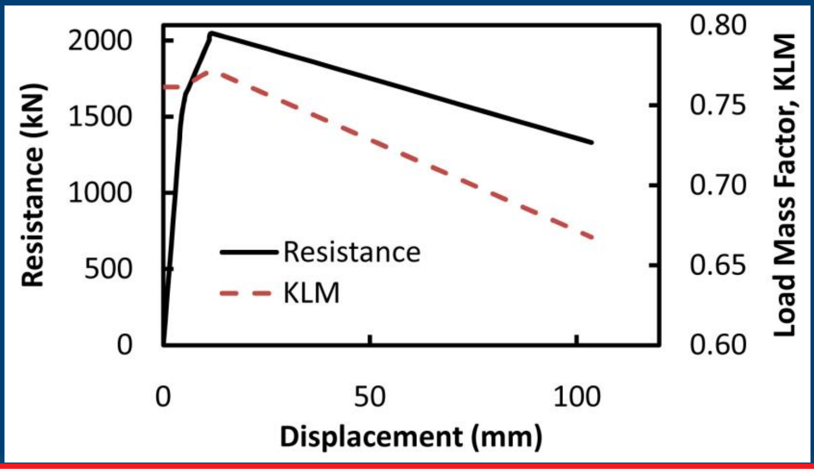
Column Capacity

Length :	3500 mm
Supports :	Fully Fixed
f'_c :	40 MPa
F_y :	400 MPa
F_{yh} :	400 MPa
P/P_o :	0.4

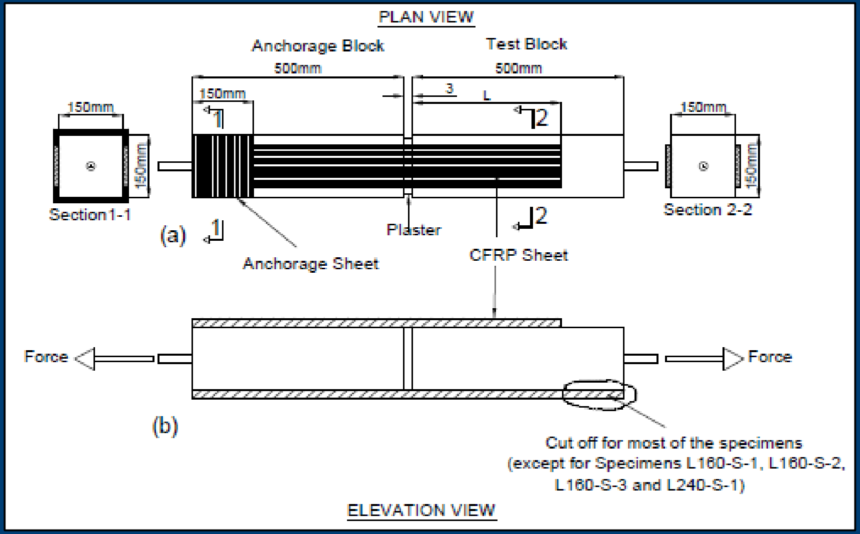


As-Built		FRP Jacket
Low	**Moment Capacity**	High
Low	**Ductility Capacity**	High





