FEMA Program to Reduce Earthquake Hazards in Steel Moment-Frame Structures

Overview of the FEMA/SAC Steel Program

A New Paradigm for Design, Evaluation and Upgrading of Steel Moment Frame Buildings

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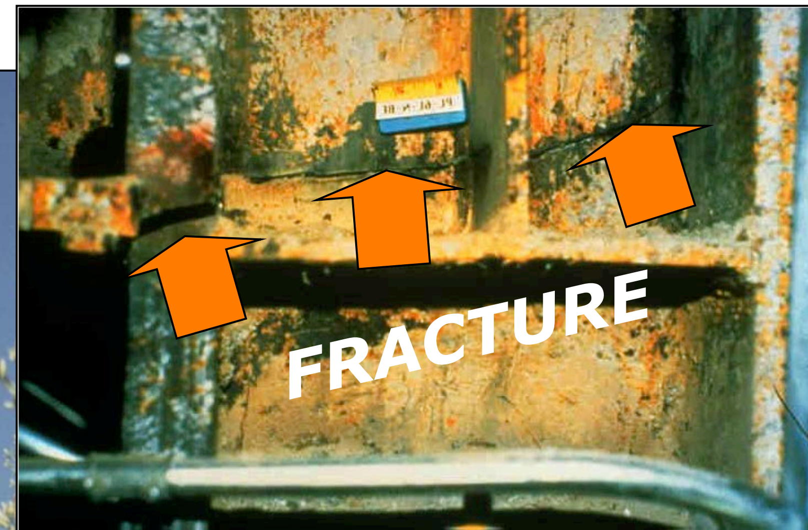
Typical Welded Steel Moment-Resisting Frame Buildings

All of these were damaged in 1994 Northridge Earthquake

Brittle Connection Fractures Detected Following 1994 Northridge Earthquake



Damage presumed if:

- *Unusually severe nonstructural damage*
- *PGA>25%g*
- *Within 1 mile of another damaged building*

Building was demolished and rebuilt

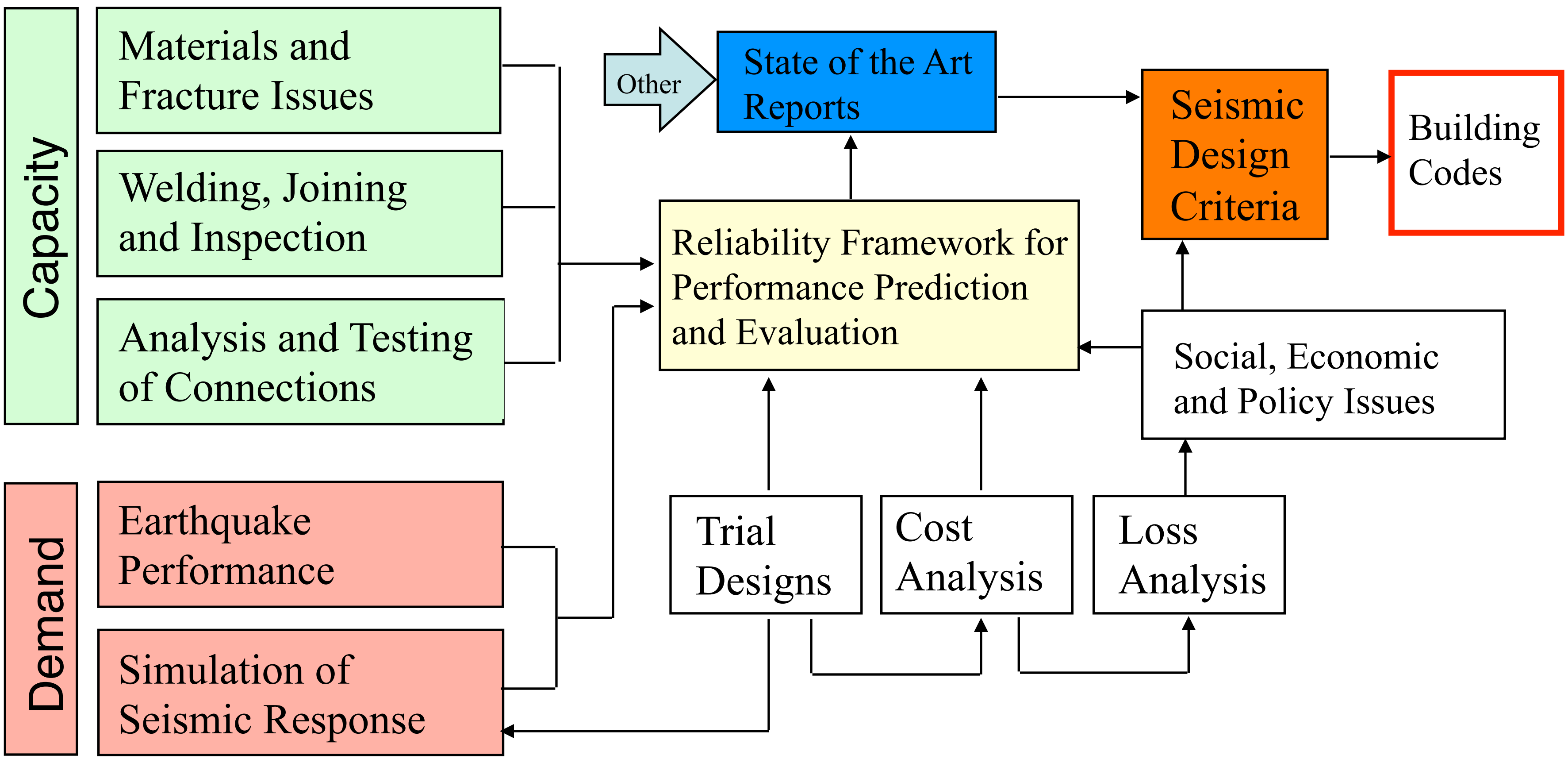
FEMA Program to Reduce the Earthquake Hazards of Steel Moment-Frame Structures

Goals: Develop reliable, practical and cost-effective guidelines and standards of practice for:

- the design and construction of **new** steel moment-frame buildings,
- the identification, inspection, evaluation and retrofit of **existing** at-risk welded steel moment-frame buildings, and
- the identification, evaluation, **repair** or upgrading of damaged buildings following earthquakes.

