Seismic Evaluation and Retrofit of Beam-Column Joints of Mid-American Bridges Part 1: Fiber Reinforced Polymer Retrofit

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Research Objectives

Develop a Comprehensive Research Program to Establish the Seismic Retrofit of a Beam/Column Joint According to Modern Seismic Design Principles Using CFRP Systems

- Plastic hinges to form at the ends of the columns
- Beams protected against any significant flexural or shear inelastic actions
- Beam/column joints retrofitted in order to minimize inelastic rotations in the beam/column joint regions

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Current Design Deficiencies

Plastic Hinges Can Form Either in the Beams or Joints under Moderate Seismic Events

- *Excessive* - Column flexural reinforcement
- *Inadequate* - Column shear reinforcement
- *Inadequate* - Beam shear reinforcement
- *Inadequate* - Beam flexural reinforcement
- *Inadequate* - Joint shear reinforcement

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Evaluation of Bridge Structures

A) Column
- A-1) Ductile Flexural Response
- A-2) Brittle Shear Response
- A-3) Confinement of Plastic Hinge
- A-4) Buckling of Longitudinal Reinforcement

B) Bent Cap
- B-1) Ductile Flexural Response
- B-2) Brittle Shear Response

C) Bent/Cap Joint
- C-1) Brittle Crushing of Diagonal Compression Strut
- C-2) Brittle Joint Shear Failure with Reinforcement Pullout

Performance Levels for a Typical Bent Cap/Column-bent Connection

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Evaluation of Bridge Structures

Bridge #	Year Built	Main Span Length	Girder Type	No. of Bents	No. of Columns/Bent
(#)	(Year)	(feet)	(type)	(#)	(#)
A-1466	1966	68	Steel Continuous	5	2
A-1931	1969	52	Steel Continuous	4	2
A-1938	1969	95	Steel Continuous	5	3
A-2024	1970	112	Steel Continuous	5	3
A-2332	1968	65	Steel Continuous	6	2
A-2333	1968	72	Steel Continuous	6	2
A-2334	1968	70	Steel Continuous	8	2
A-2336	1968	65	Steel Continuous	6	2
A-2427	1968	93	Steel Continuous	5	3
A-2429	1968	90	Steel Continuous	5	4
A-2430	1971	113.75	Steel Continuous	4	3
A-3478	1976	75	Steel Continuous	4	4
A-2428	1968	87	Steel Continuous	5	3

Evaluation of Bridge Structures

Bridge #	Bent Cap		Column
	Flexural Failure	Joint Shear Failure	Column Shear
(#)	(PASS/ FAIL)	(PASS/ FAIL)	(PASS/ FAIL)
A-1466	FAIL	PASS	PASS
A-1931	PASS	MARGINAL	PASS
A-1938	PASS	MARGINAL	PASS
A-2024	PASS	MARGINAL	FAIL
A-2332	PASS	FAIL	MARGINAL
A-2333	PASS	MARGINAL	MARGINAL
A-2334	PASS	MARGINAL	MARGINAL
A-2336	PASS	FAIL	MARGINAL
A-2427	FAIL	PASS	PASS
A-2429	PASS	FAIL	PASS
A-2430	PASS	FAIL	PASS
A-3478	FAIL	FAIL	MARGINAL
A-2428	FAIL	FAIL	FAIL

