Seismic Evaluation and Retrofit of Concentrically Braced Frames

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Lehigh NHERI Workshop 2016

UNIVERSITY *of* WASHINGTON

NCBFs IN THE FIELD

EERI Tohoku EQ Clearinghouse

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EERI Tohoku EQ Clearinghouse

Kelly et al. 2000

Research Motivation

NSF and AISC Funded Studies

> **Expectation of poor seismic behavior but not well understood**

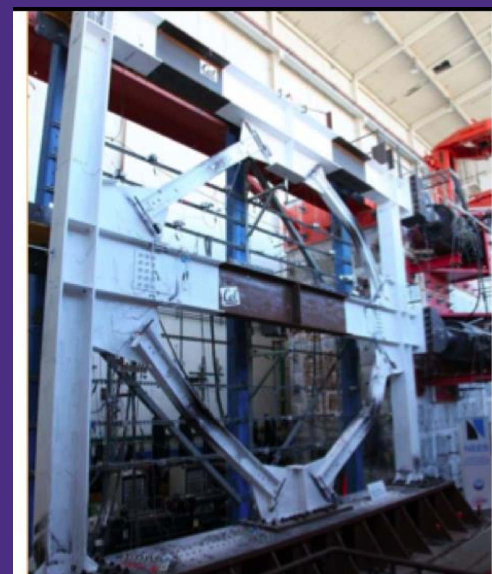
> **Substantial building stock of NCBFs**

> **Shifting cultural expectations of seismic performance, resiliency**

> **Limited retrofit guidance**

Large-Scale Experiments Were Critical

Single-story, single-bay tests at UW to explore connection and brace behavior



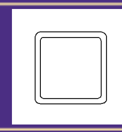
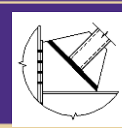
Two-story at NEES@Berkeley: weak-axis columns and weak-beam chevron frames

Two-story tests at NCREE: composite beams in weak-beam chevron frames

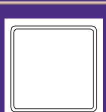
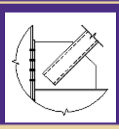
Evolution of CBF Design

- **Pre-1988**: Non-Seismic (NCBFs)
- **1988-1997**: CBFs – capacity based design
- **1997-Today**: Special (SCBF) – additional detailing for regions of high seismicity
- **2008**: Introduction of Balanced Design Procedure (BDP) for improved performance of SCBFs

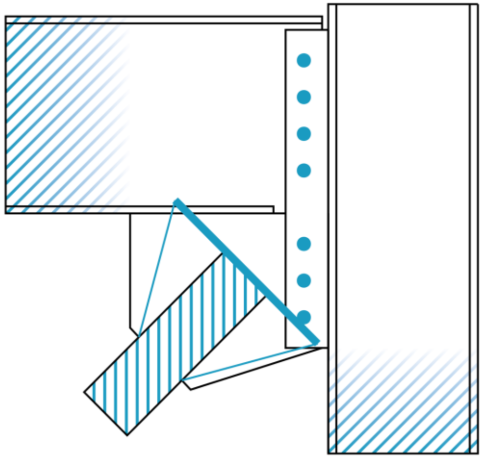
“Current” SCBF Design

	Criterion	Requirements
Brace	Brace Slenderness	KL/r < 100
	Brace Compactness	Seismically Compact 
	Brace End Rotation Clearance	Required 
Connection	GP-to-Frame Connection Design	Design for Expected Brace Capacity
	Weld Metal Toughness	Minimum Toughness for Demand Critical Welds
Frame	Framing Member Compactness	Seismically Compact
	Framing Member Design	Design for Expected Brace Capacity

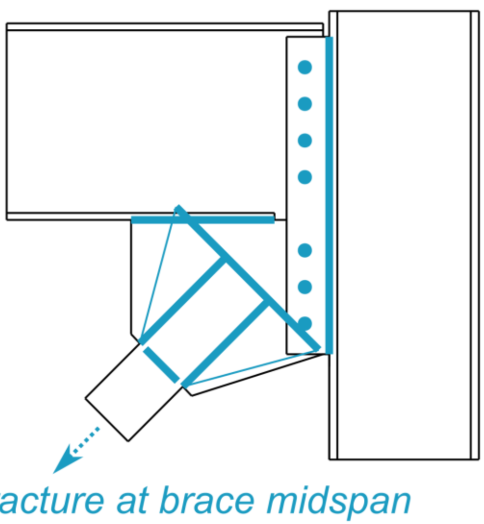
NCBF Design (pre-1988)

	Criterion	Requirements
Brace	Brace Slenderness	No Limit
	Brace Compactness	No Limit 
	Brace End Rotation Clearance	No Limit 
Connection	GP-to-Frame Connection Design	Design for Seismic Loads
	Weld Metal Toughness	No Limit
Frame	Framing Member Compactness	No Limit
	Framing Member Design	Design for Seismic Loads

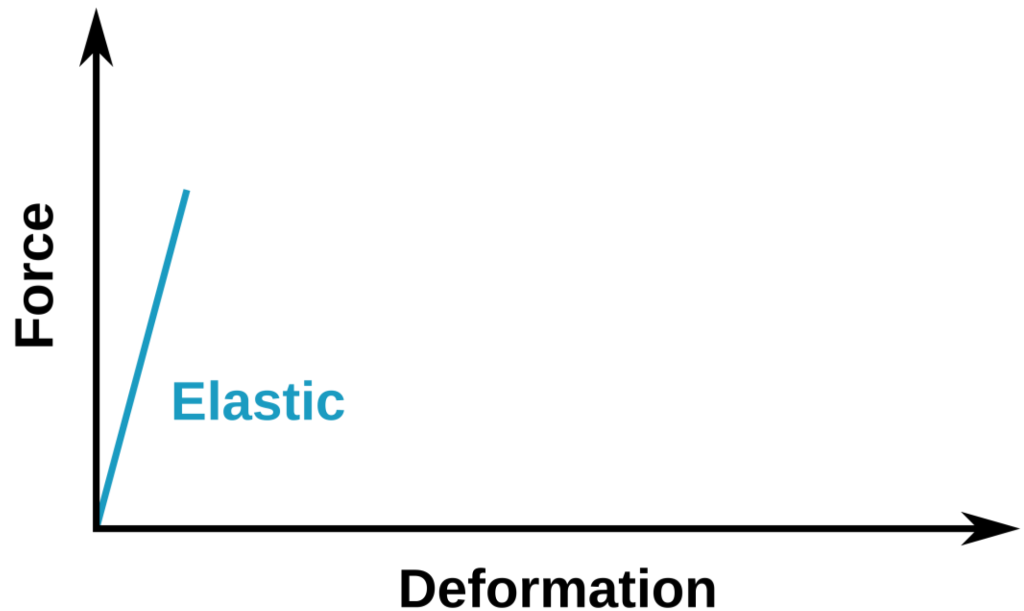
SCBF System Behavior: Elastic Response



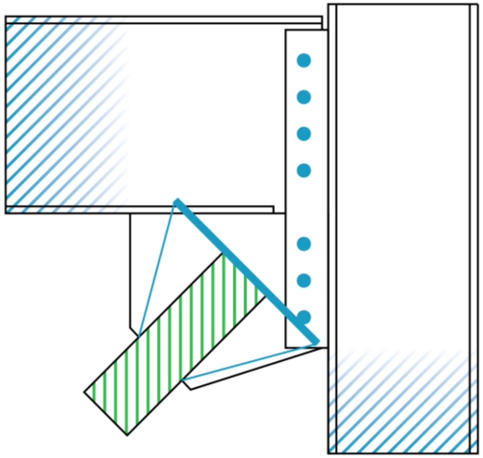
Yielding Mechanisms



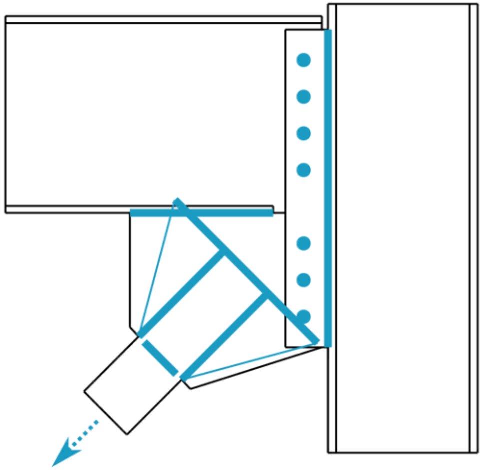
Failure Modes



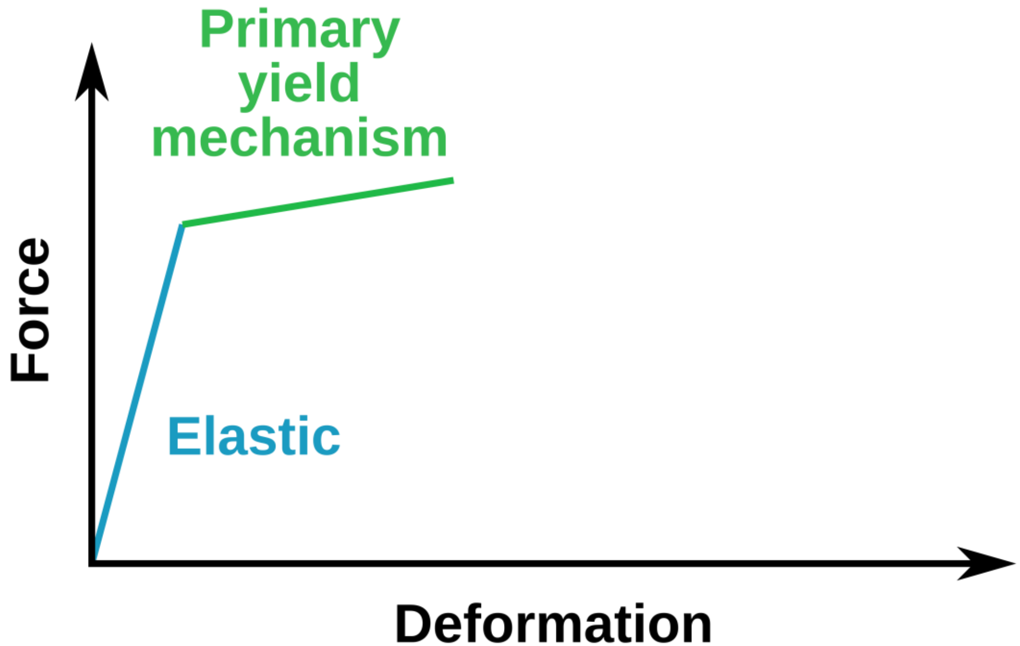
SCBF System Behavior: Primary Yield Mechanism



Yielding Mechanisms



Failure Modes



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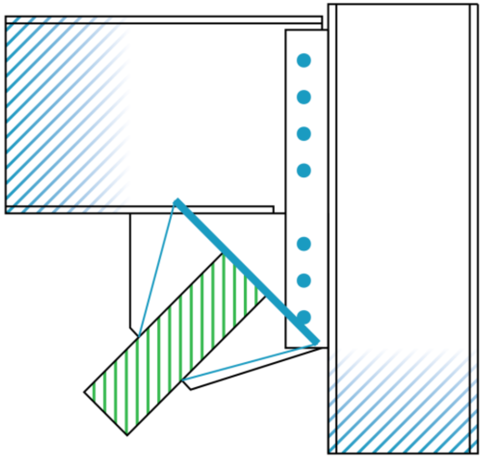
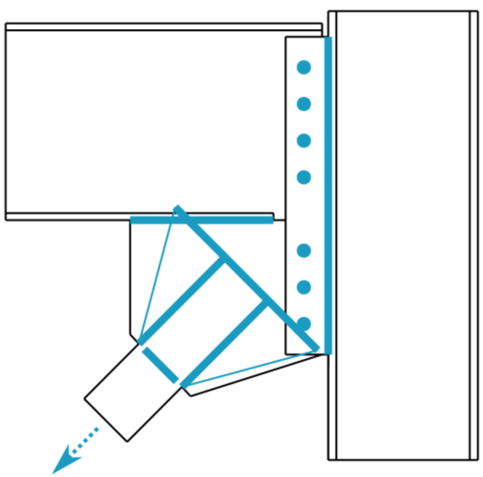
SCBF System Behavior: Failure Mechanism