The FEMA/SAC Steel Project

Holistic "Performance-based" Approach to Guideline Development and Validation

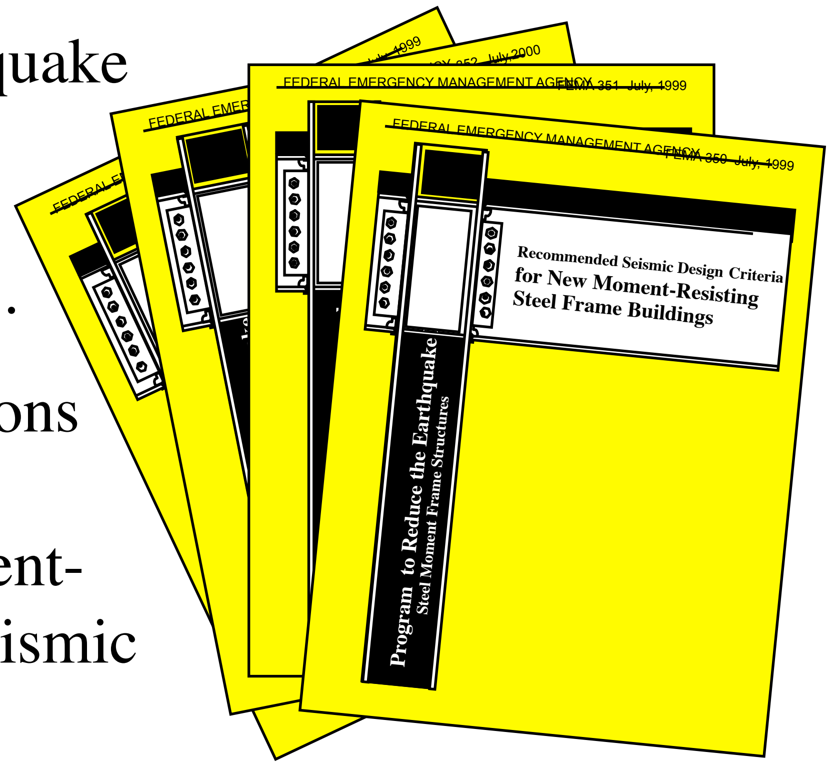


The Guidelines

FEMA-350: Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings.

FEMA-351: Recommended Seismic Evaluation and Upgrade Criteria for Existing Welded Steel Moment-Frame Buildings.

FEMA-352: Recommended Post-earthquake Evaluation and Repair Criteria for Welded, Steel Moment- Frame Buildings.



FEMA-353: Recommended Specifications and Quality Assurance Guidelines for Steel Moment-Frame Construction for Seismic Applications.

FEMA-354: Policy Guide for Steel Frame Construction

80+ Technical Reports Synthesized into State-of-the-Art Reports

FEMA-355A: Base Metals and Fracture

FEMA-355B: Welding and Inspection

FEMA-355C: Systems Performance

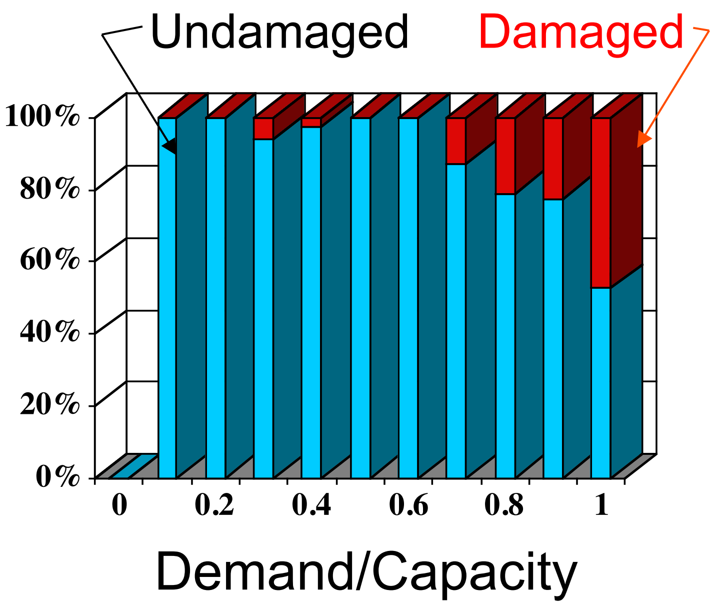
FEMA-355D: Connection Performance

FEMA 355E: Past Performance of Steel Moment-Frame Buildings in Earthquakes

FEMA-355F*:* Performance Prediction and Evaluation

Early Assertion: Damage due to unusual severity of ground shaking?

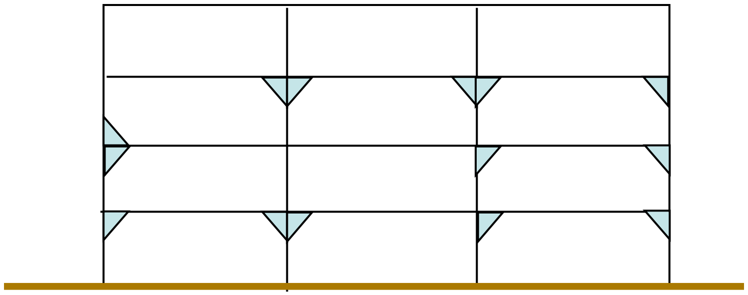
- While ground motion was severe, it was not greater than anticipated in design of many damaged buildings.
- Most buildings were substantially (two to three times) stronger than minimum code forces.
- Many fractures occurred in buildings that should have responded elastically
- Typically, D/C < 2



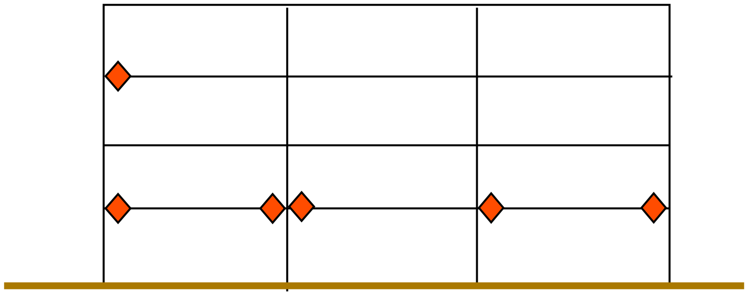
Assertion: Damage was due to inadequate field workmanship?

Early Assertion: We can predict damage locations by computer analysis

- Only modest correlation of local damage location to predictions from nonlinear time history analyses
  - Fracture criteria uncertain?
  - Results very sensitive to modeling assumptions
- Regions (floors) with higher D/C ratios tend to have higher damage