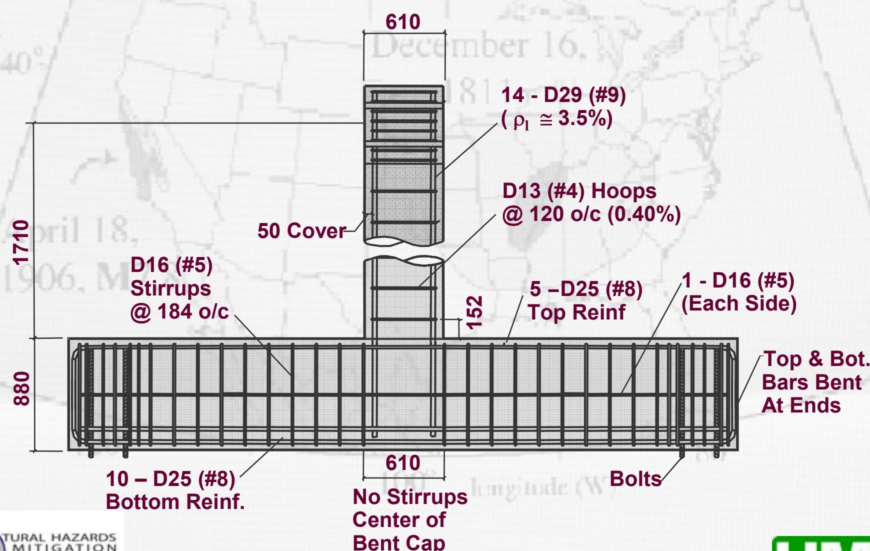
Test Matrix

Design of Two Test Units for Evaluation of Retrofit of Beam/Column Systems Using Carbon-FPP Composites

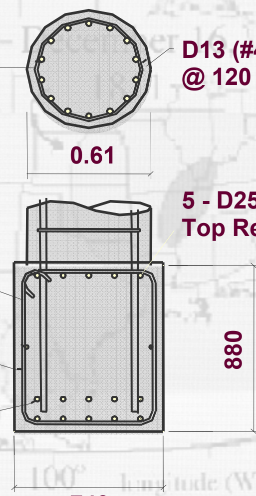
- **Unit 1 – Incremental retrofit at different performance levels**
- **Unit 2 – Complete retrofit before testing**

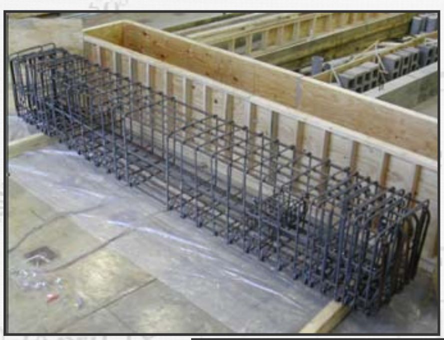
Prototype Structure

Longitudinal Section

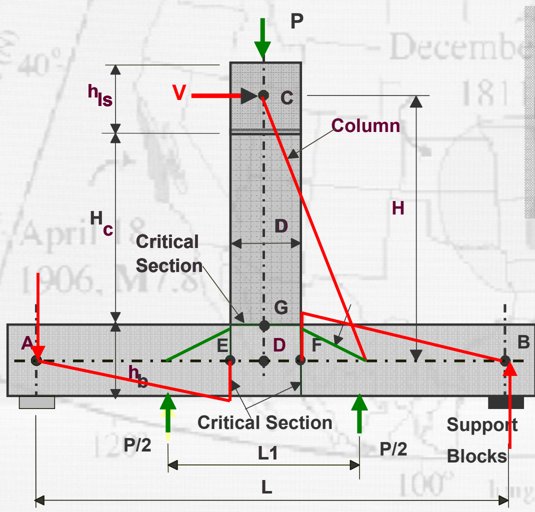


Beam & Column X-Sections





Demand Evaluation



$$M_B^{cr} = \begin{cases} \dfrac{M_C^o}{2} \cdot \dfrac{H}{L} \cdot \dfrac{(L-D)}{\left(H - \frac{h_b}{2}\right)} + \\ \dfrac{P \cdot (L_1 - D)}{4} \end{cases}$$

$$V_B^{cr} = \begin{cases} \dfrac{M_C^o}{L} \left(\dfrac{H}{H - \frac{h_b}{2}} \right) + \\ \dfrac{P}{2} \end{cases}$$