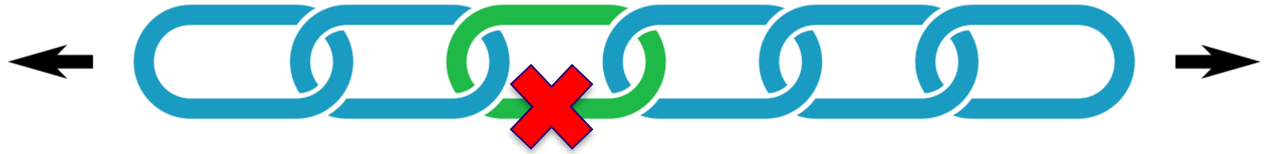


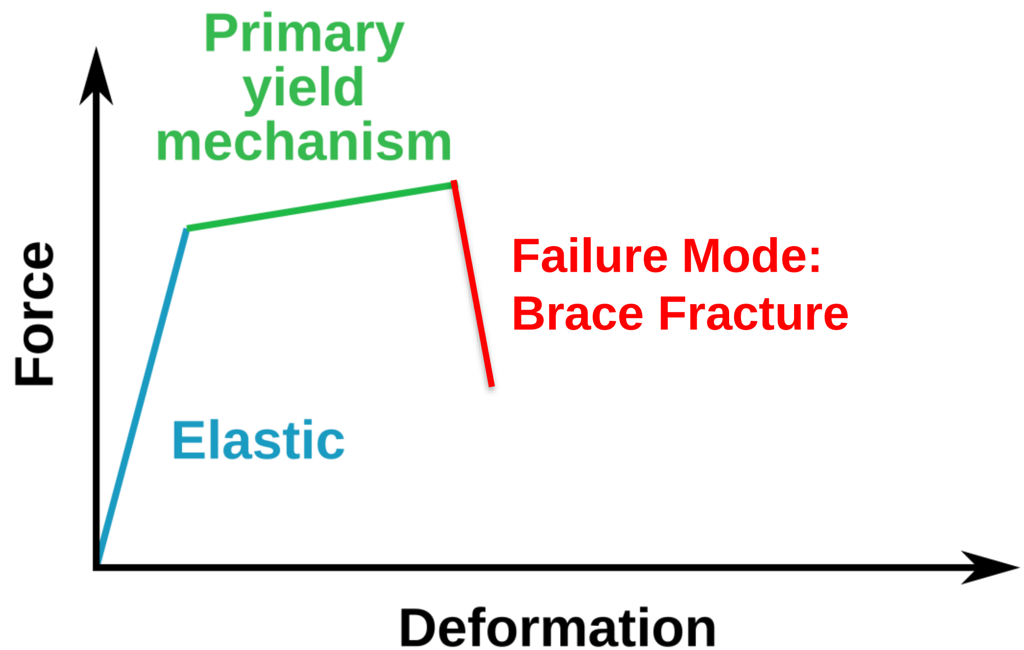
Yielding Mechanisms



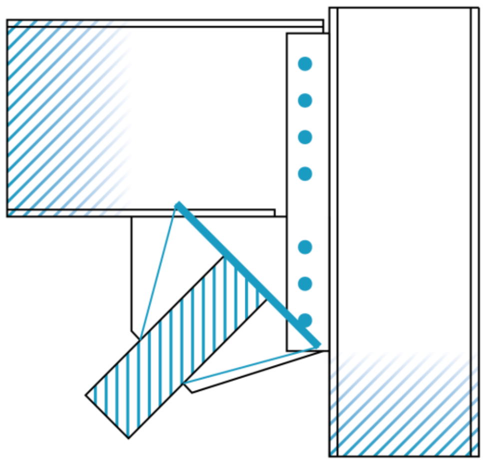
Fracture at brace midspan

Failure Modes

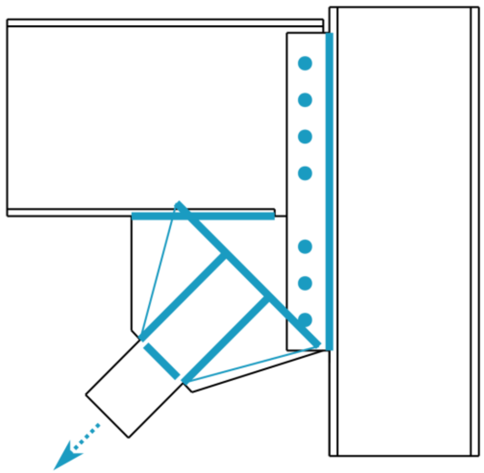




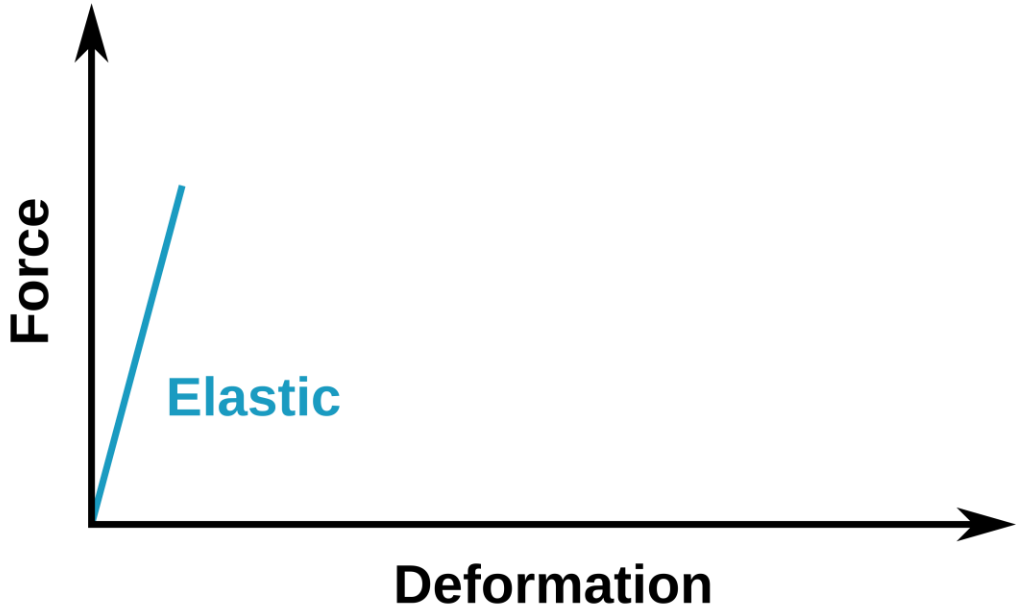
Balanced Design Procedure (BDP)
SCBF System Behavior



Yielding Mechanisms



Failure Modes



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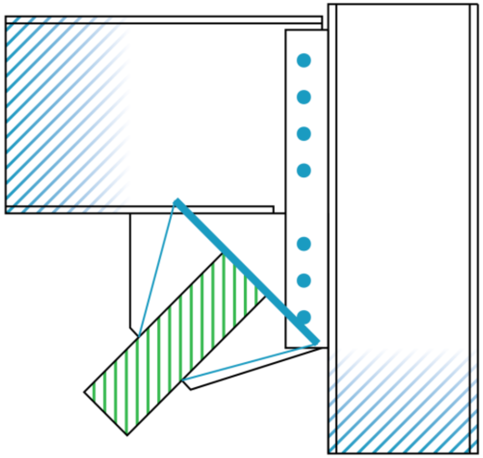
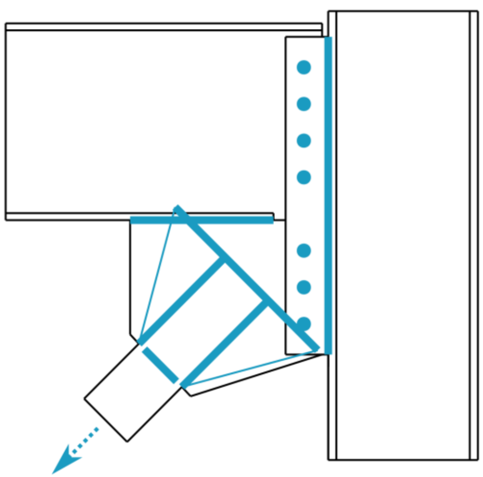
BDP-SCBF System Behavior: Primary Yield Mechanism

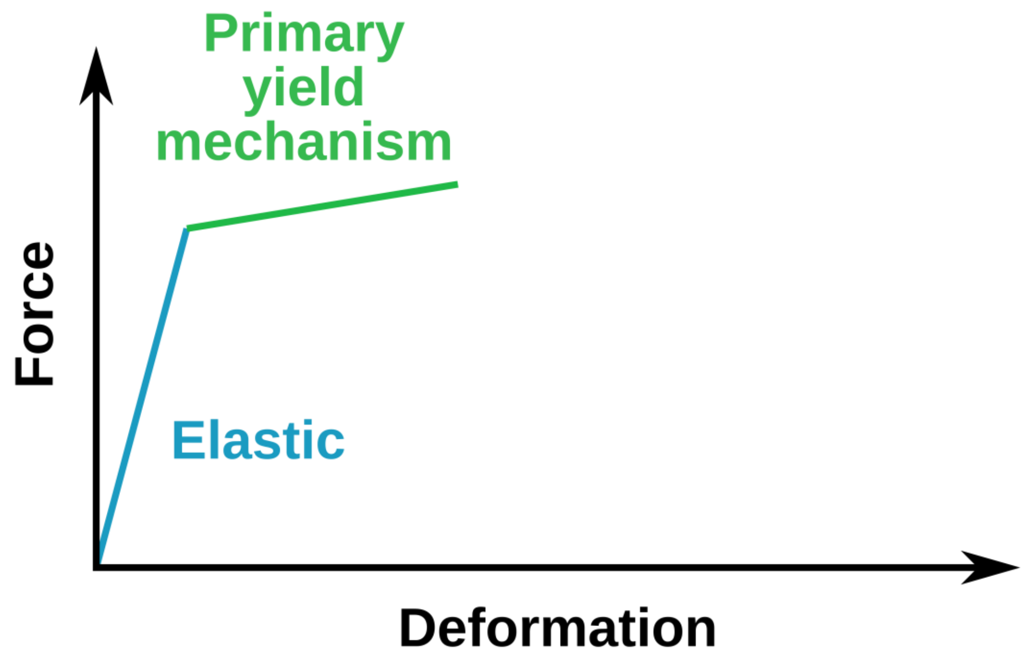


Yielding Mechanisms

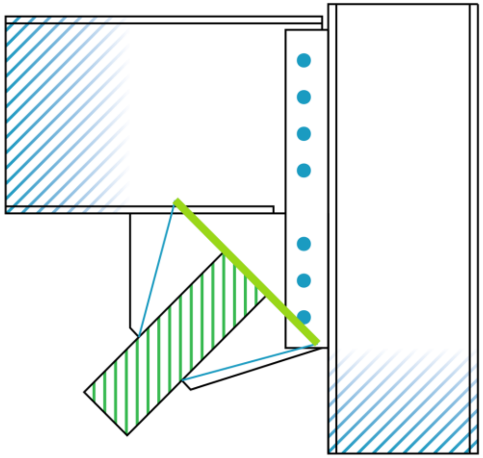


Fracture at brace midspan

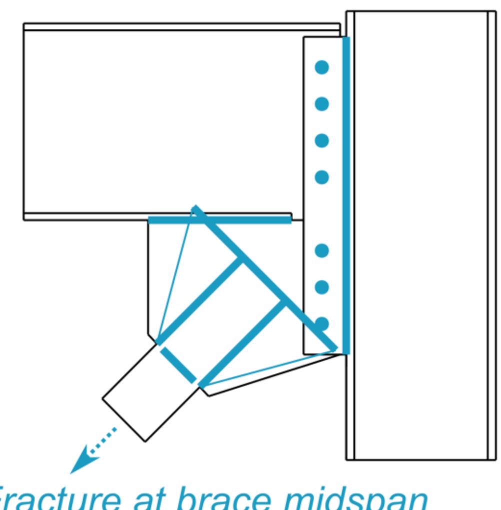
Failure Modes



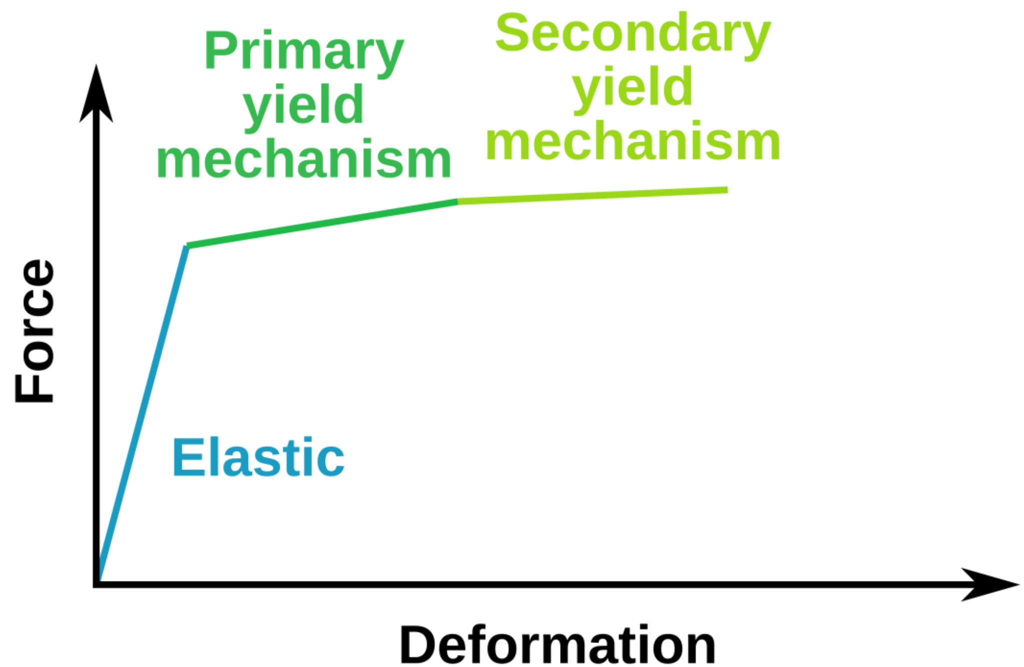
BDP SCBF System Behavior: Secondary Yield Mechanism