13 Fractured Connections



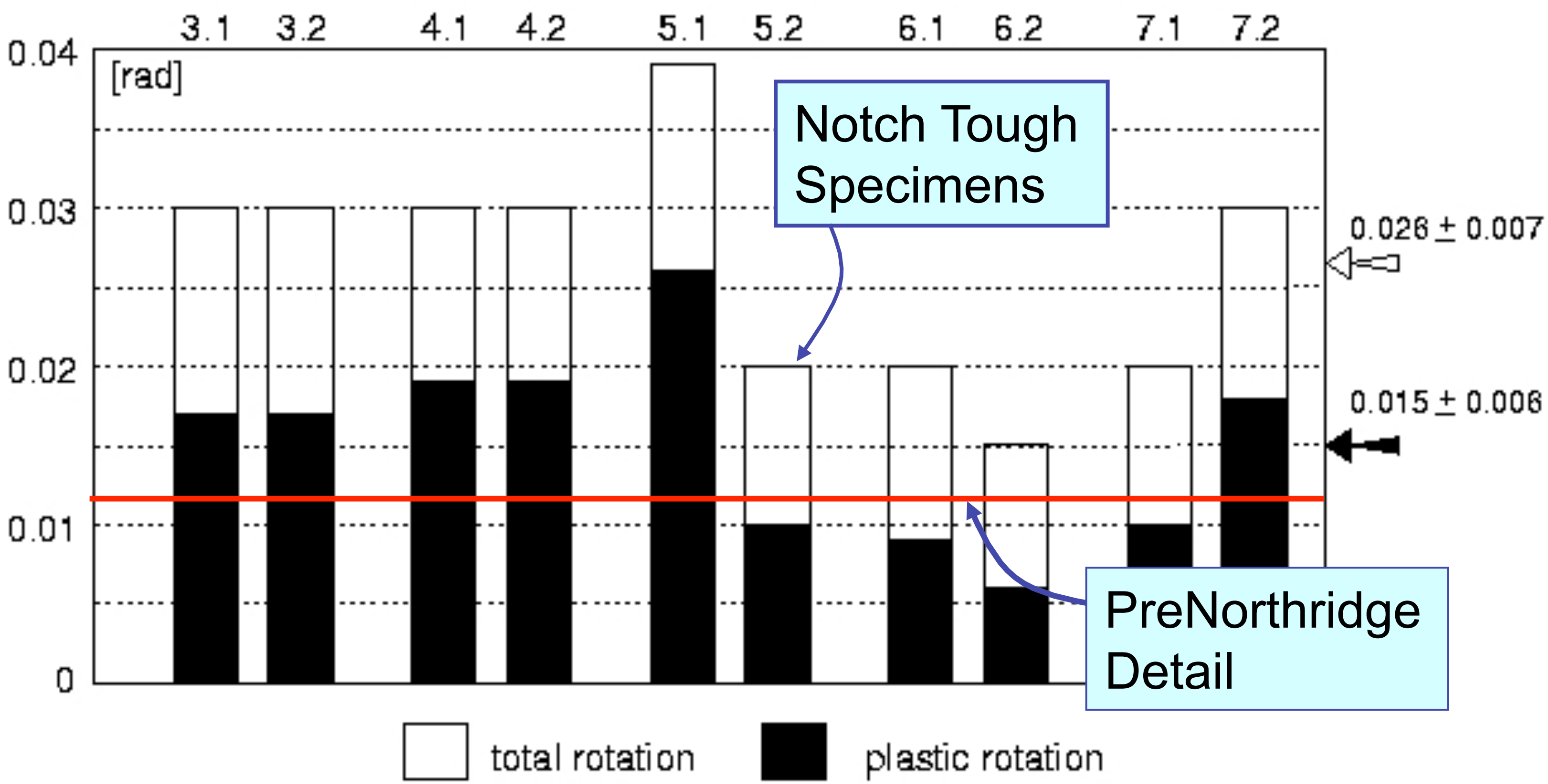
6 Highest D/C Ratios from Analysis

Pre-Northridge Welded Connections

Behavior of Pre-Northridge welded steel moment connections influenced by many interacting factors, including:

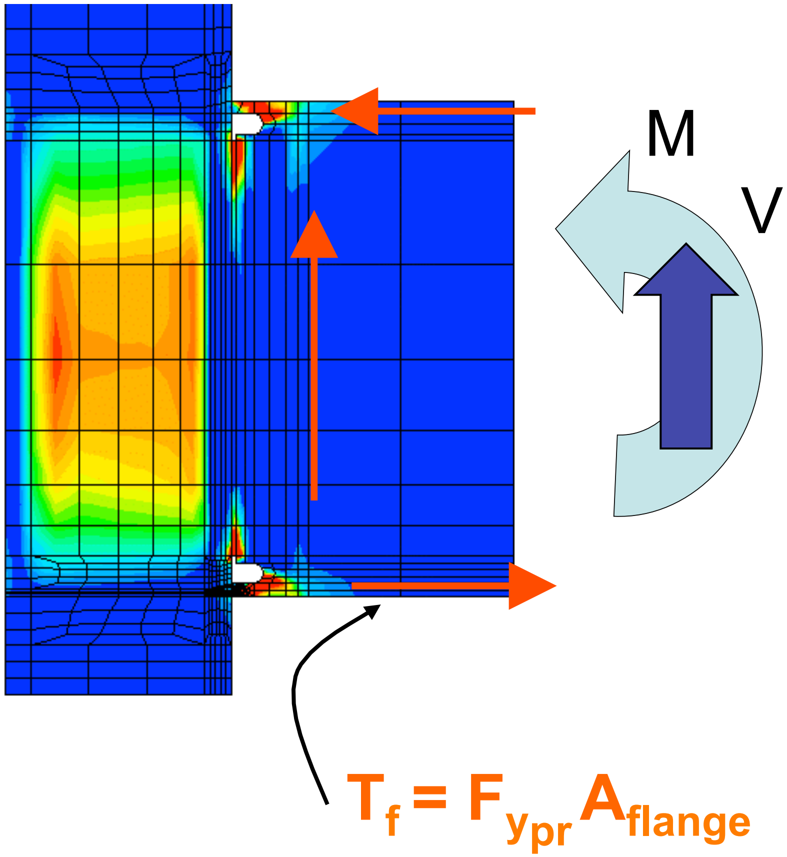
- Load transfer mechanism
  - Frame configuration
  - Basic geometry of connection
  - Shear transfer mechanism
  - Panel zone deformations, etc.
- Quality of Welds
- Fracture sensitivity of typical connection details