Material Properties

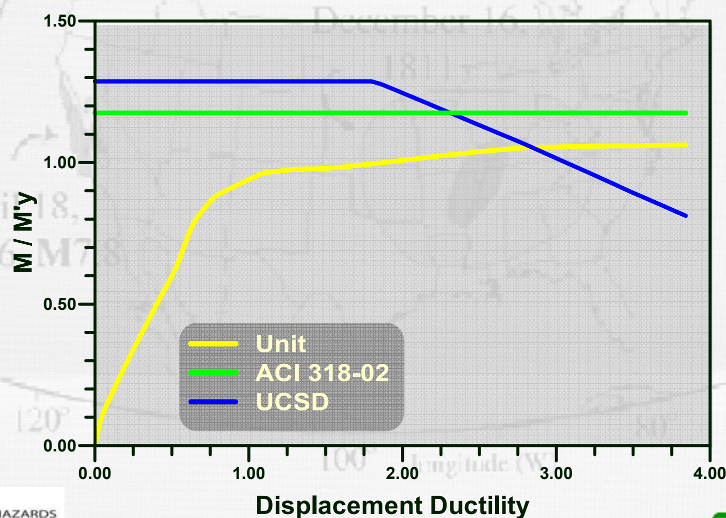
Concrete

		28 Day Strength	Strength at Time of Testing
		(psi)	(psi)
Specimen #1	Beam	5026	5342
	Column	3525	3697
Specimen #2	Beam	4216	4609
	Column	4993	5419