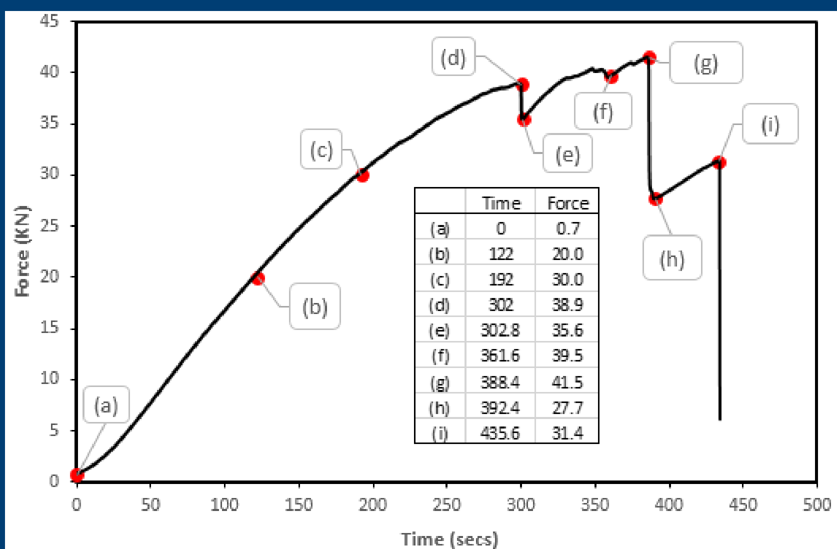
FRP Bond Under High Strain Rates

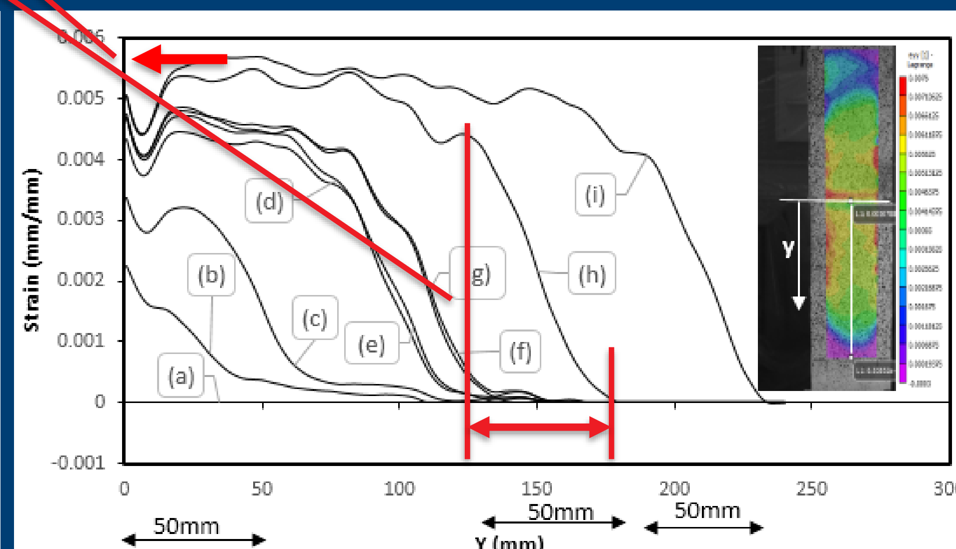


Static Testing

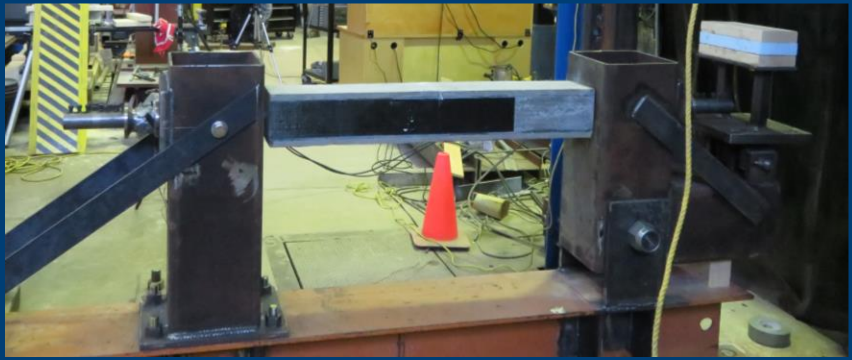
- Debonding strains between 0.45% and 0.70%
- Development length measured to be approximately 50mm