Rotation capacities for Stage I unreinforced, notch-tough connections

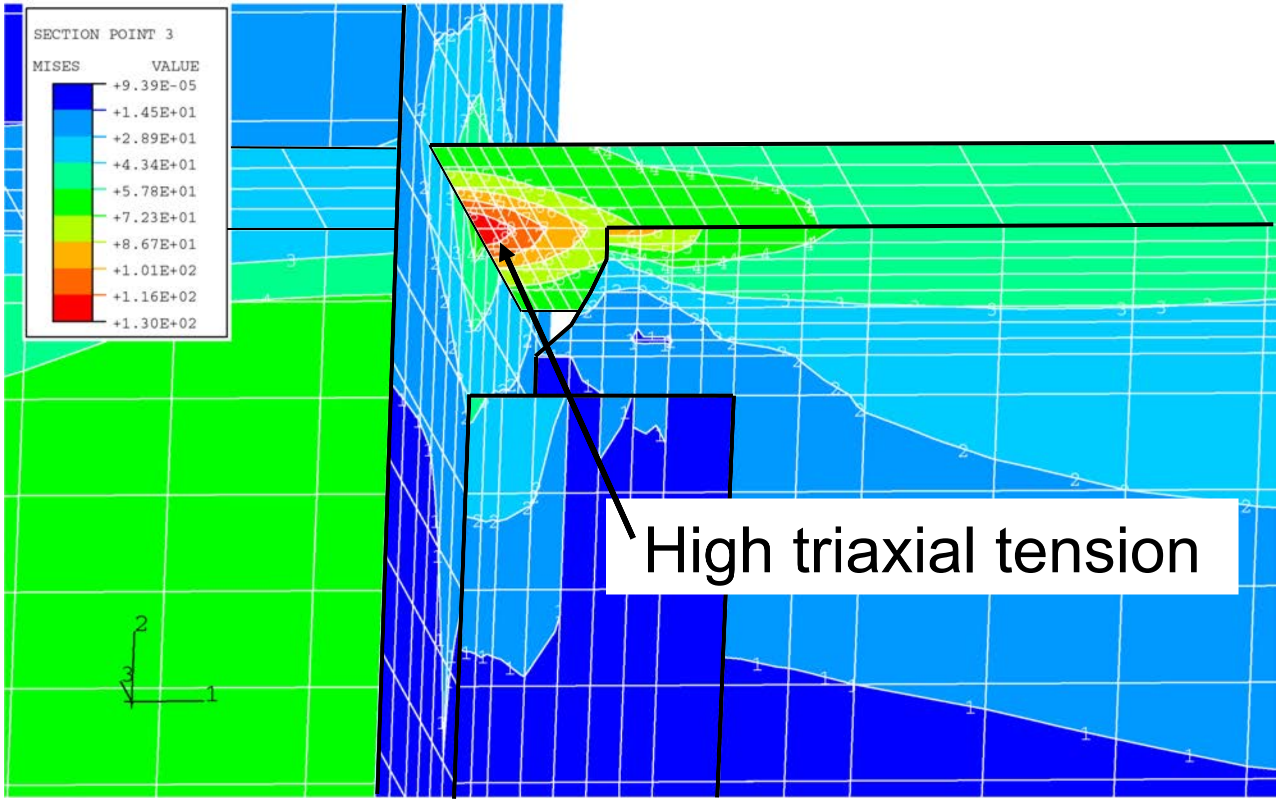


What forces should the welds resist?

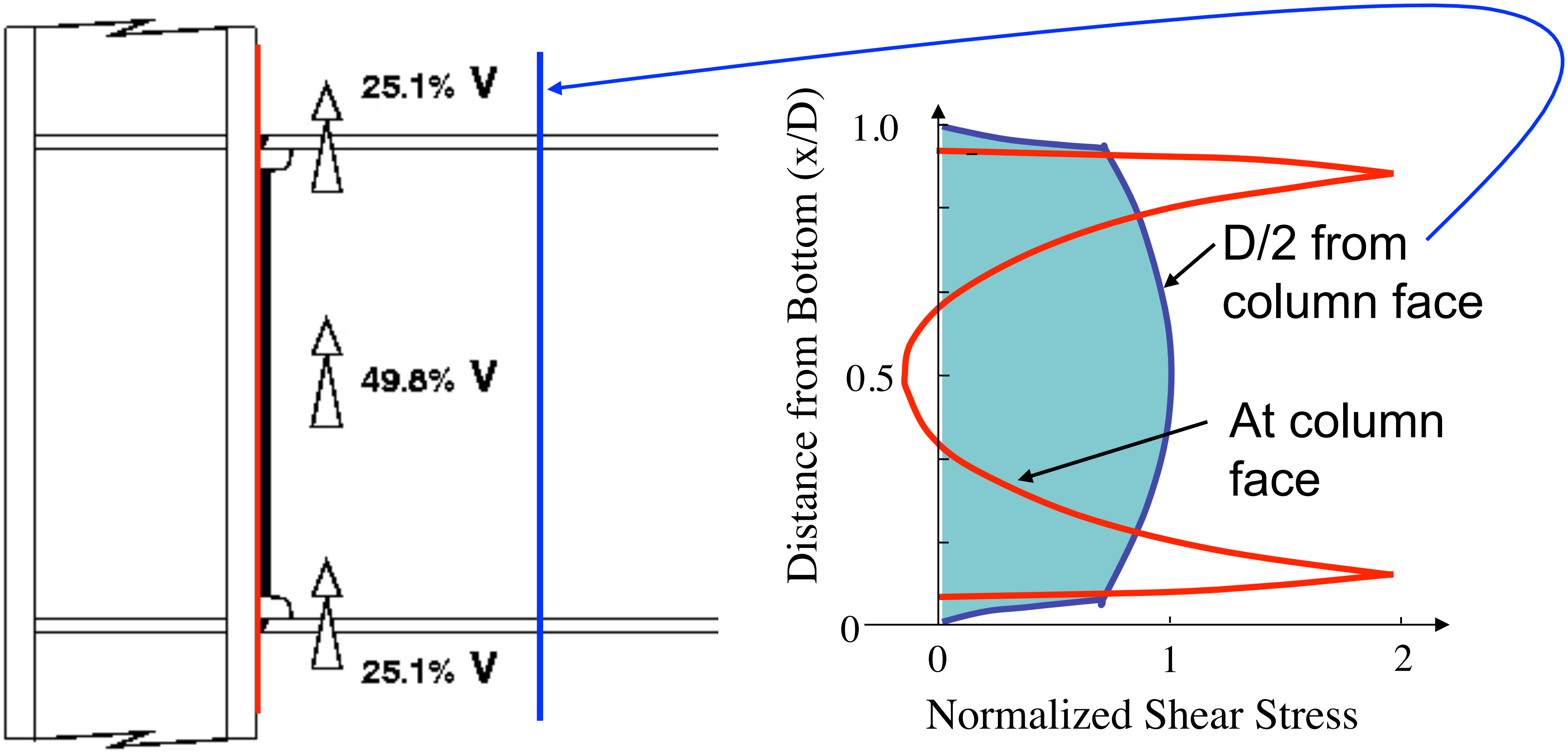
- Flanges typically assumed to be subjected to pure tension or compression
- Such typical beam design are assumptions known to be flawed near connection (St. Venant 1855)