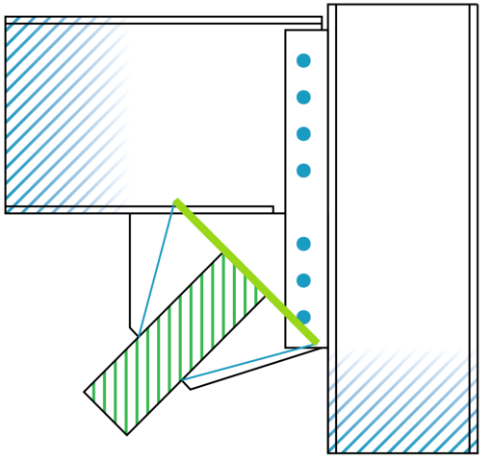
Yielding Mechanisms



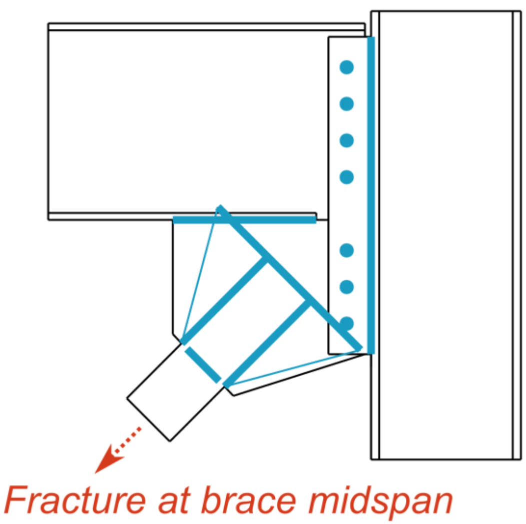
Failure Modes



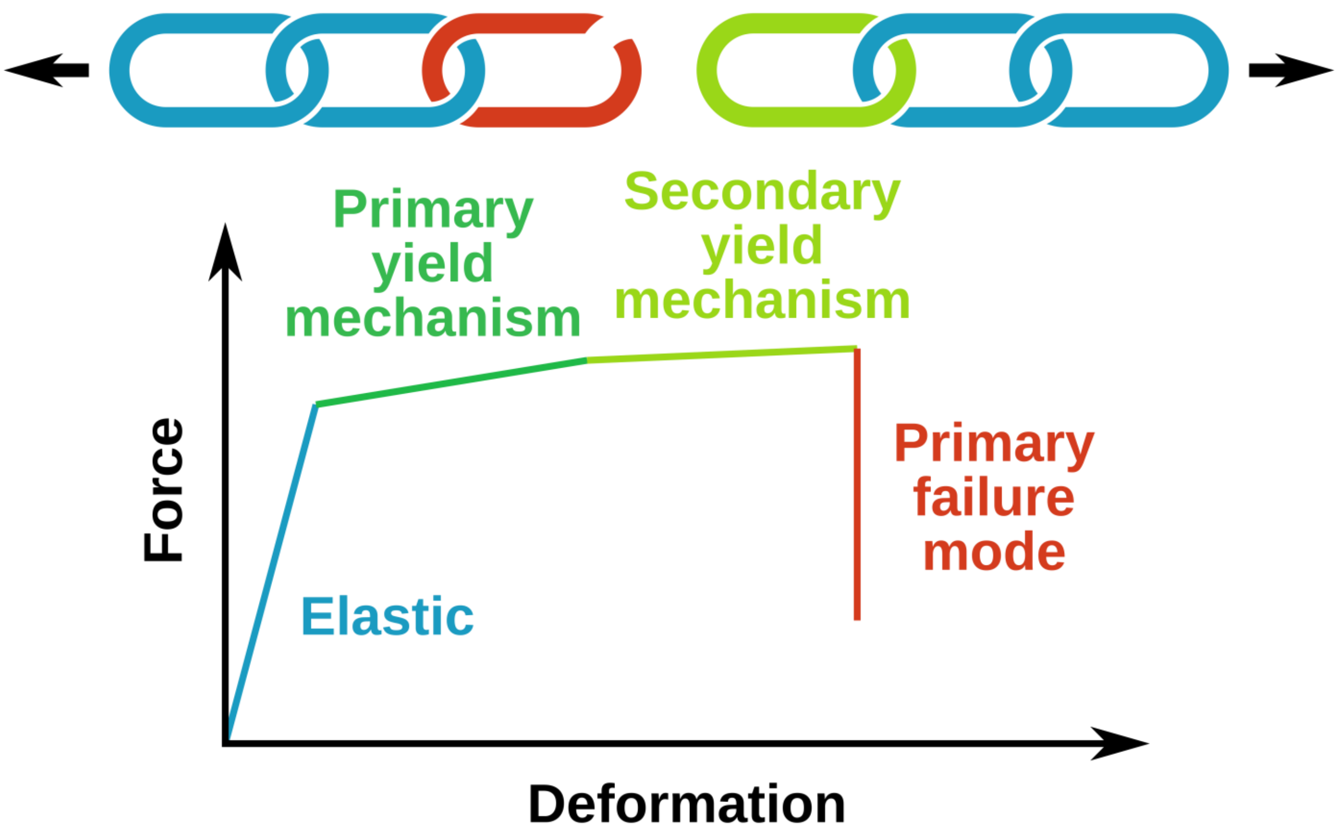
BDP SCBF System Behavior: Primary Failure Mode



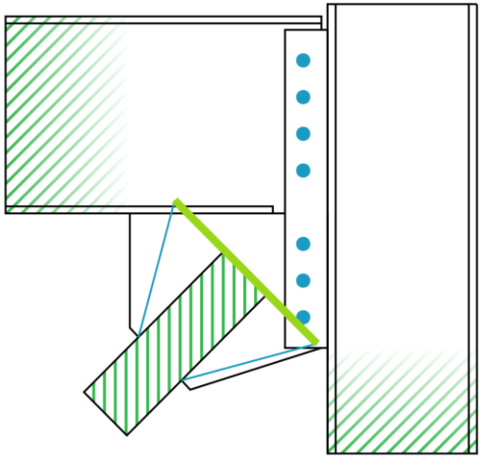
Yielding Mechanisms



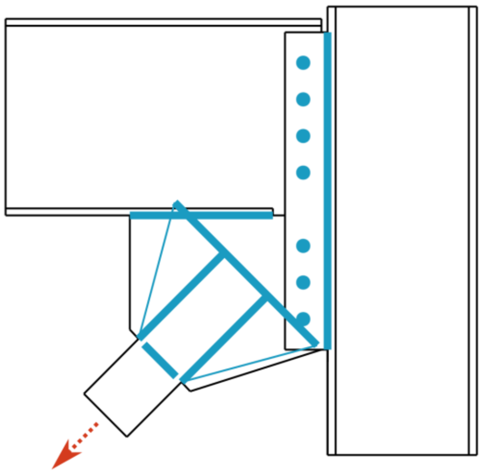
Failure Modes



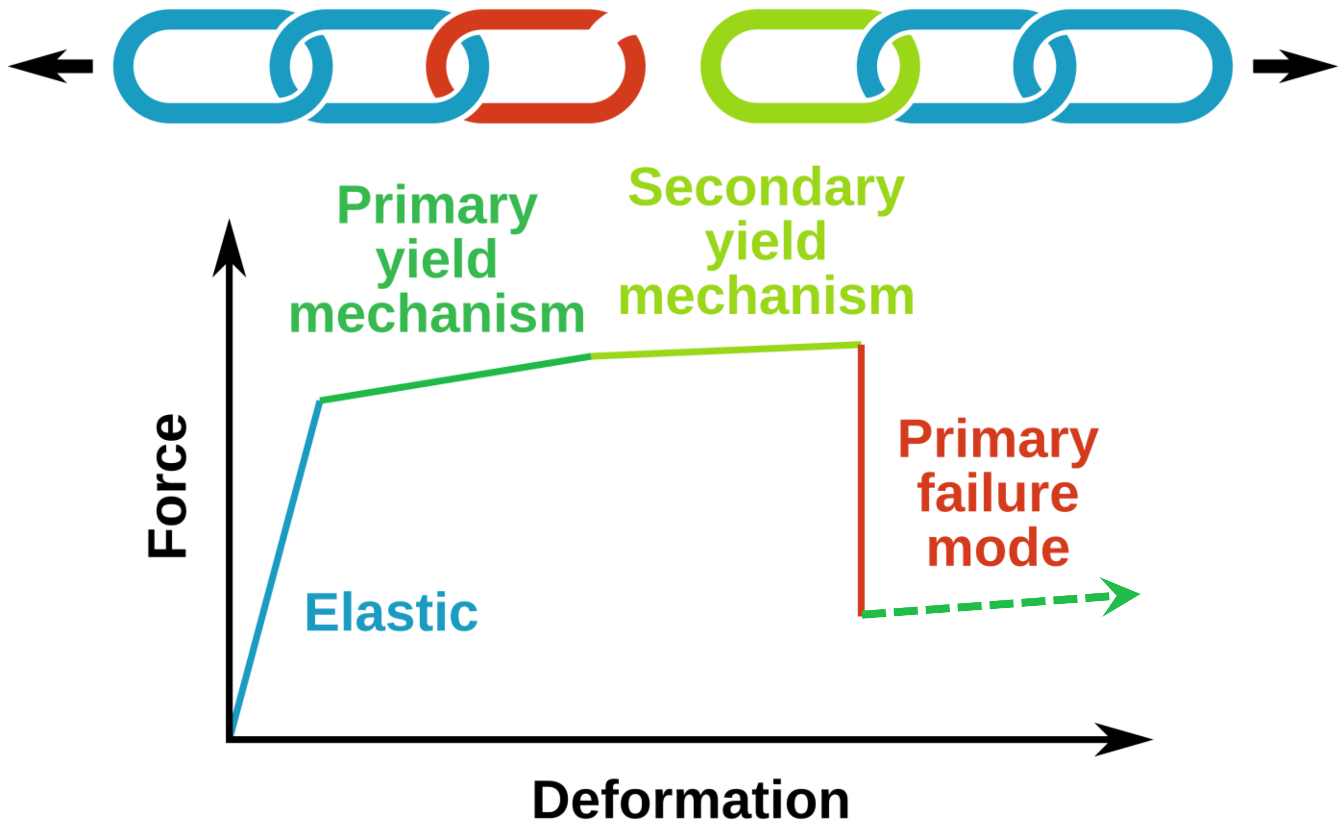
System Behavior: Residual Capacity (Collapse-Resistance)



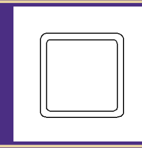
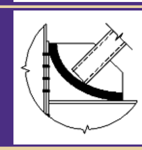
Yielding Mechanisms

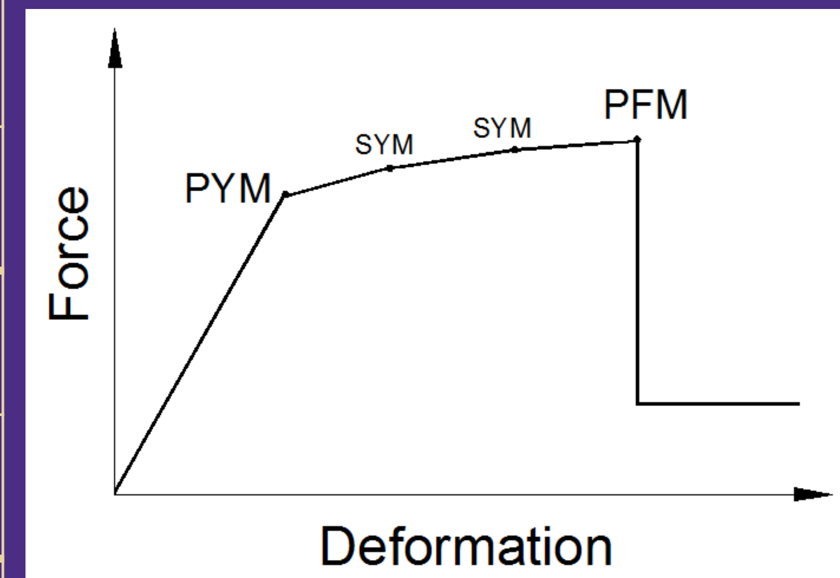


Failure Modes



SCBF Design with BDP

	Criterion	Requirements
Brace	Brace Slenderness	KL/r < 100
Brace	Brace Compactness	Seismically Compact 
Brace	Brace End Rotation Clearance	Required 
Connection	GP-to-Frame Connection Design	Design for Yield Strength of GP
Connection	Weld Metal Toughness	Minimum Toughness for Demand Critical Welds
Frame	Framing Member Compactness	Seismically Compact
Frame	Framing Member Design	Design for Expected Brace Capacity



Evaluation and Retrofit Methodology

Based on Demand/Capacity Ratios (DCRs) and Balanced Design

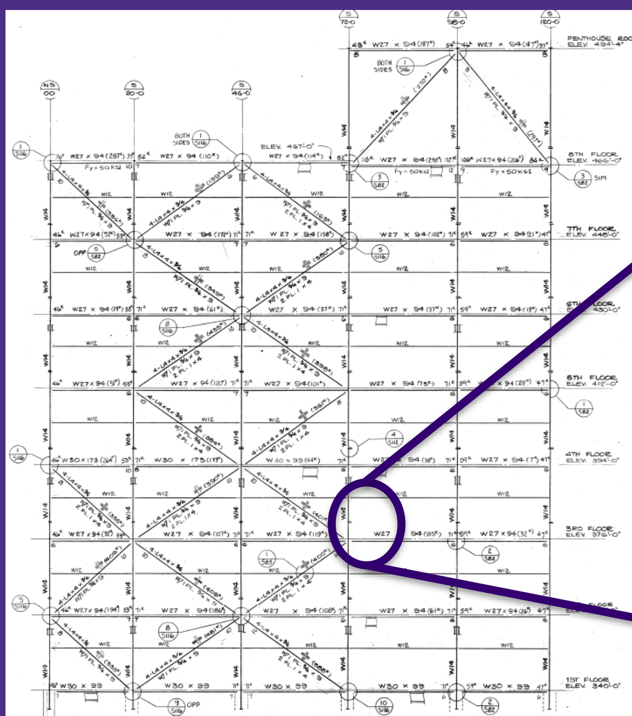
Evaluate the Frame → Identify Deficiencies → Determine Frame Performance → Select & Design Retrofit Strategy

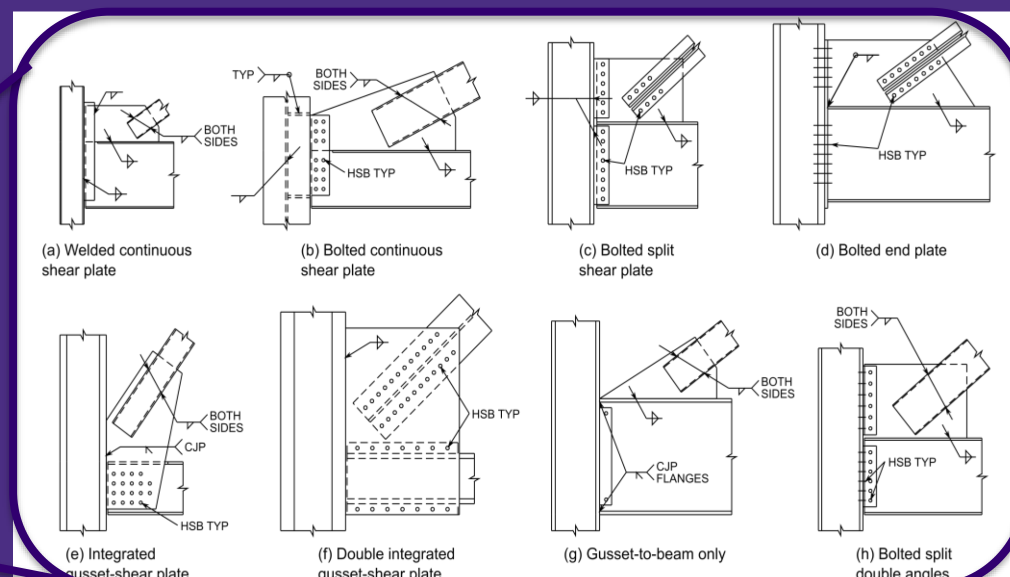
Step 1:
Evaluate Building

Background: Infrastructure Review
(Sloat 2014)

Building Survey
- **12 Buildings; 8 Connection Types**
- **Designed Before 1988**
- **Regions of High Seismicity**

Survey Results
- **Non-Compact Braces**
- **Connection Deficiencies**
- **System Level Deficiencies**