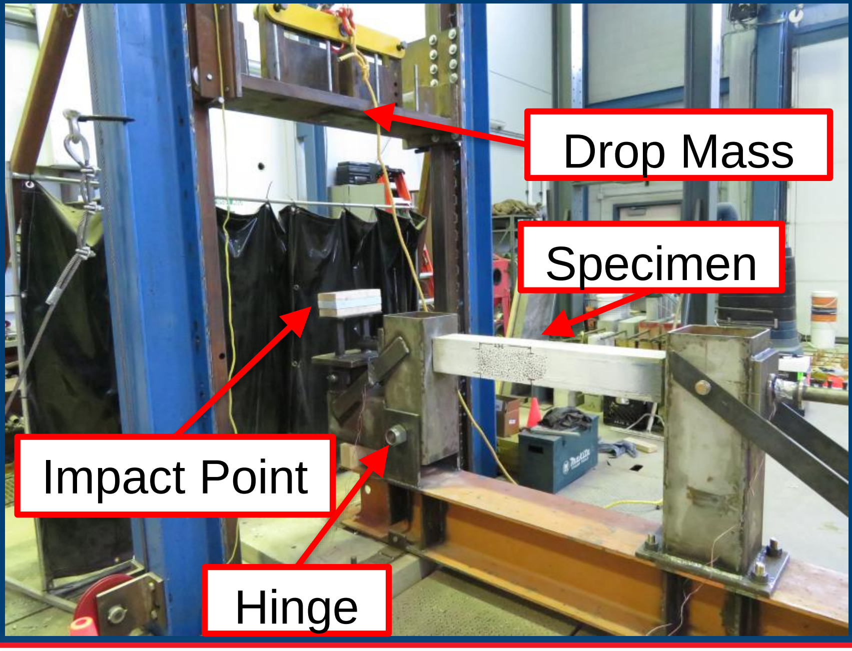
Longitudinal Strain (%)		
Individual	Average	Variance
0.52	0.54	0.0062
0.64		
0.55		
0.45		
0.70	0.64	0.0029
0.65		
0.65		
0.57		
0.57	0.57	0.0023
0.54		
0.52		
0.63		