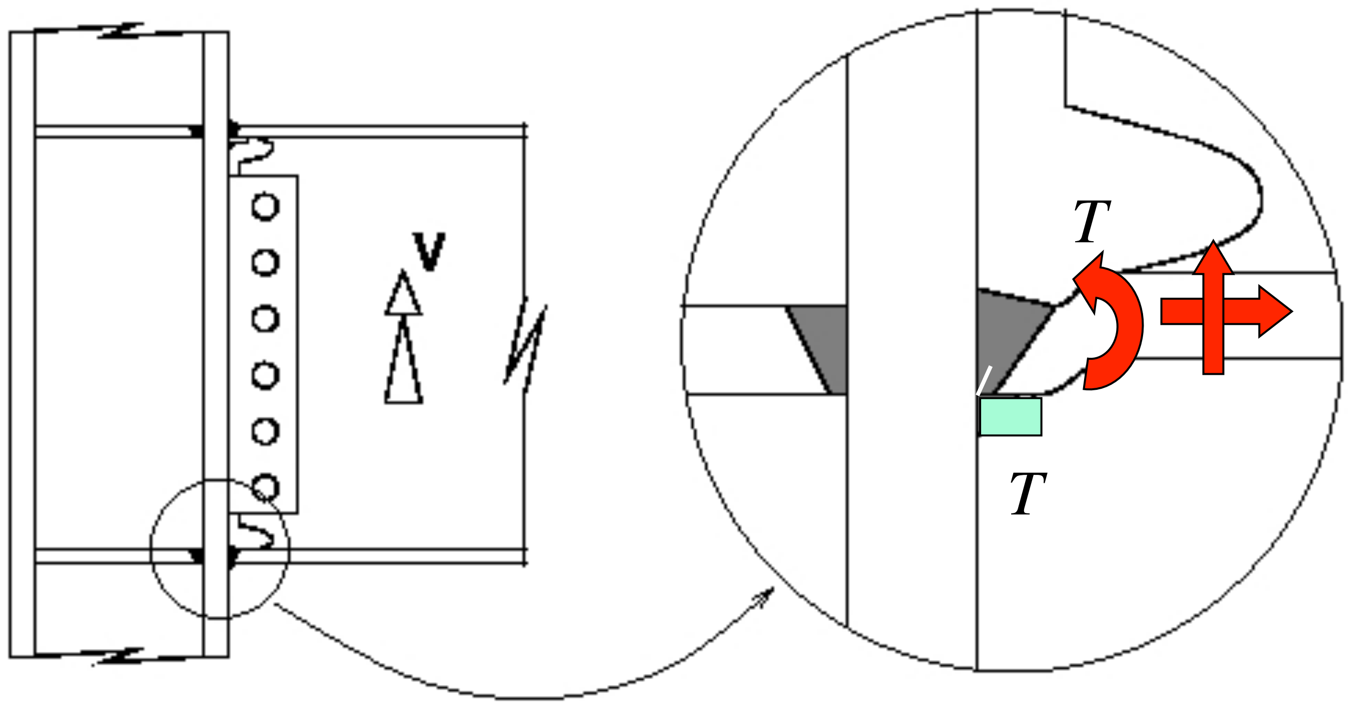
Non-uniform distribution of axial stresses in beam flange at column face



Beam flanges carry considerable shear

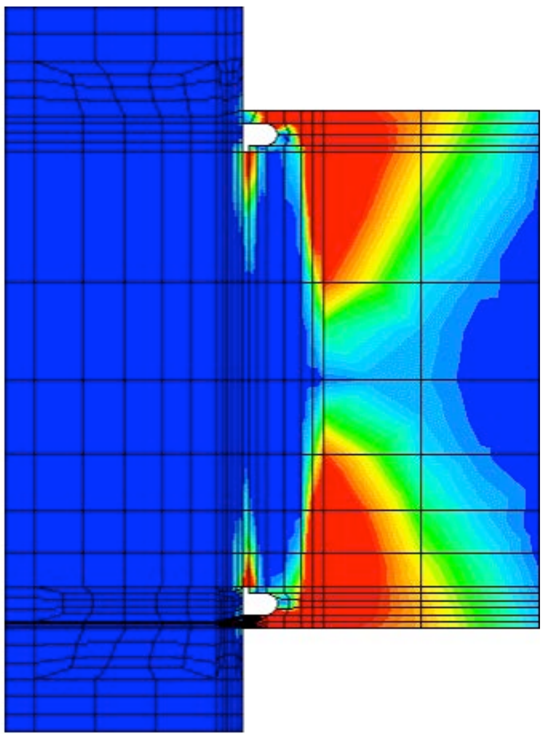


Local Flange Deformation

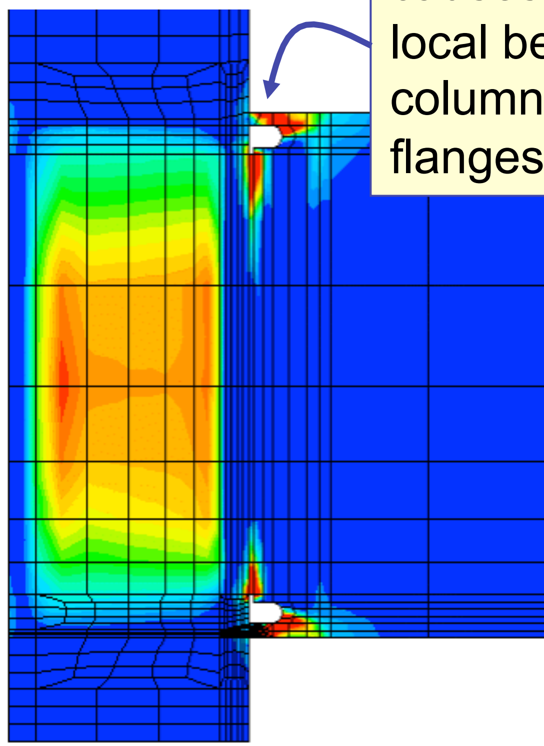


Shear in flanges develops significant additional local bending (tensile) stresses