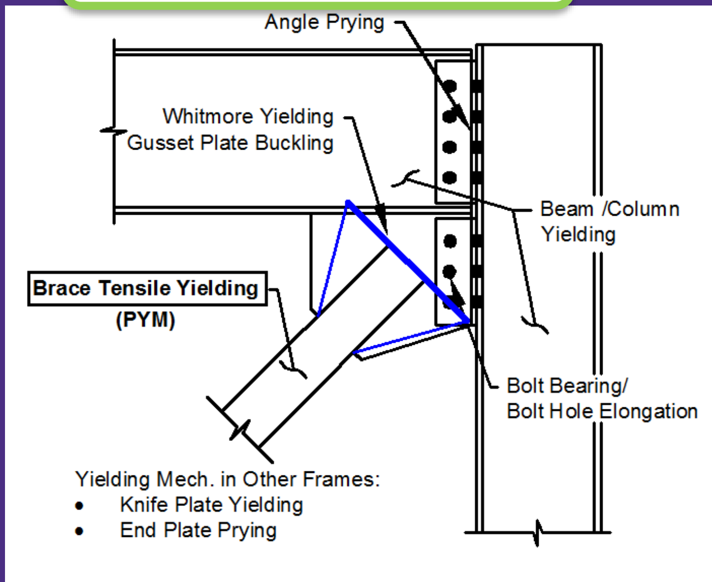




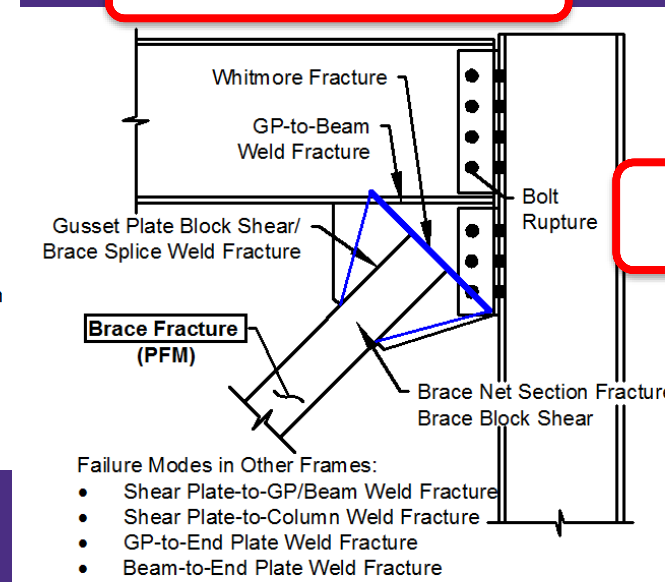
Evaluate the Frame

Demand-to-Capacity Ratios (DCRs)

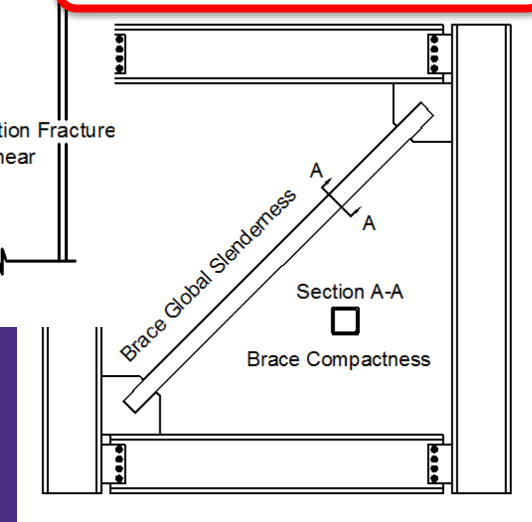
Yielding Mechanisms



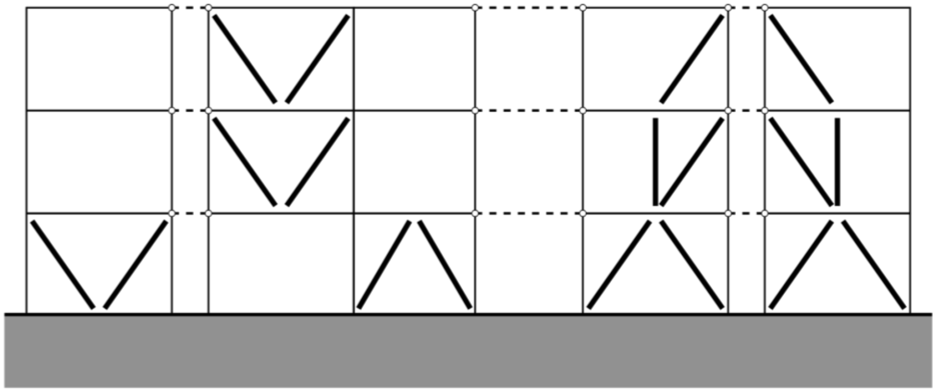
Failure Modes



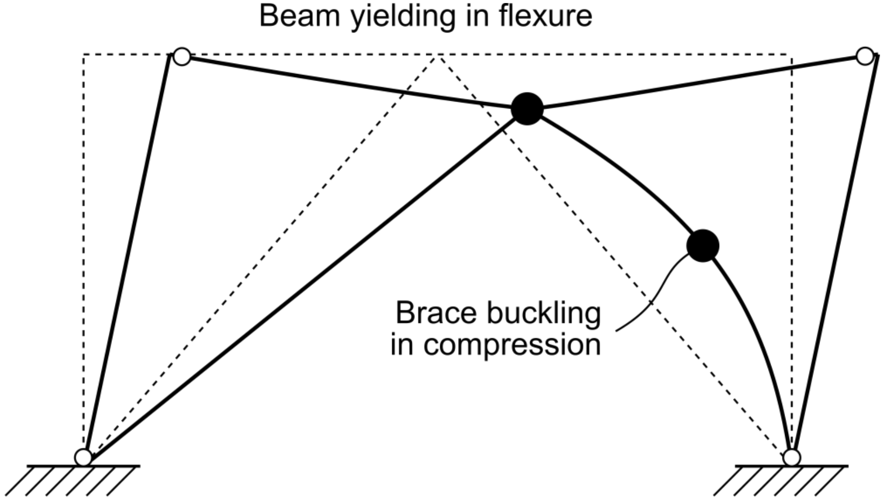
Geometric Limits

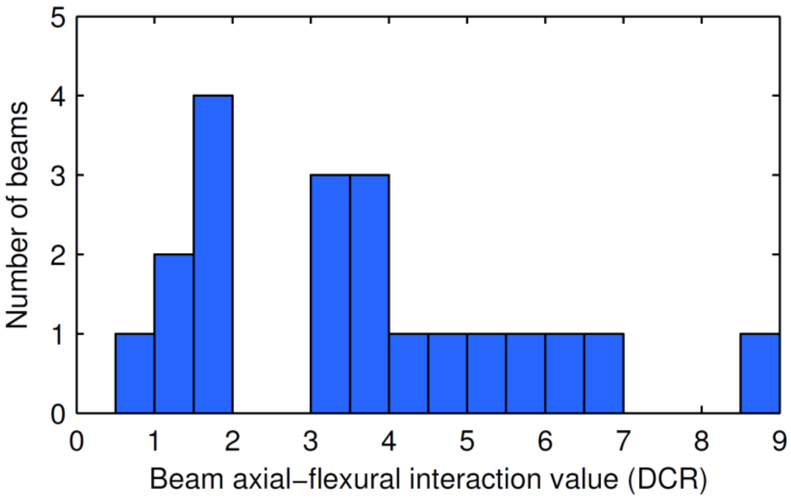


Evaluate the System



VERTICAL IRREGULARITIES





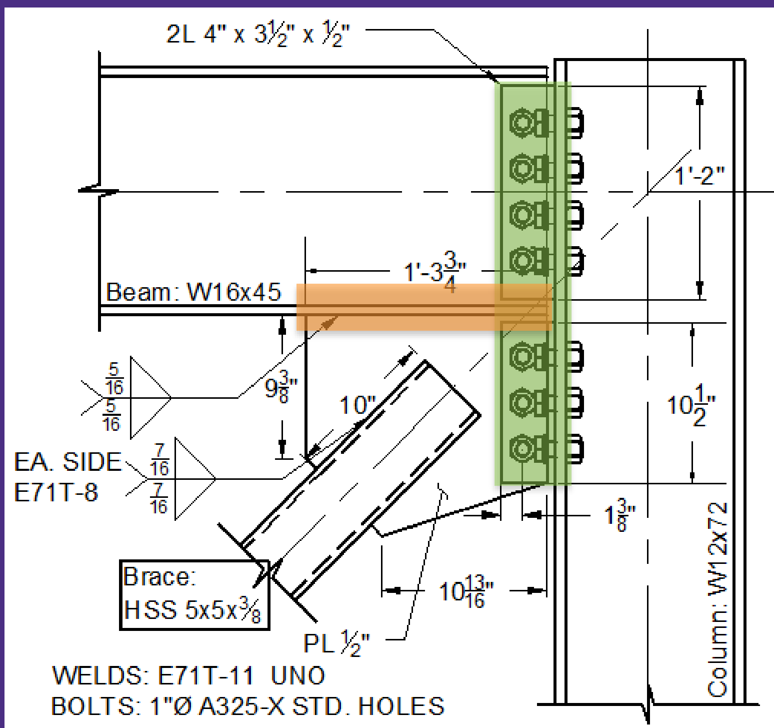
YIELDING-BEAM MECHANISM

Step 2:
Identify Deficiencies

Evaluate the Connection: Compute Demand/Capacity Ratios

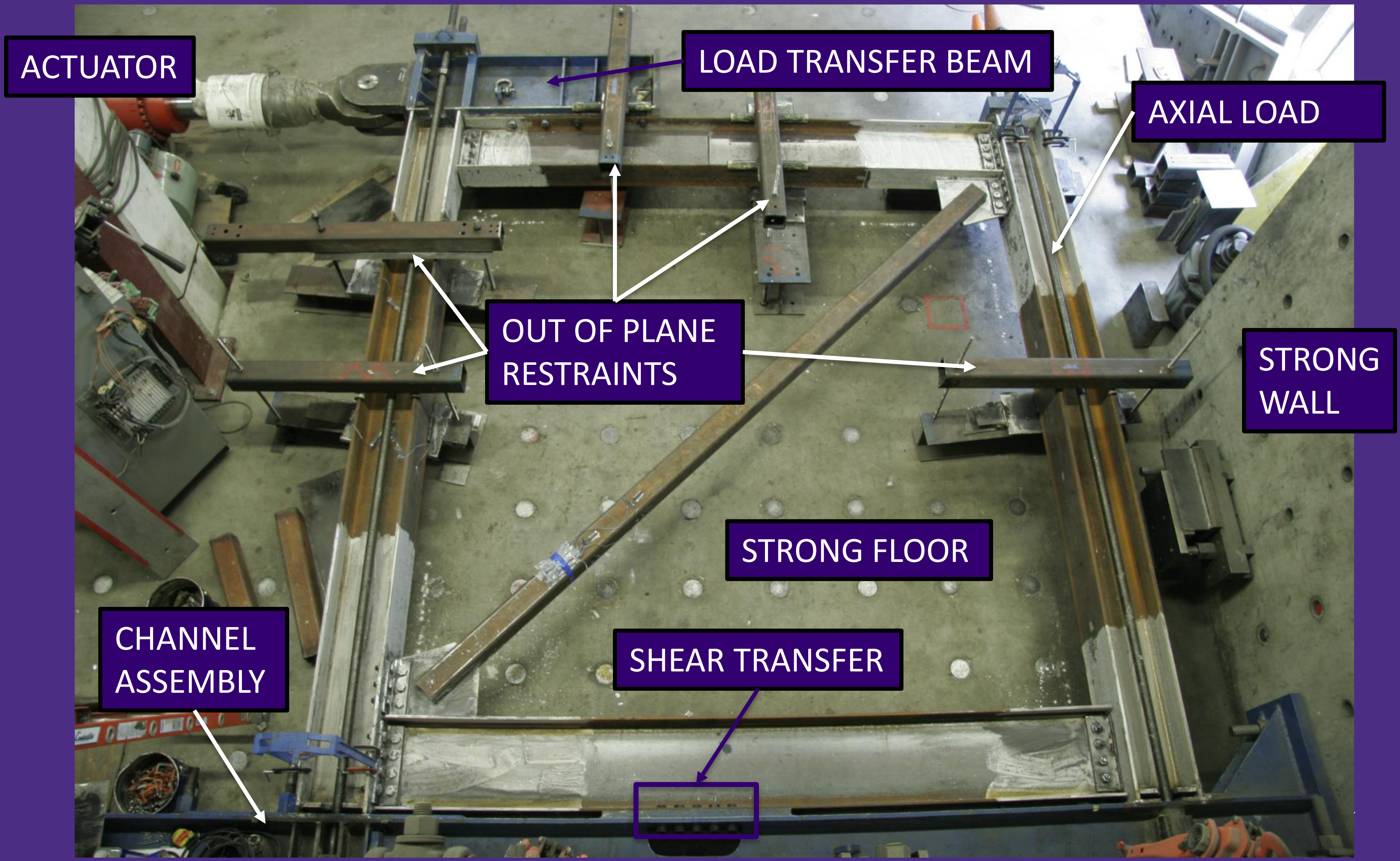
	Limit State	AISC Design Resistance ($ØR_n$)	Balanced Design Resistance (βR_n)
Yield Mech	Whitmore Yielding	$\phi R_y F_y B_w t_p$	$\beta R_y F_y B_w t_p$
	Bolt Bearing	$\phi\left(1.5L_c t_p F_u \leq 3.0 d_h t_p F_u\right) \geq UFM$	$\beta\left(1.5L_c t_p F_u \leq 3.0 d_h t_p F_u\right) \geq R_y F_y l_b t_p$
	GP Buckling	$\phi B_w t_p F_{cr}$	$\beta B_w t_p F_{cr}$
	Prying Action	$\phi\sqrt{4Bb'/pF_u} \geq t_p$	
Failure Modes	Brace Net Section Fracture	$\phi U R_{tb} F_{ub} A_{nb}$	$\beta U R_{tb} F_{ub} A_{nb}$
	GP-to-Brace Weld	$\phi(0.6)F_{EXX} N_w L_c (0.707) w_{br}$	$\beta(0.6)F_{EXX} N_w L_c (0.707) w_{br}$
	Brace Block Shear	$\phi(0.6F_y A_{gv} + U_{bs} F_u A_{nt})$	$\beta(0.6F_u A_{gv} + U_{bs} F_u A_{nt})$
	GP Block Shear	$min\begin{cases}\phi(0.6F_u A_{nv} + U_{bs} F_u A_{nt})\\ \phi(0.6F_y A_{gv} + U_{bs} F_u A_{nt})\end{cases}$	$\beta(0.6)(1/2)(R_y F_y + R_t F_u)A_{nv}$
	Whitmore Fracture	$\phi R_t F_u B_w t_p$	$\beta R_t F_u B_w t_p$
	Interface Welds	$\phi c C_1 (16 w_b) t_w \geq UFM$	$2(1.5)\beta(0.6)F_{EXX}(0.707)w_b \geq R_y F_y t_p$
	Bolt Rupture	$\phi c F_{nv} \geq UFM$	$F_{nv}\pi(d_b/2)^2 \geq \left(1.5L_c t_p F_u \leq 3.0 d_h t_p F_u\right)$
Geometric Limits	Brace Compactness	$b/t \geq 0.55\sqrt{E/(R_y F_y)}$	$b/t \geq 0.55\sqrt{E/(R_y F_y)}$
	Slenderness	$KL/r < 100$	$KL/r < 100$