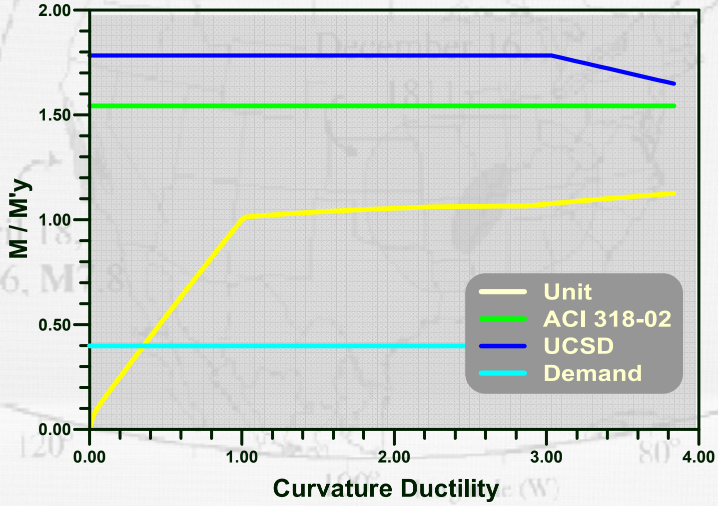
Steel Rebar

Bar #	Yield Strength (ksi)
4	87
5	60
8	80
9	78

Column Shear Capacity Evaluation

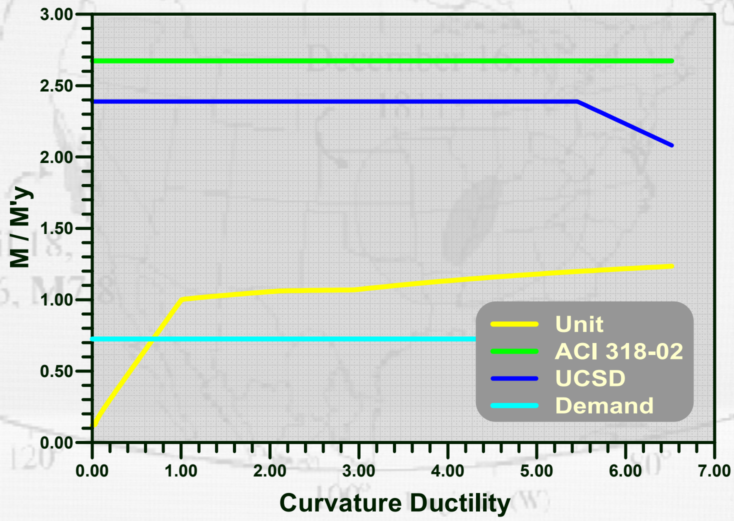


Beam Shear Capacity Evaluation



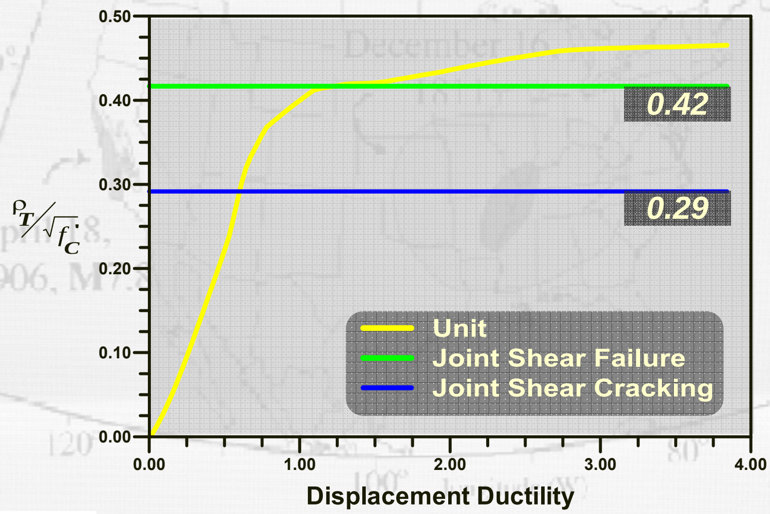
Negative Moment

Beam Shear Capacity Evaluation



Positive Moment

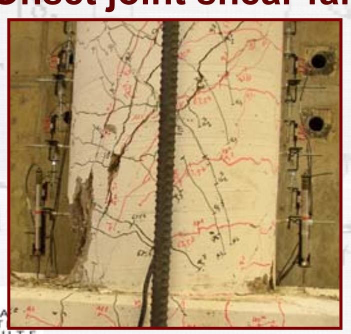
Joint Principle Stresses Evaluation



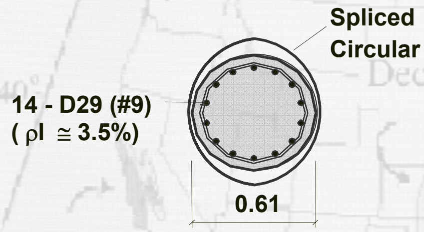
Principal Tensile Stresses

Predicted Seismic Response Un-strengthened System

1. **Column shear failure at μ_Δ < 3 or onset of column cover concrete spalling**
2. **Onset joint shear failure at μ_Δ > 2**



Column Retrofit

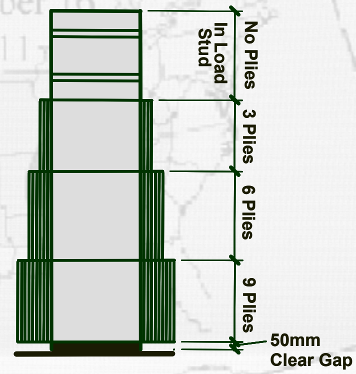


Shear (2 Plies)

$$t_j = \frac{V^{o}/\varphi_S - (V_C + V_S + V_P)}{0.5\,\pi\, f_{uj}\, D \cot\theta}$$

Confinement (9 Plies)

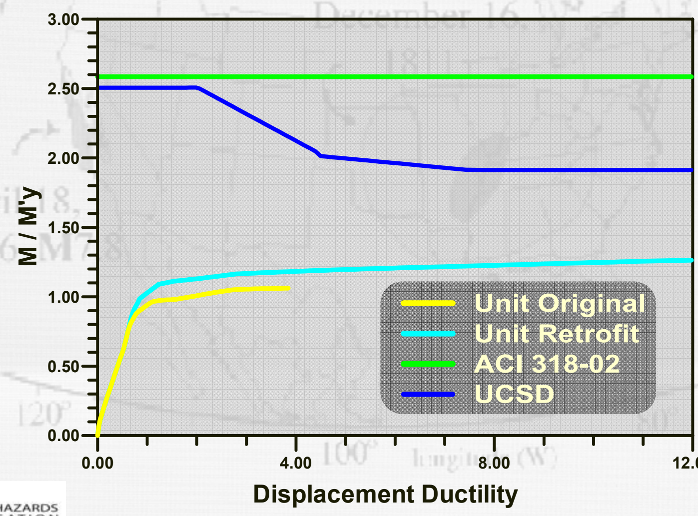
$$t_j = \frac{0.10\,(\varepsilon_{Cu} - 0.004)}{\varepsilon_{uj} f_{uj}} D f'_{CC}$$