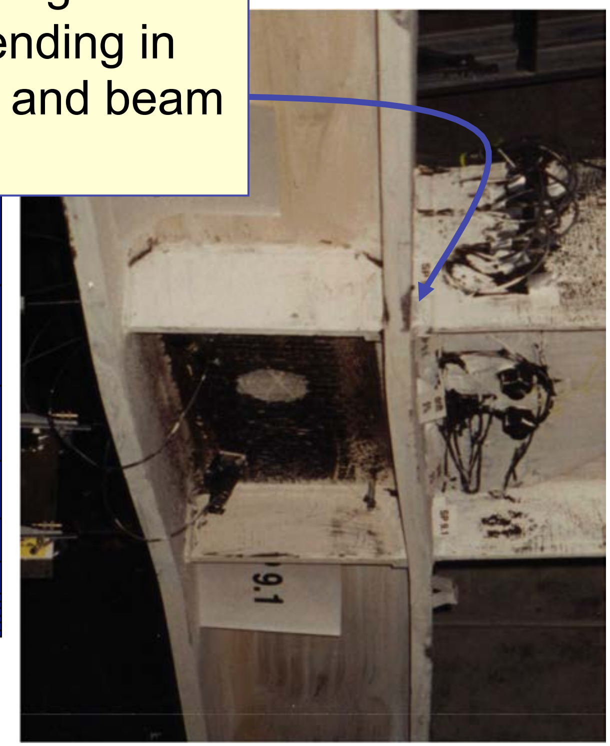
Panel Zone Yielding



Strong Panel Zone

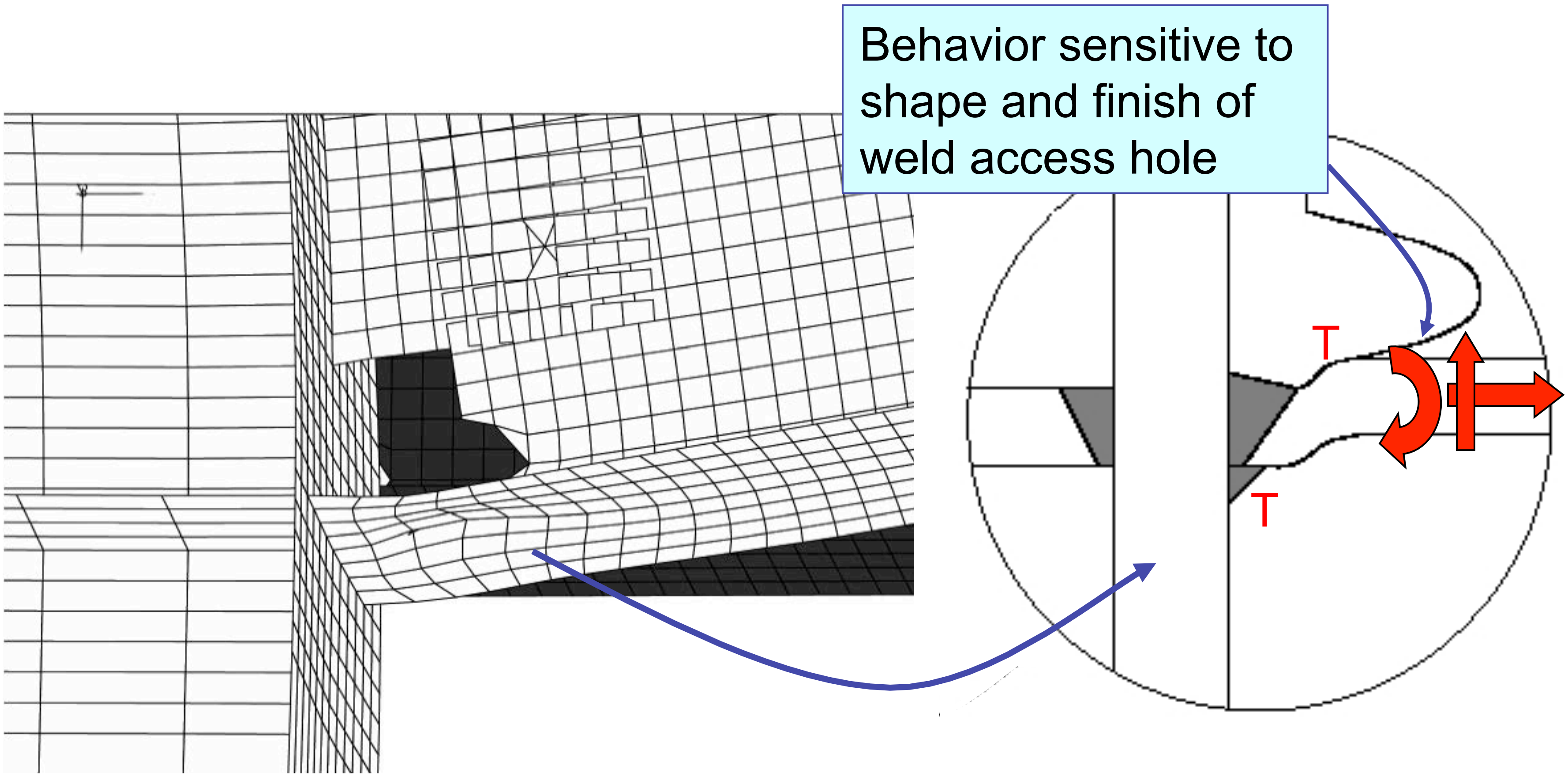


“Kinked” column causes high local bending in column and beam flanges



-------------- Weak Panel Zone --------------

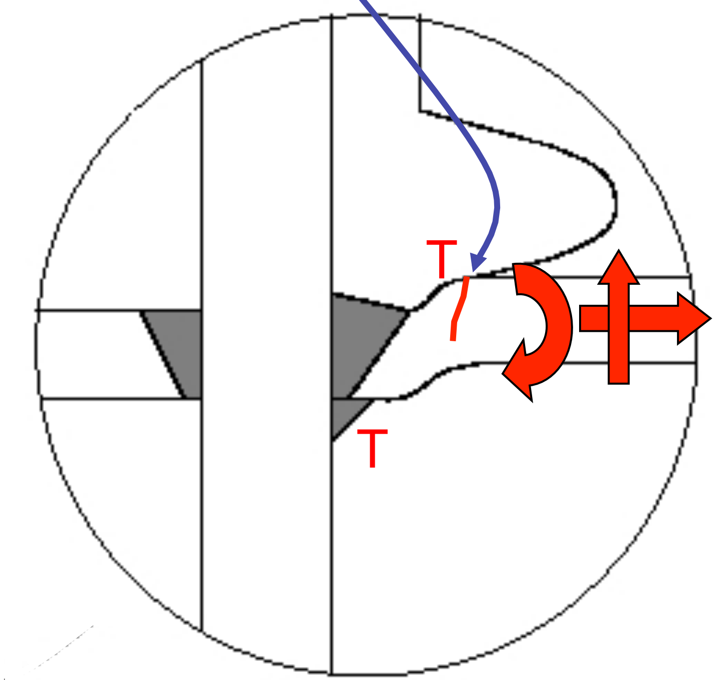
Bi-directional bending in beam flange at toe of weld access hole



Eccentric “shear link” action

Weld at column face protected by improved design, but failure shifts to next weakest link

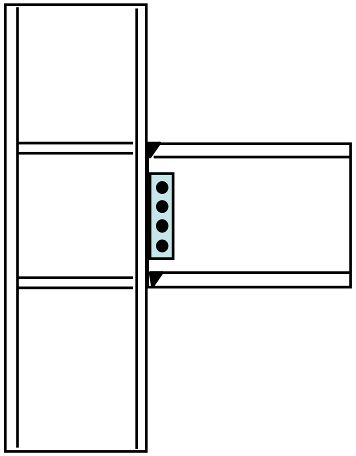
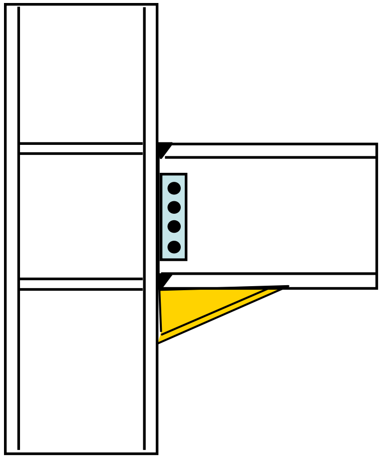
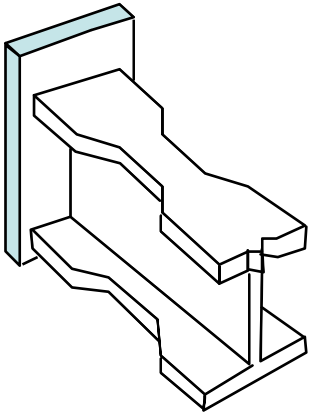
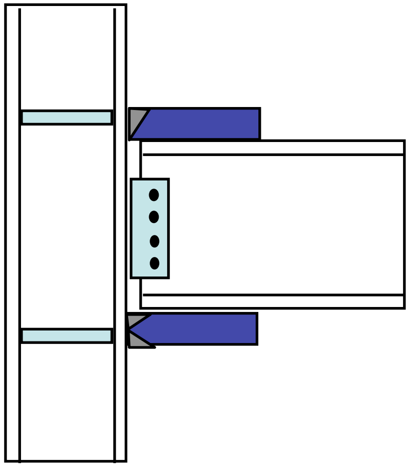
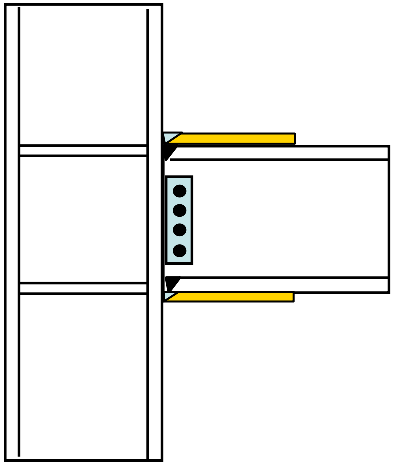
Plastic Crack Initiation and Gradual Growth Under Cyclic Loading