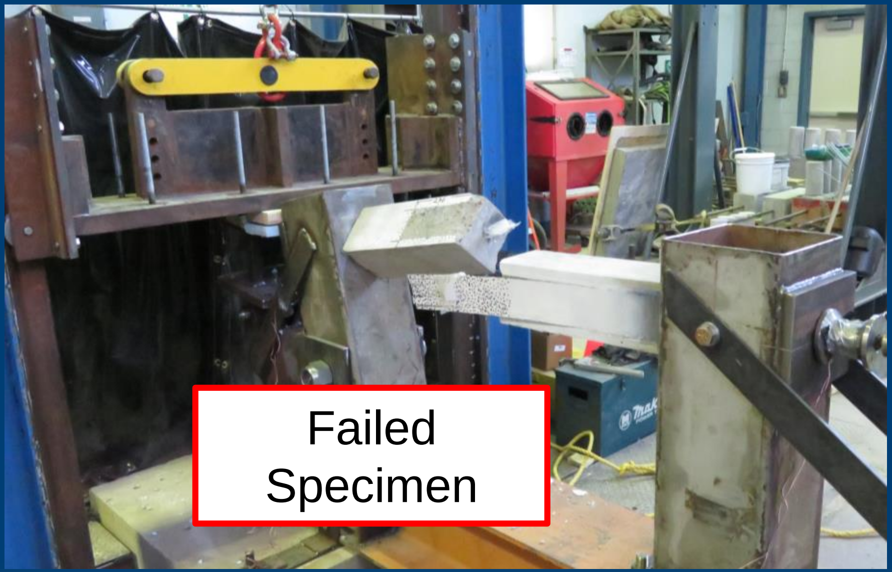




Impact Testing







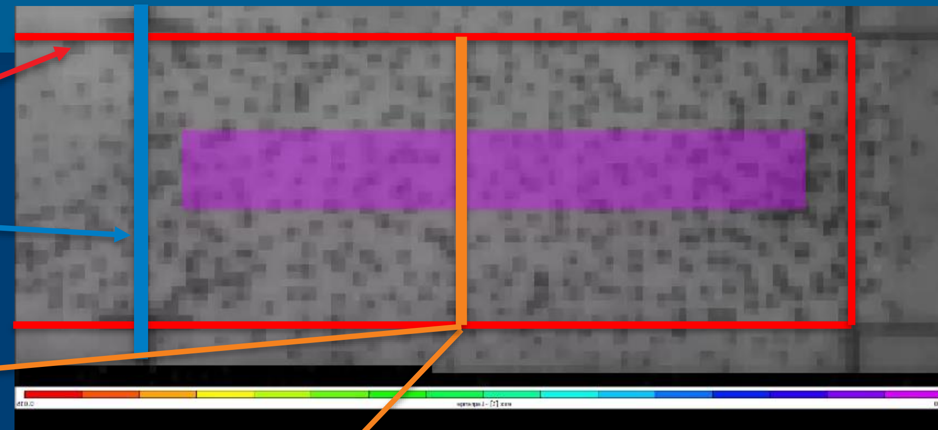
Impact Response

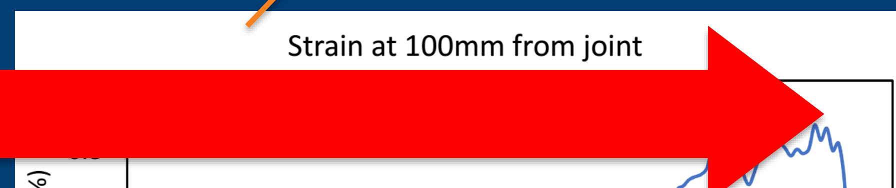
Optical Measurement of Longitudinal Strain

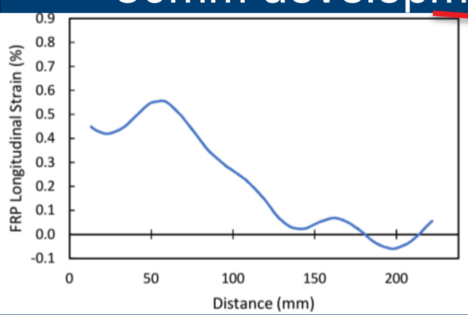
- Playback at 4000 times slower than real time
- Boundary between prisms
- Bounds of FRP
- Stain vs. time and strain rate measured 100mm from joint
- Progression of debonding working away from joint

Time

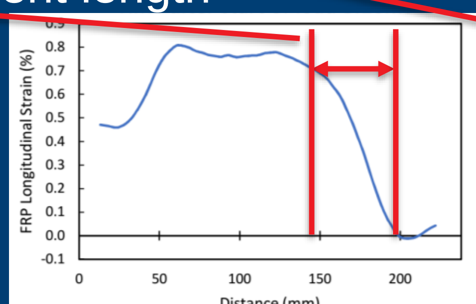
50mm development length



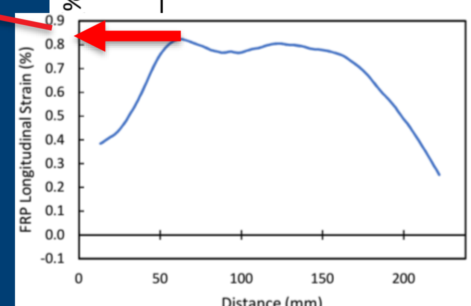




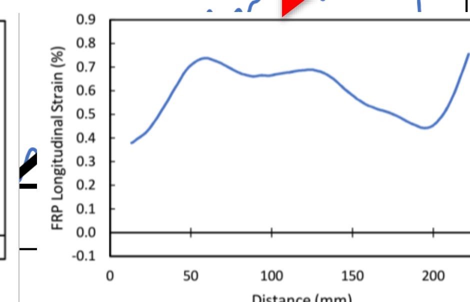
Bonded



Bonded



Bonded



At Failure

High Strain Rate Response of FRP

- Test are too preliminary to draw conclusions
- Potential increase in FRP bond stress under high strain rates
- For the above specimen

$\varepsilon_{max,dynamic}$	0.82%
$\varepsilon_{max,static}$	0.64%
$\dot{\varepsilon}$	$3.5\ to\ 5.5s^{-1}$
$DIF = \frac{\varepsilon_{max,dynamic}}{\varepsilon_{max,static}}$	1.28

Conclusions

- FRP jackets can enhance ductility and allow for higher design limits
- FRP strengthening should be used with care as brittle failure modes can occur
- FRP bond potentially has a dynamic increase factor allowing for higher FRP strains under high strain rates