Retrofit Design

Target μ_Δ=12.0

Column Retrofit Evaluation

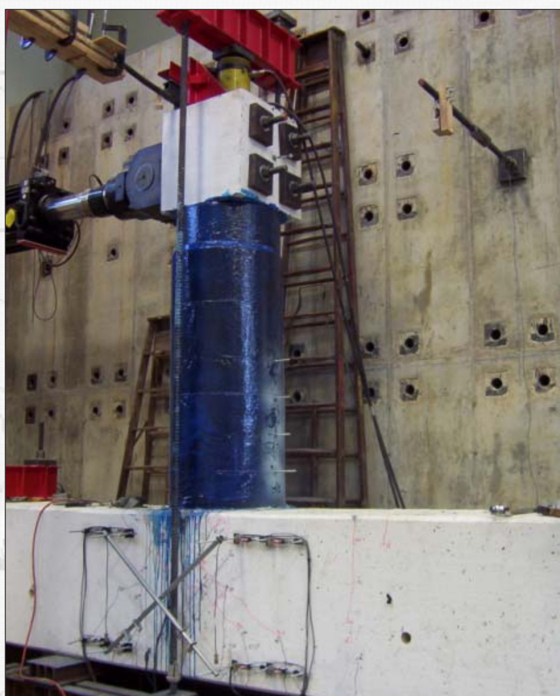


Material Properties

Carbon Fiber Reinforced Polymer (CFRP)

	Specimen # 1 and 2
Ultimate Tensile Strength	550 ksi
Ultimate Rupture Strain	1.67%
Tensile Modulus	33,000 ksi
Fabric Width	24 in.
Nominal Thickness	0.0065 in/ply

Column



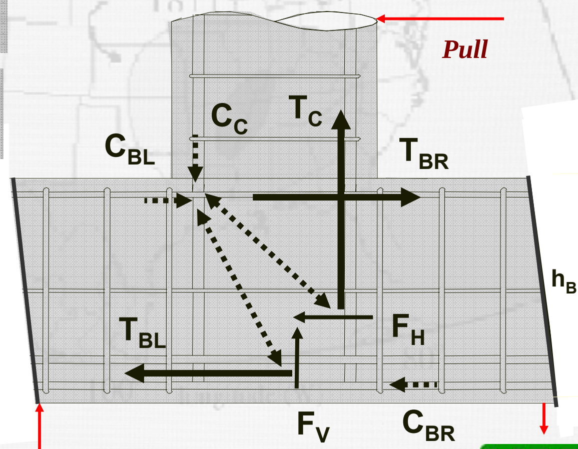
Retrofit

Joint Retrofit

$$F_{CFRP} = \sqrt{(F_H)^2 + (F_V)^2}$$

$$F_H = T_C\left(\frac{0.7D - 0.5c_U}{0.5h_b}\right)$$

$$F_V = T_B\left(\frac{D - 0.5c_U}{0.5D}\right)$$



Joint Retrofit (3 Plies)