Some Alternatives Considered

<u>Welded Connections</u>

- "Improved" unreinforced connections.
- Reinforced connections
- Welded flange plate connections
- Reduced beam section connections

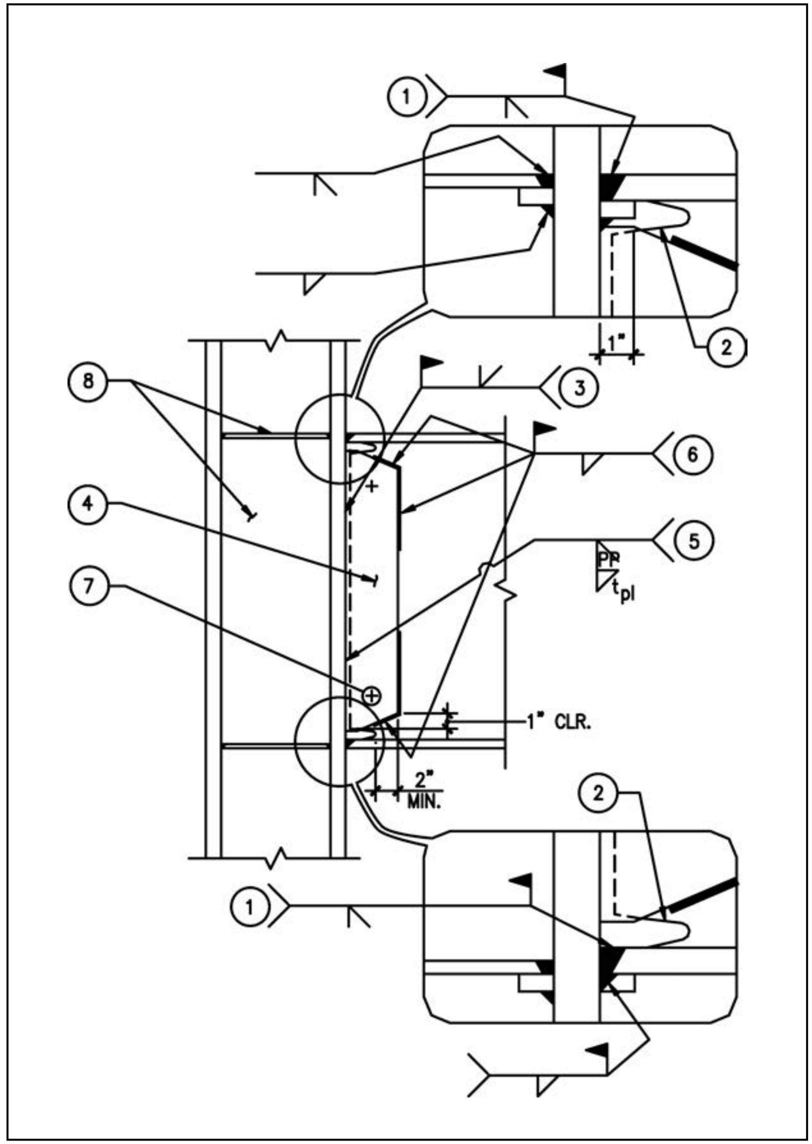
<u>Bolted Connections</u>

<u>Prequalified Connections</u> deemed to satisfy requirements of code

Acceptance Criteria:

- OMF: θ_{SD}=0.02, θ_U=0.03
- SMF: θ_{SD}=0.04, θ_U=0.06

Detailed Design and Construction Requirements Specified for Prequalified Connections

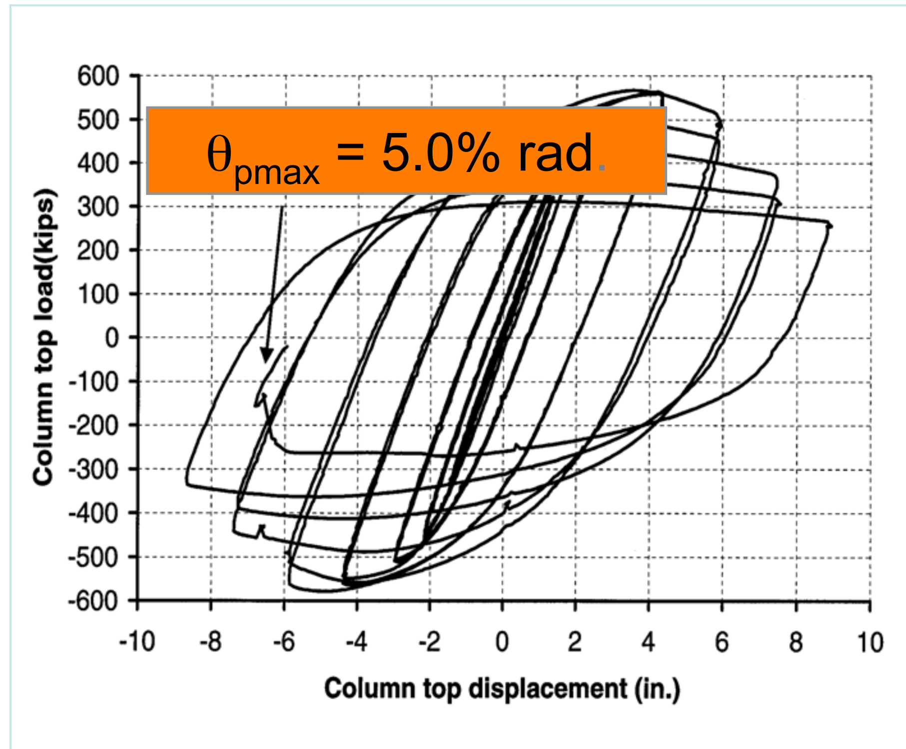


Welded Unreinforced Flange-Welded Web (WUF-W) Connection

Continued refinement leads to "prequalified" connections

Identify and characterize all local failure modes; Specify design method that controls connection behavior