Identifying Deficiencies



Yielding Mechanisms	AISC DCR	BDP DCR
Whitmore Yielding	0.8	0.7
GP Bolt Bearing	0.9	1.3
Beam Bolt Bearing	1.3	1.5
Prying Action	3.6	
Failure Modes	**AISC DCR**	**BDP DCR**
GP-Brace Weld Fracture	0.7	0.7
Whitmore Fracture	0.6	0.5
GP Block Shear	0.7	0.6
GP-Beam Weld Fracture	0.5	1.1
GP Bolt Rupture	0.6	1.5
Geometric Limits		
Brace Compactness Ratio	0.92	
Slenderness	89.4	

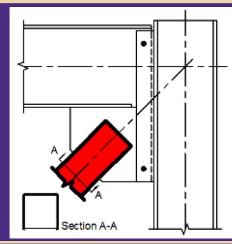
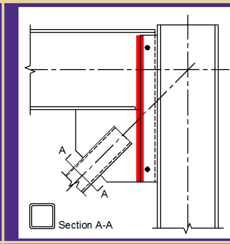
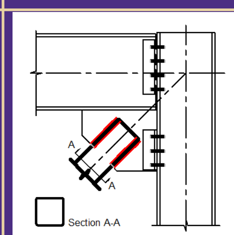
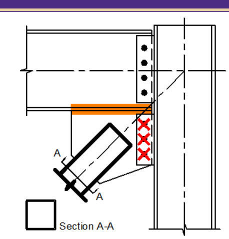
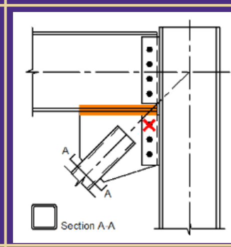
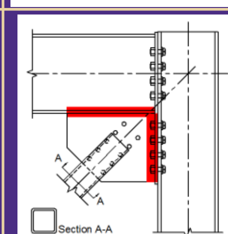
Experimental Setup



LFM

PFM

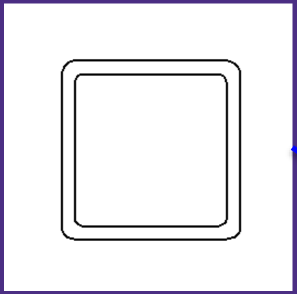
Evaluation of NCBFs

Connection Type	NCBF	NCBF w/ Brace Retrofit	NCBF w/ 2 Retrofits
Welded			
Bolted Continuous			
Bolted Split	 		
End Plate			

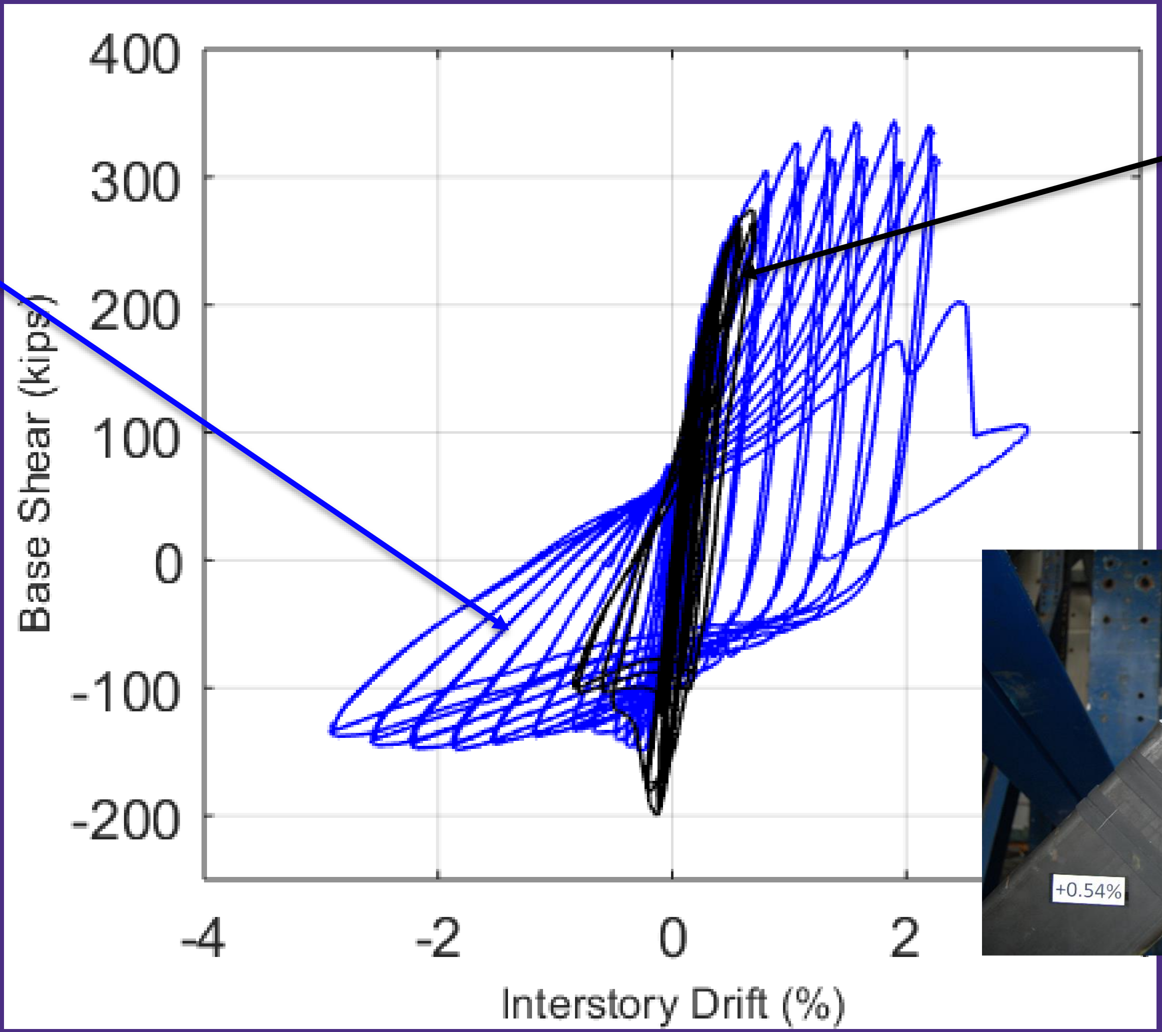
Identify Deficiencies:

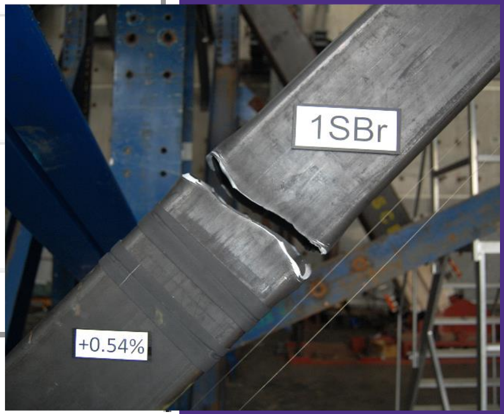
Non-Compact Braces

DCR = 1.0

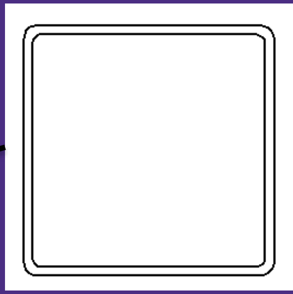


HSS
5x5x3/8





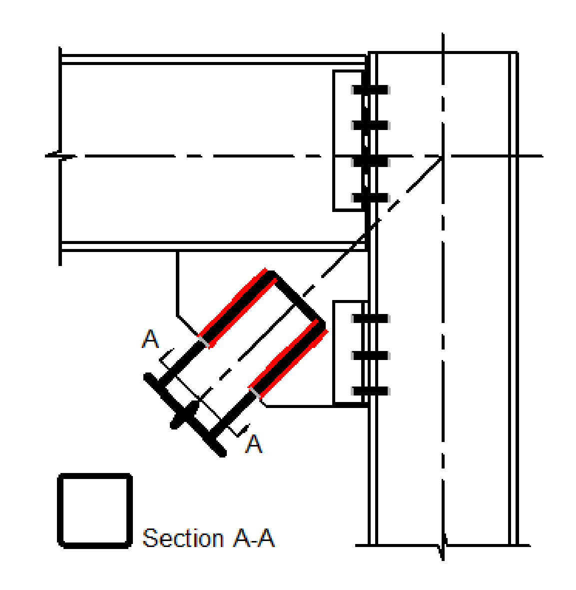
DCR = 2.3

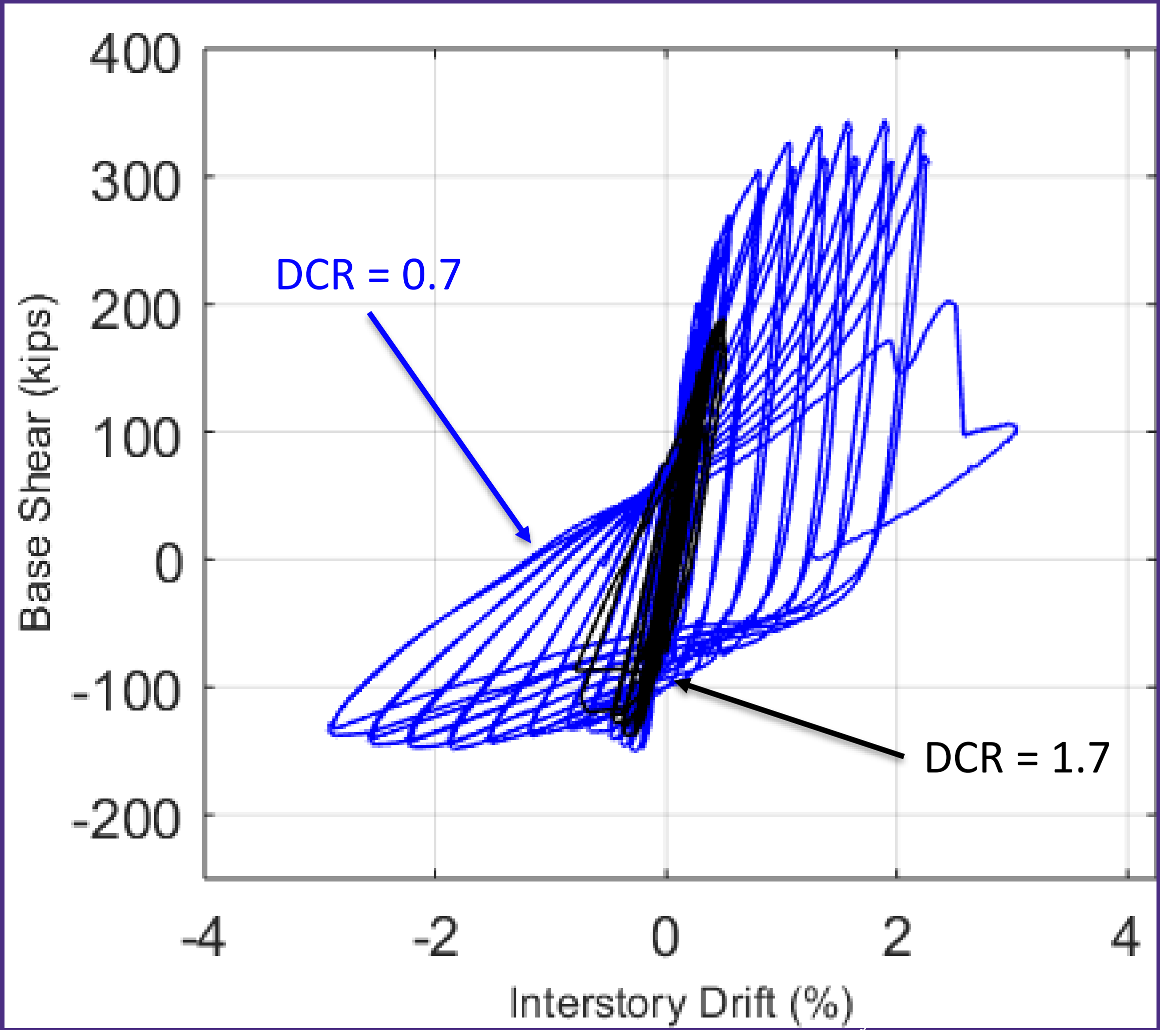


HSS
7x7x1/4

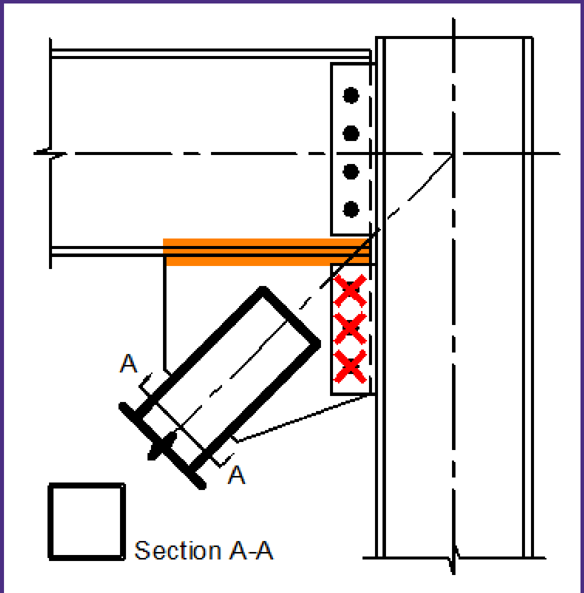
Identify Deficiencies:

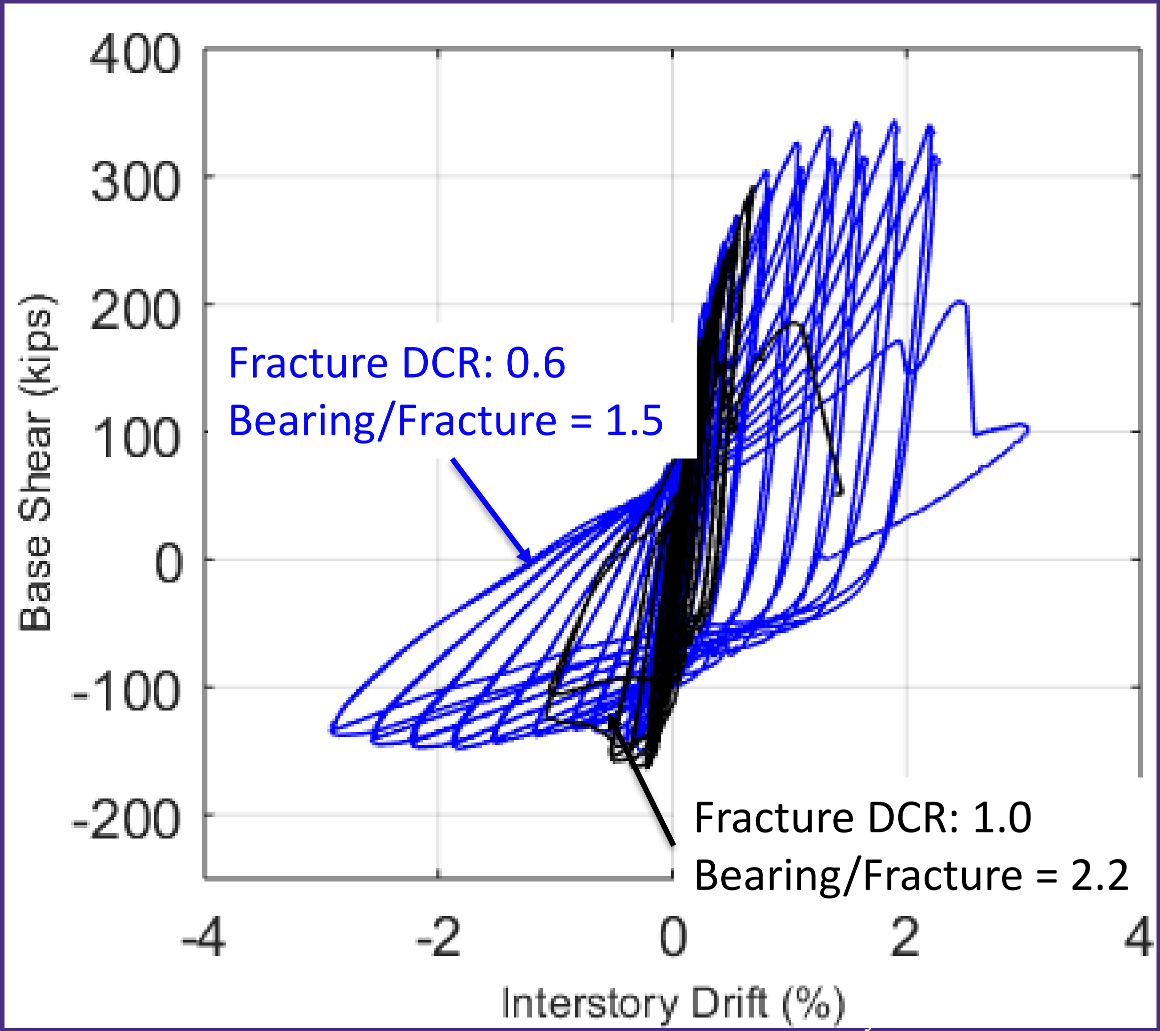
Deficient GP-to-Brace Weld





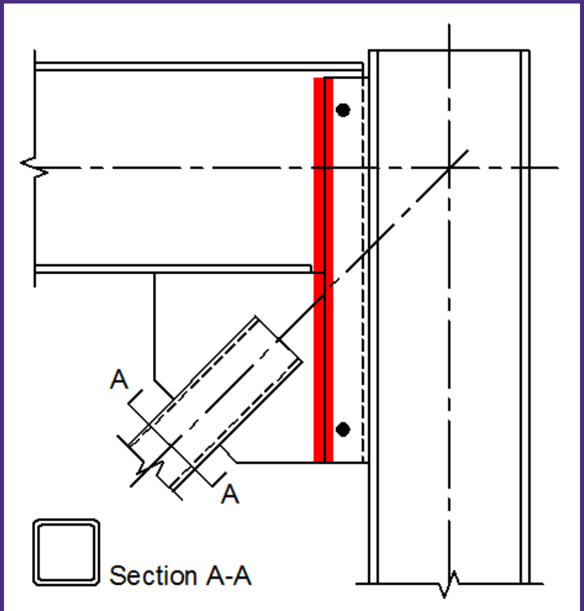
Identify Deficiencies:
Deficient Bolts

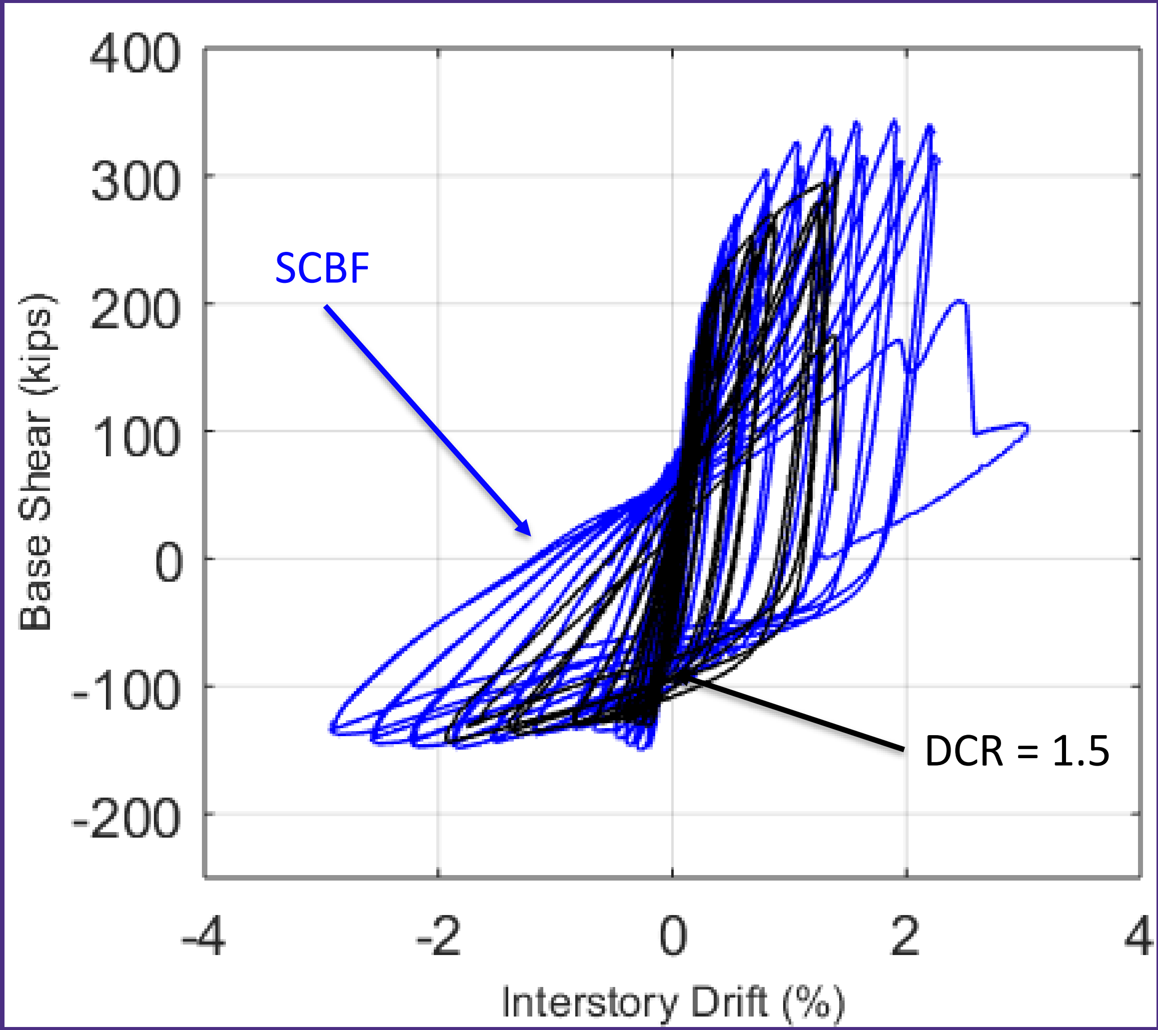




Identify Deficiencies:

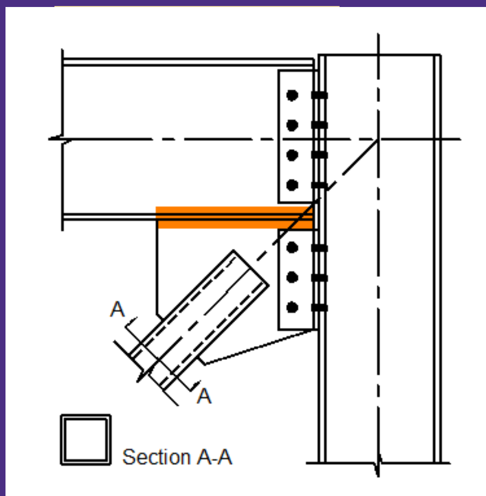
Deficient Shear Plate Weld

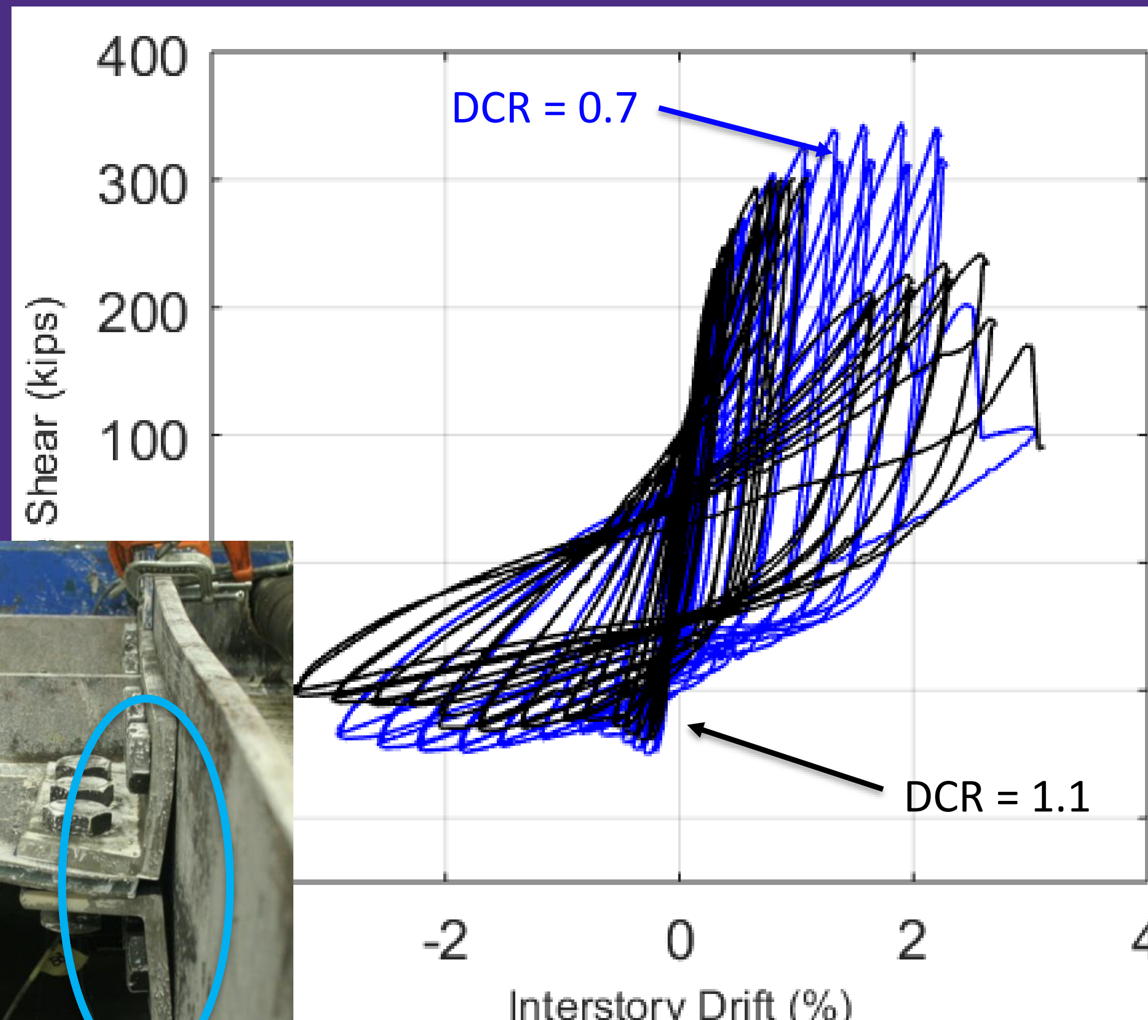




Identify Deficiencies:

Deficient GP-to-Beam Weld





Step 3:

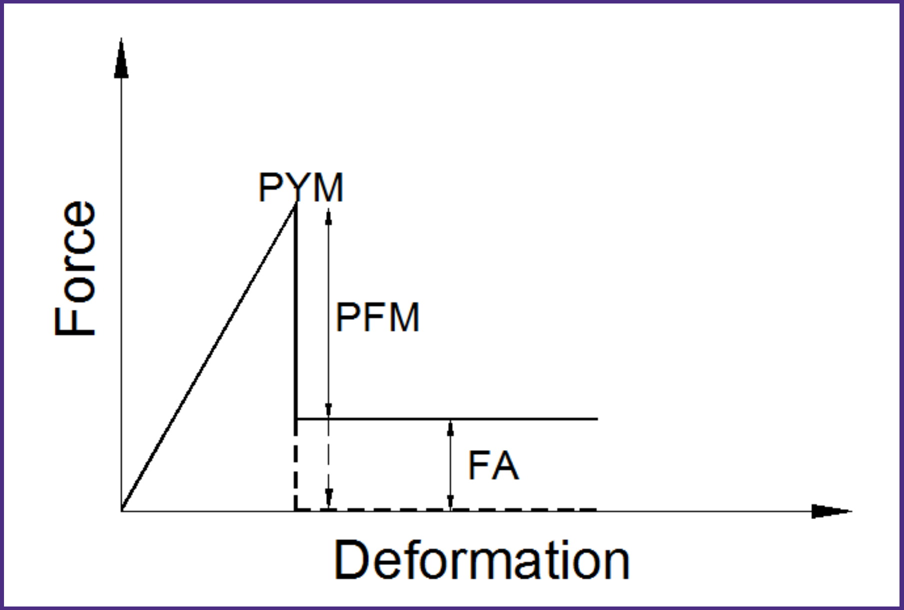
Determine Frame Performance

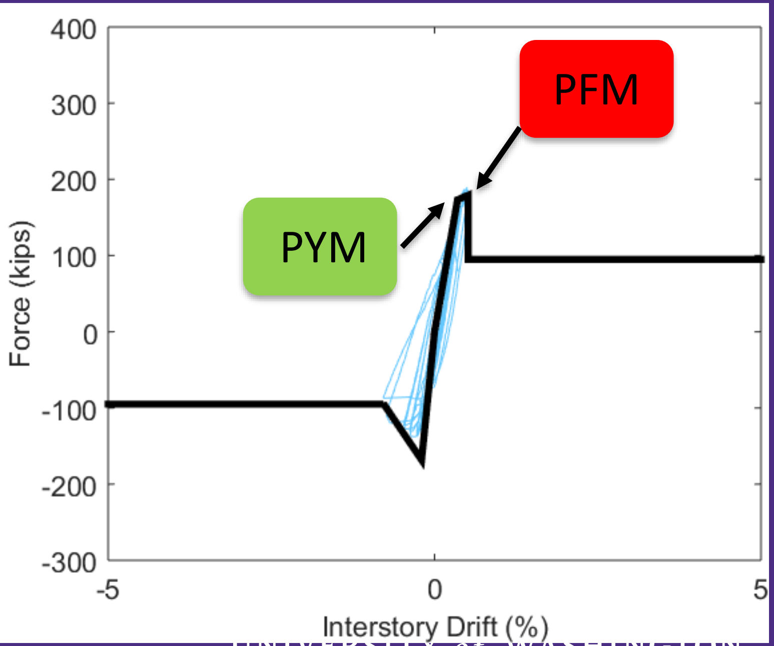
Determine Frame Performance

Type 1 Yield and Failure Hierarchy

PYM
Brace Buckling/ Yielding

PFM
Brace Fracture (GP-Brace Weld or Bolt Fracture)





Determine Frame Performance

Type 2 Yield and Failure Hierarchy

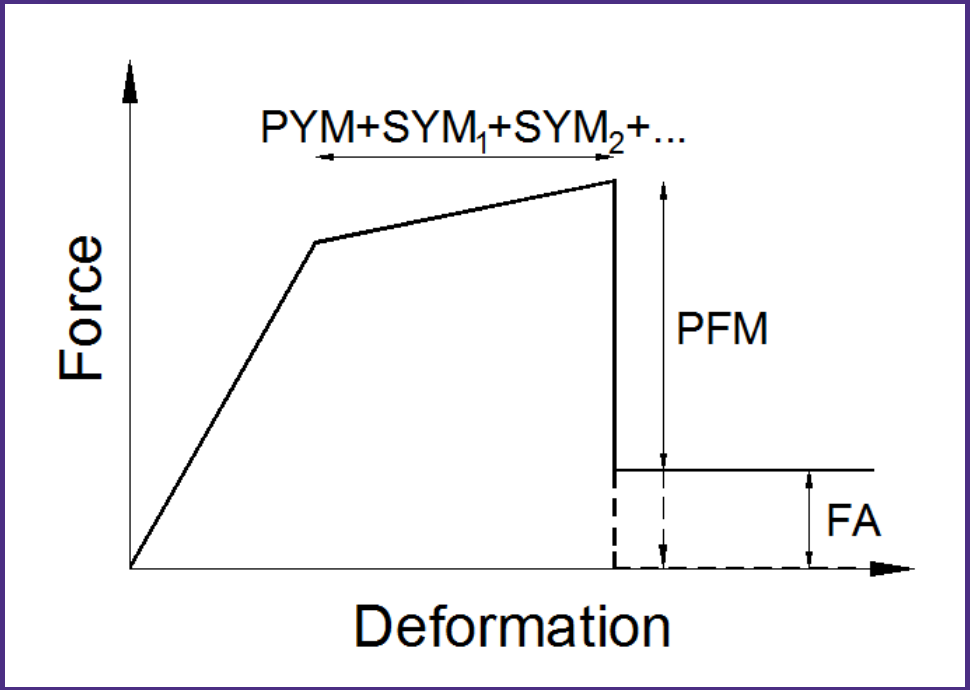
PYM
Brace Buckling/
Yielding

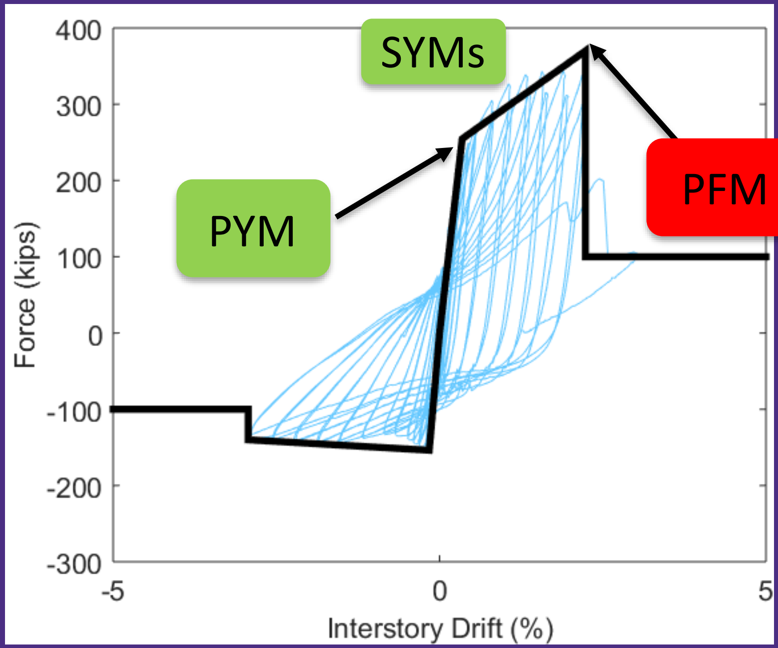
→

SYM

→

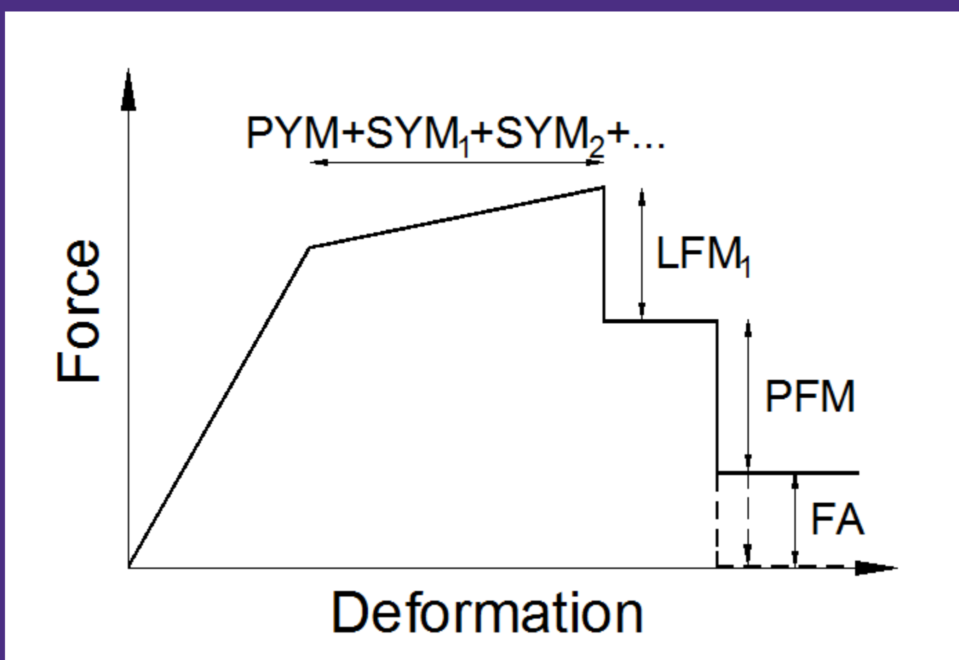
PFM
Brace Fracture

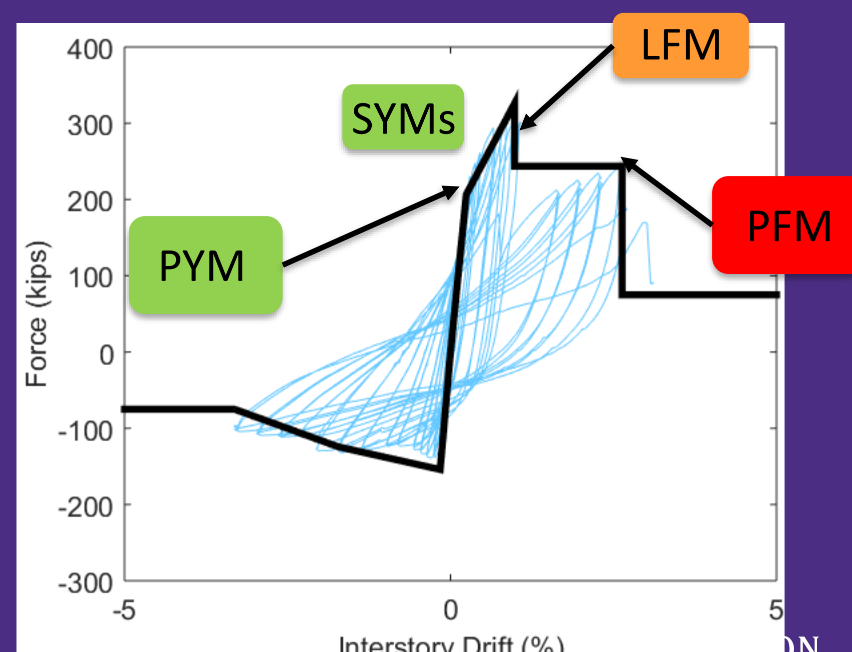




Determine Frame Performance
Type 3 Yield and Failure Hierarchy

PYM Brace Buckling/ Yielding → **SYM** → **LFM** → **PFM** Brace Fracture





Step 4:
Select Retrofit Strategy

Retrofit Prioritization

Priority	Deficiency	Deficiency severity
High	Locally slender HSS braces	> 1.5
	Brace-to-gusset plate welds	> 1.3
Moderate	Gusset plate interface welds	> 0.75 (BDP)
	Gusset plate clearance	< $2t_p$ elliptical
Low	Gusset plate clearance	< $4t_p$ elliptical
	Shear plate bolts	> 1.2
	Beam yielding (chevron)	> 2.5
Minimal	Whitmore yielding	> 1.3

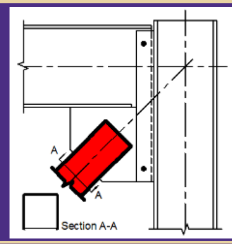
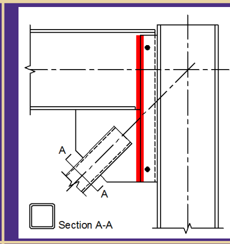
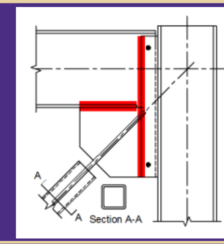
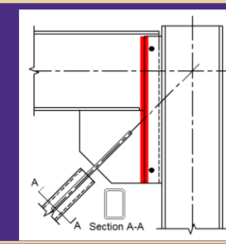
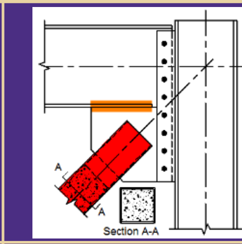
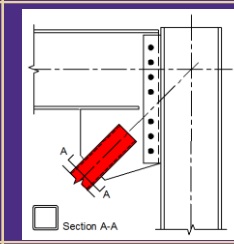
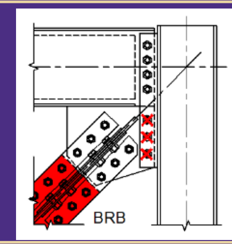
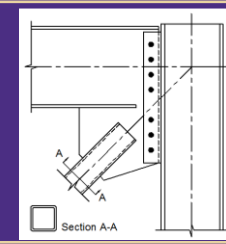
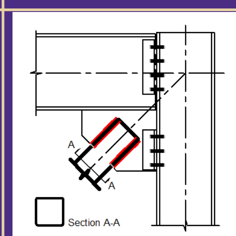
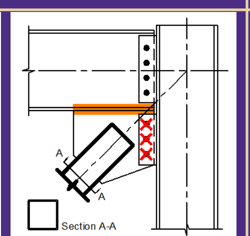
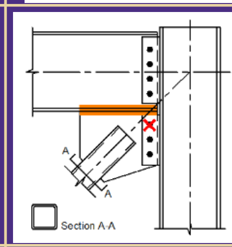
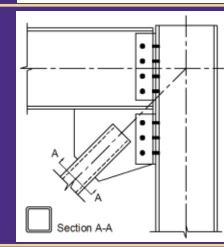
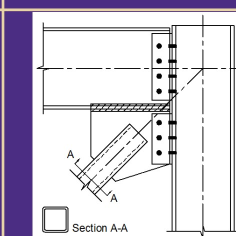
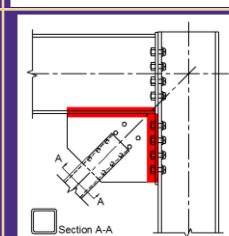
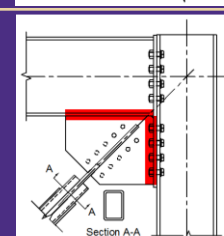
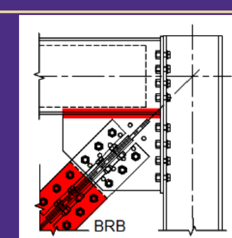
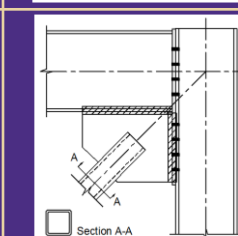
Tested Retrofit Strategies