$$n_j t_j = \frac{F_{CFRP}}{2}\frac{1}{w_j f_{uj}}$$

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Joint Retrofit

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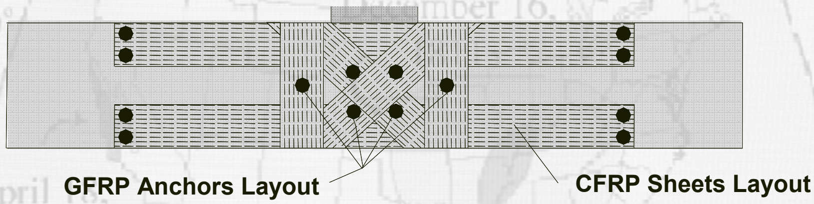
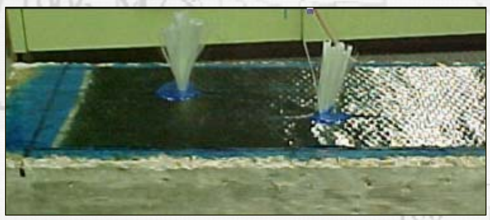
Unit 2 – Retrofit Specimen





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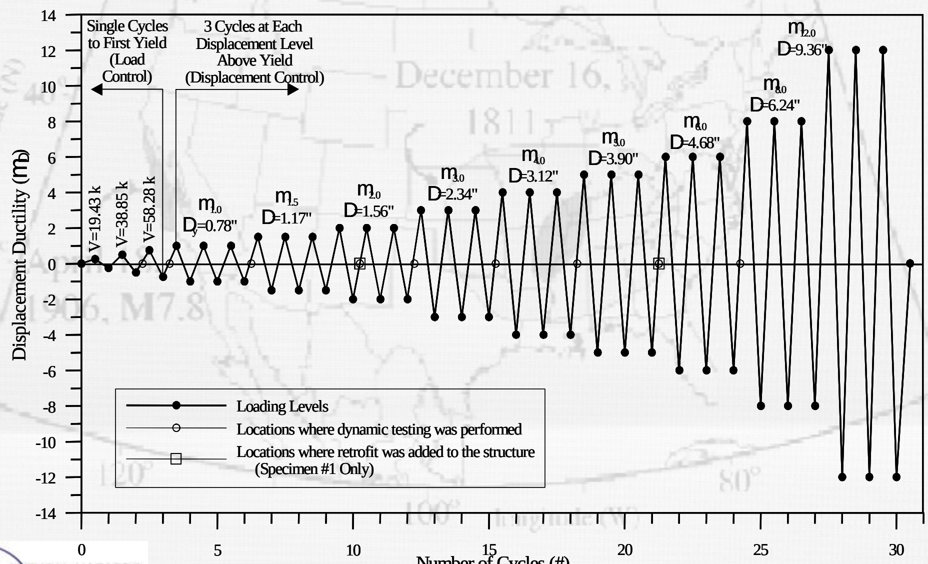
Experimental Results



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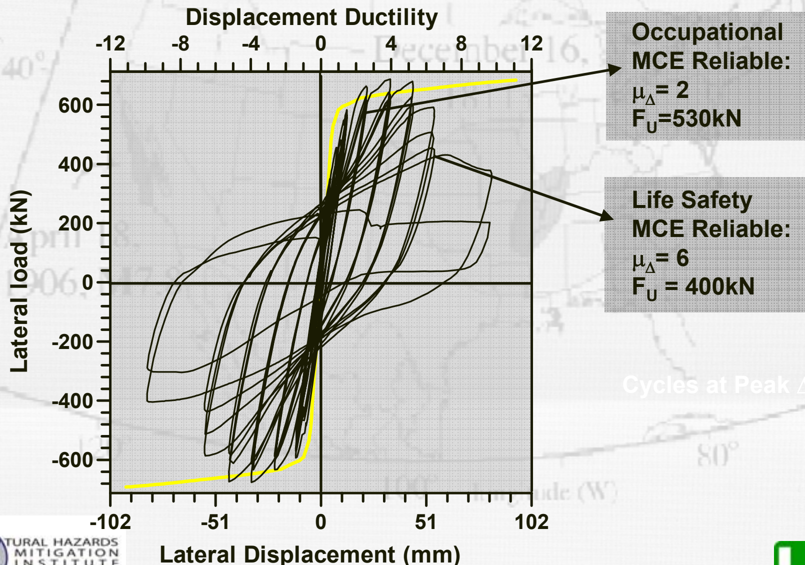
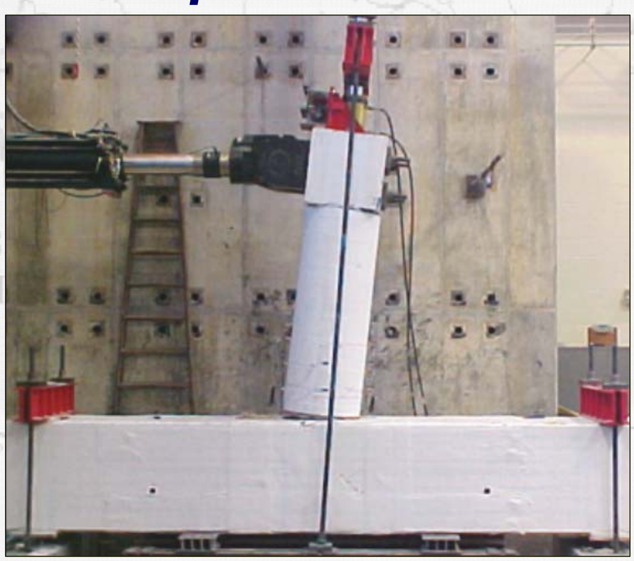
Unit 2: Experimental Results