Specimen C2 upon completion of testing



Lateral load-displacement relationship

Systems Approach

Need method to relate capacities and demands

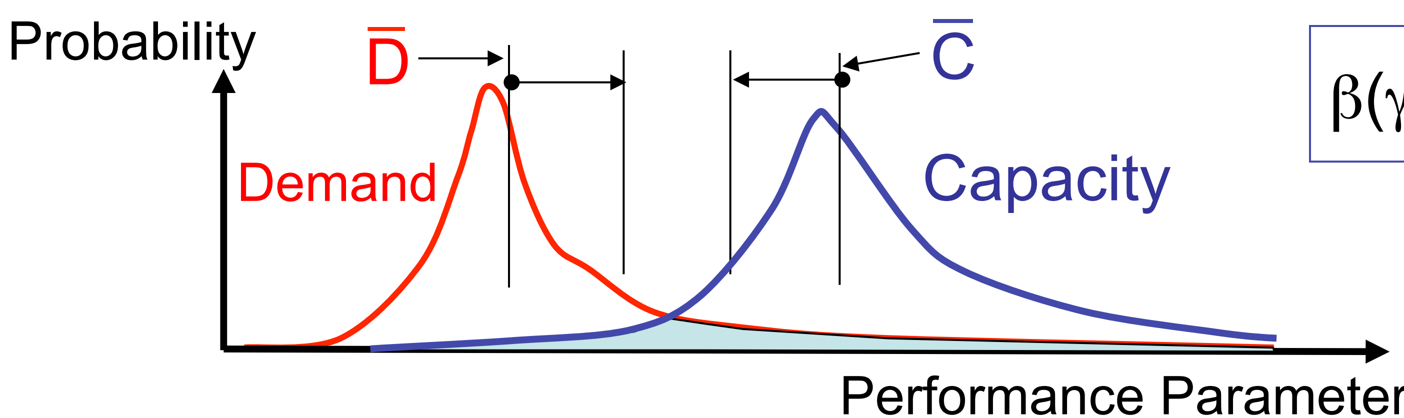
Built upon transparent reliability framework

- Manage risk and uncertainties
- Performance-based engineering concepts

$$\bar{D}(1+\alpha_d\sigma_d) > \bar{C}(1-\alpha_c\sigma_c)$$

Load and Resistance Factor Design Format

$$\beta(\gamma\bar{D}) < \Phi\bar{C}$$



New SAC Approach

Frame Problem as:

I am highly/moderately/not confident that a stated performance level will be achieved for a given seismic hazard; for example,...

> I am 50% confident that the structure will not collapse if subjected to an earthquake with a 2% probability of occurring in 50 years.

SAC targets for new construction (2% in 50 year event)

- 90% confidence for avoiding global collapse
- 50% confidence for avoiding local damage leading to local collapse

PRECURSOR to PEER PBEE methodology and FEMA 795 and P58

Analysis Methods & Adjustment Factors

Structural Characteristics				Analytical Procedure			
Performance Level	Fundamental Period, T	Regularity	Ratio of Column to Beam Strength	Linear Static	Linear Dynamic	Nonlinear Static	Nonlinear Dynamic
Immediate Occupancy	$T \leq 3.5T_s$[1]	Regular or Irregular	Any Conditions	Permitted	Permitted	Permitted	Permitted
	$T > 3.5\ T_s$[1]	Regular or Irregular	Any Conditions	Not Permitted	Permitted	Not Permitted	Permitted
Collapse Prevention	$T \leq 3.5T_s$[1]	Regular[2]	Strong Column[3]	Permitted	Permitted	Permitted	Permitted
			Weak Column[3]	Not Permitted	Not Permitted	Permitted	Permitted
		Irregular[2]	Any Conditions	Not Permitted	Not Permitted	Permitted	Permitted
	$T > 3.5T_s$	Regular	Strong Column[3]	Not Permitted	Permitted	Not Permitted	Permitted
			Weak Column[3]	Not Permitted	Not Permitted	Not Permitted	Permitted
		Irregular[2]	Any Conditions	Not Permitted	Not Permitted	Not Permitted	Permitted

For New Construction

Representative confidences of not exceeding performance criteria in Los Angeles for 2% in 50 year earthquake hazard

	Performance Criteria	
Building Height	Global Stability	Local Stability
3 stories	99%	99%
9 stories	99%	95%
20 stories	96%	96%

SAC vs. 1994 UBC Designs

Representative confidences of not exceeding performance criteria in Los Angeles for 2% in 50 year earthquake hazard

Building Height	Performance Criteria			
	Global Stability		Local Stability	
	SAC	1994	SAC	1994
3 stories	99%	88%	99%	22%
9 stories	99%	57%	95%	29%
20 stories	96%	57%	96%	39%

Reliabilities for different age building

Representative confidences of not exceeding performance criteria in Los Angeles for 2% in 50 year earthquake hazard

	Performance Criteria			
Building Height	Local Stability			
	SAC	1994	1985	1973
3 stories	99%	22%	9%	2%
9 stories	95%	29%	21%	7%
20 stories	96%	39%	42%	2%

Reliabilities for different age building

Representative confidences of not exceeding performance criteria in Los Angeles for 50% in 50 year earthquake hazard

Building Height	Performance Criteria			
	Local Stability			
	SAC	1994	1985	1973
3 stories	99%	99%	99%	99%
9 stories	99%	99%	99%	99%
20 stories	99%	99%	99%	99%

Summary

- Powerful performance-based evaluation method accounting for system and local level behavior of steel buildings developed, evaluated and implemented for:
  - evaluating and upgrading existing buildings,
  - assessing repair or upgrade strategies, and
  - designing new structures to targeted performance levels.
- Details used for welded steel moment frame structures prior to 1994 have been shown to be vulnerable to brittle fracture contrary to the intent of building codes.
- New details, with “simple” design methods and stringent limitations on ranges of parameters that can be used, have been identified that are believed to satisfy building code life safety objectives.

Summary

- While tremendous advances were made in seismic resistant design of steel moment frame construction, the underlying systematic performance-based approach was highly effective and successful.
  - Integrated research, guideline development and training
  - Focused substantial resources and expertise to solve complex technical, social and economic problems associated seismic loss reduction.
  - Widespread review by independent technical experts, design professionals, building officials, contractors, fabricators, and manufacturers.
- But, many problems remain unresolved….

SAC represented the work of many

- More than 80 projects and 250 active participants
- Tireless efforts by topical team leaders, guideline writers, and investigators
- Thanks to FEMA! (and Cal OES)
- Special remembrance of tremendous contributions by Allin Cornell, Helmut Krawinkler and Egor Popov

Had opportunity to work with many great people