Deficiency	Retrofit objective	Retrofit strategy
Brace local slenderness	Improve brace deformation capacity	Replace brace (BRB, HSS, In-plane)
		Fill brace with concrete
Brace-to-gusset weld	Develop brace capacity	(Address in brace replacement)
Gusset plate interface welds	Mitigate demands	Replace brace (in-plane buckling)
		Replace brace (BRB)
	Reinforce	Add bolts
		Overlay weld

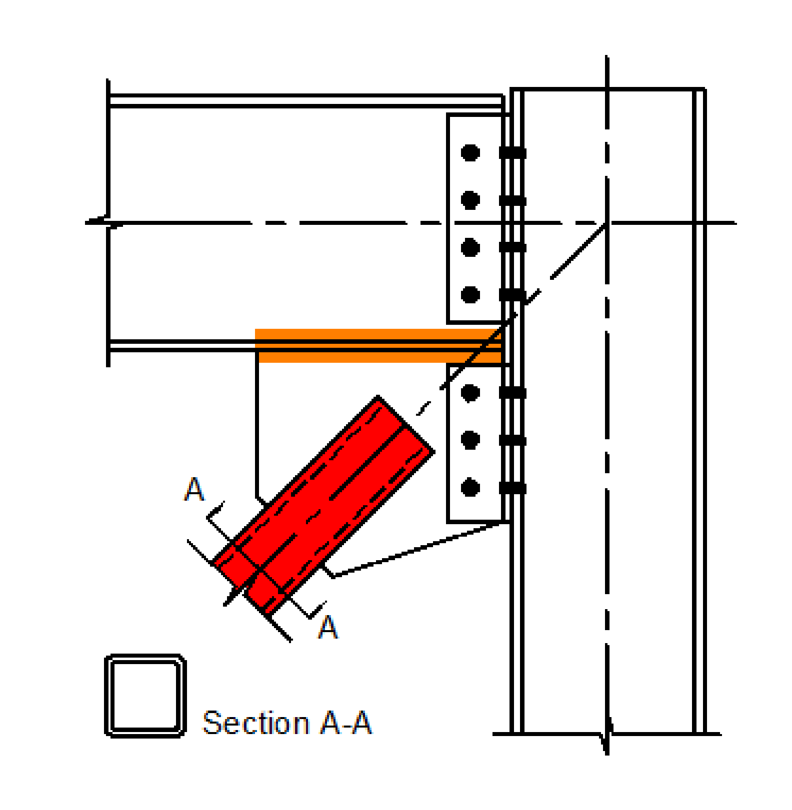
LFM

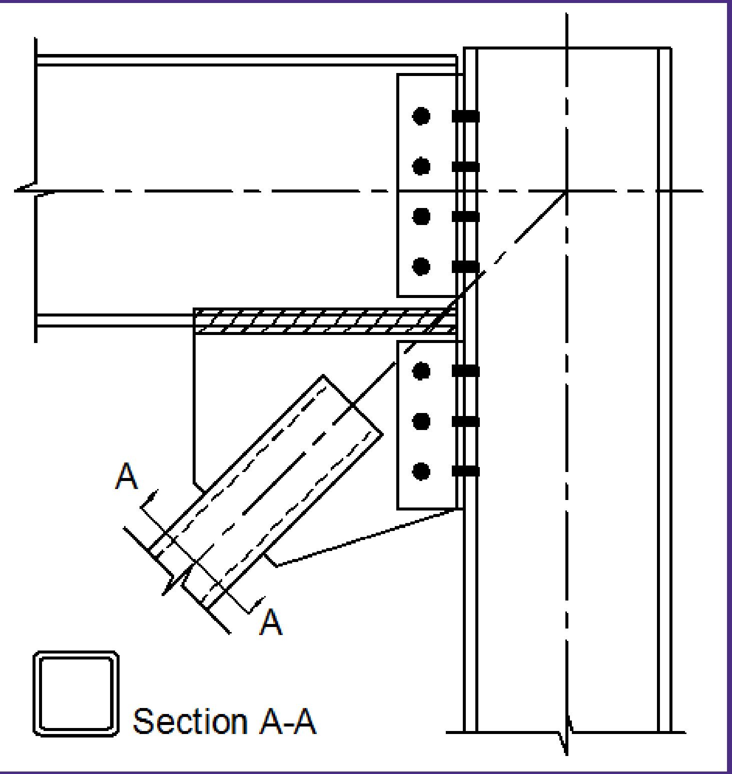
PFM

Retrofit of NCBFs

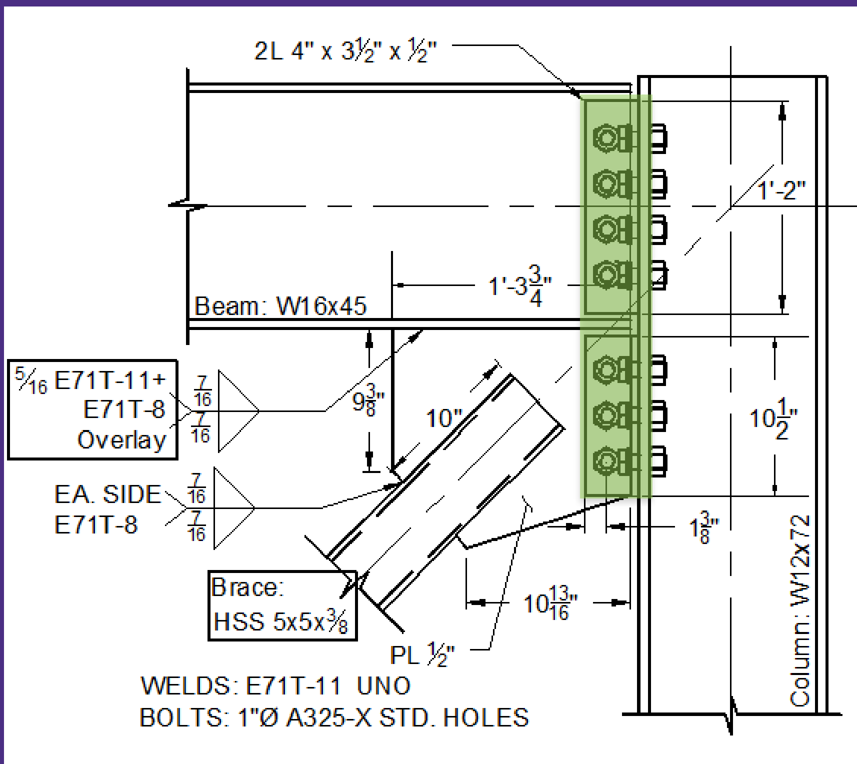
Connection Type	NCBF	NCBF w/ Brace Retrofit	NCBF w/ 2 Retrofits
Welded		  	
Bolted Continuous		  	
Bolted Split	 	 	
End Plate		  	

Bolted-Bolted Split Double Angles w/ Weld Overlay



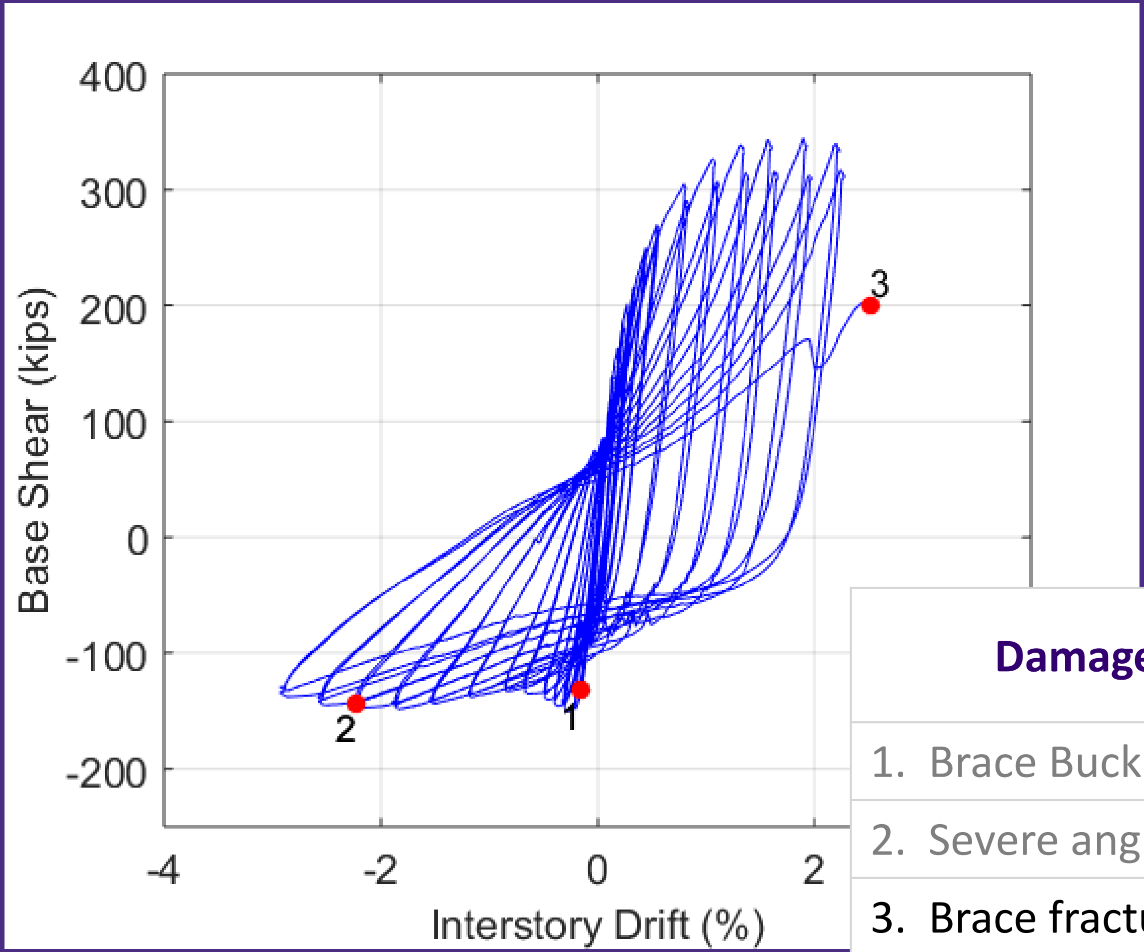


Bolted-Bolted Split Double Angles w/ Weld Overlay



Yielding Mechanisms	**AISC DCR**	**BDP DCR**
Whitmore Yielding	0.8	0.7
GP Bolt Bearing	0.9	1.3
Beam Bolt Bearing	1.3	1.5
Prying Action	3.6	
Failure Modes	**AISC DCR**	**BDP DCR**
GP-Brace Weld Fracture	0.7	0.7
Whitmore Fracture	0.6	0.5
GP Block Shear	0.7	0.6
GP-Beam Weld Fracture	0.3	0.7
GP Bolt Rupture	0.4	0.6
Geometric Limits		
Brace Compactness Ratio	0.92	
Slenderness	89.4	

Bolted-Bolted Split Double Angles w/ Weld Overlay



Damage Progression	Drift Range
1. Brace Buckling	0.3%
2. Severe angle prying.	3.9%
3. Brace fracture.	5.1%

Concluding Thoughts

- Large-scale testing critical to determine yield mechanisms and failure modes.
- Analysis alone would be insufficient
- New design and retrofit should maximize yielding by **balancing** the **brace capacity** & **secondary yield mechanisms** with undesired failure modes.
- NCBFs have low drift capacity because of **non-compliant braces**. Advised retrofit: **brace replacement** (HSS, BRBs). Size brace for connection **DCRs < 1**.
- Response of connection can determine the seismic performance of the retrofitted system. In particular welded (E70T-11) connections sustain early fracture**. Weld overlays** and supplemental bolts are valid retrofit strategies.

Questions

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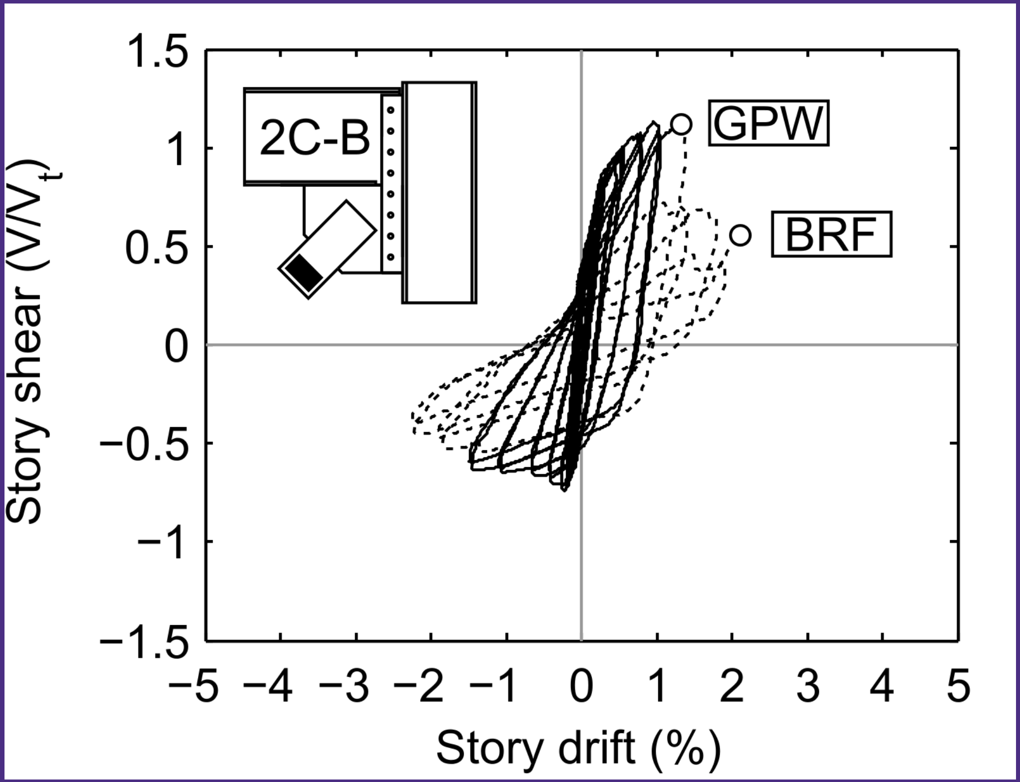
Concrete-Filled Brace

FILL BRACE WITH CONCRETE & ADD BOLTS to WELDED SHEAR PLATE



Replace with BRB

Note that beam-to-gusset weld still vulnerable