Unit 2: Experimental Results



Unit 2 - Conclusions

- Column shear capacity was enhanced by applying CFRP sheets in the hoop direction
- Strengthening of the joint region was adequate in preventing joint shear failure
- Some level of strength degradation was observed in the joint region
- Main failure mode was characterized by fracture of the column long. reinforcement

Elastic Shear Forces

Distance From NMSZ (km)	SA %g	VE (kN)
1.60	2.99	2130
16.0	1.39	1000
160	0.91	650

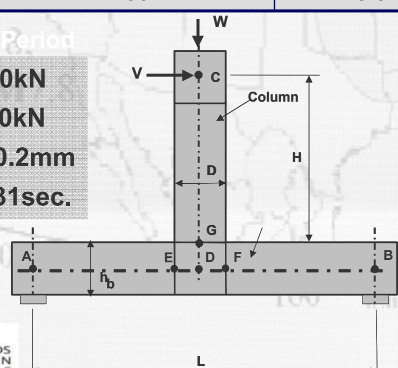
Natural Period

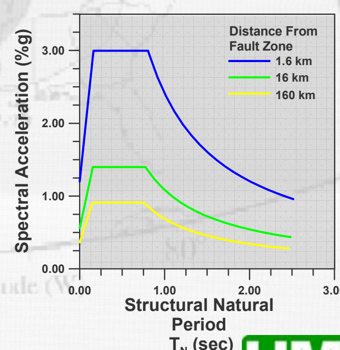
$W = 710kN$

$F_Y = 320kN$

$\Delta_Y = 10.2mm$

$T_N = 0.31sec.$





New Madrid Seismic Zone

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Seismic Demand

Distance From NMSZ (km)	Performance Objective	R	Demand (kips)	System Capacity (kips)
1.6	Life Safety	2.55	832	400
	Operational	1.31	1623	535
16	Life Safety	2.61	378	400
	Operational	1.32	752	535
160	Life Safety	2.66	240	400
	Operational	1.33	485	535

Life Safety
MCE Reliable:
$\mu_\Delta = 6$
$F_U = 400kN$

Occupational
MCE Reliable:
$\mu_\Delta = 2$
$F_U = 530kN$

Response Modification Factor

$$R = 1 + (\mu_\Delta - 1)\frac{T}{1.25\,T_s}$$

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Seismic Evaluation Conclusions

- Column shear capacity was enhanced by applying CFRP sheets in the hoop direction

  Adequate for any Seismic Level Hazard

- Strengthening of the joint region was adequate in preventing joint shear failure

  Life Safety: 16km from the NMSZ fault

  Operational: 160km from the NMSZ fault