Probabilistic Fracture Mechanics Based Design of Seismic Column Splices

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Acknowledgments

- Dimitrios!!
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- Jim Malley (Degenkolb)
- Mark Saunders (Rutherford and Chekene)
- AISC Committee on Seismic Effects
- Herrick Corporation

Earthquake induced fracture in steel structures (Northridge)

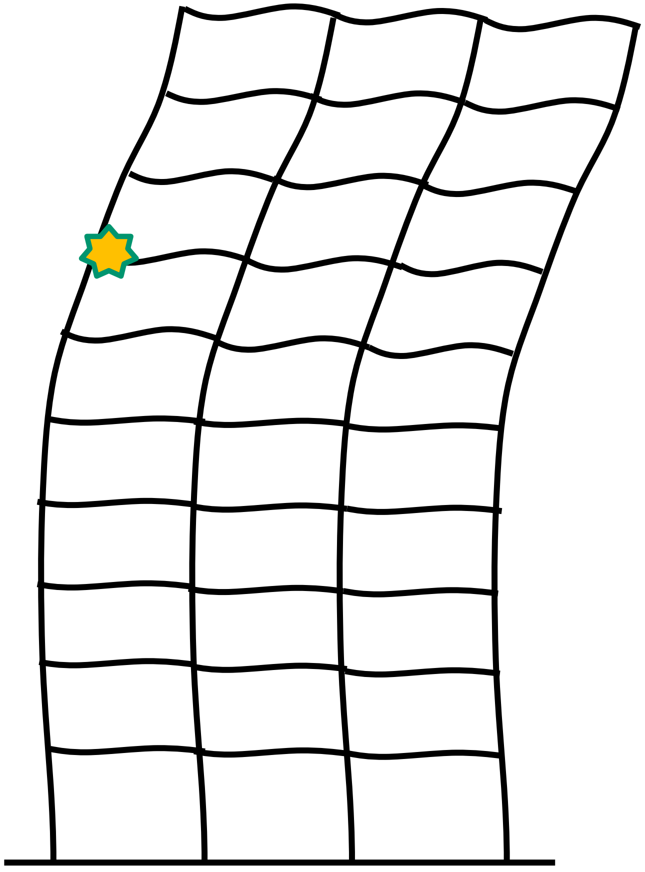

Photo Acknowledgment - AISC

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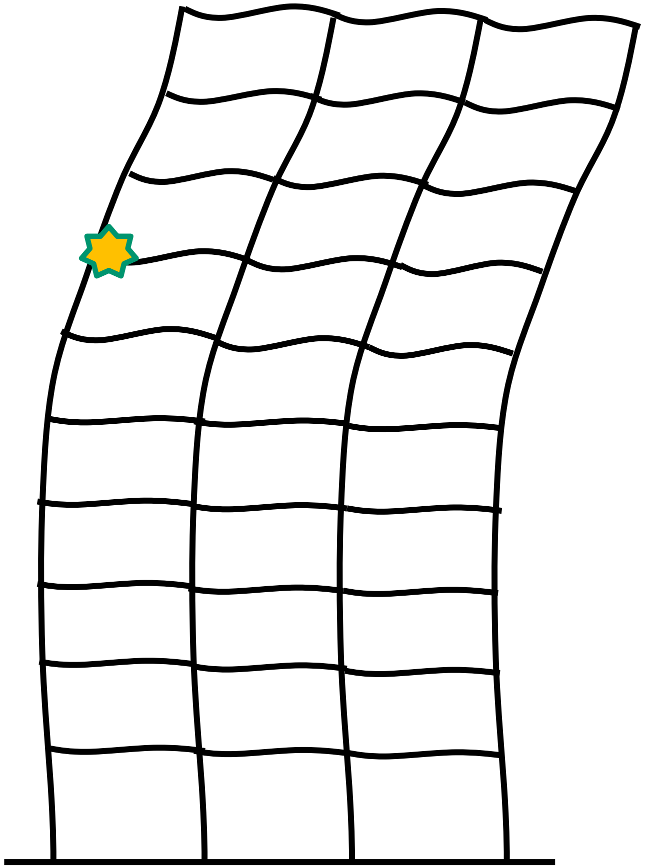
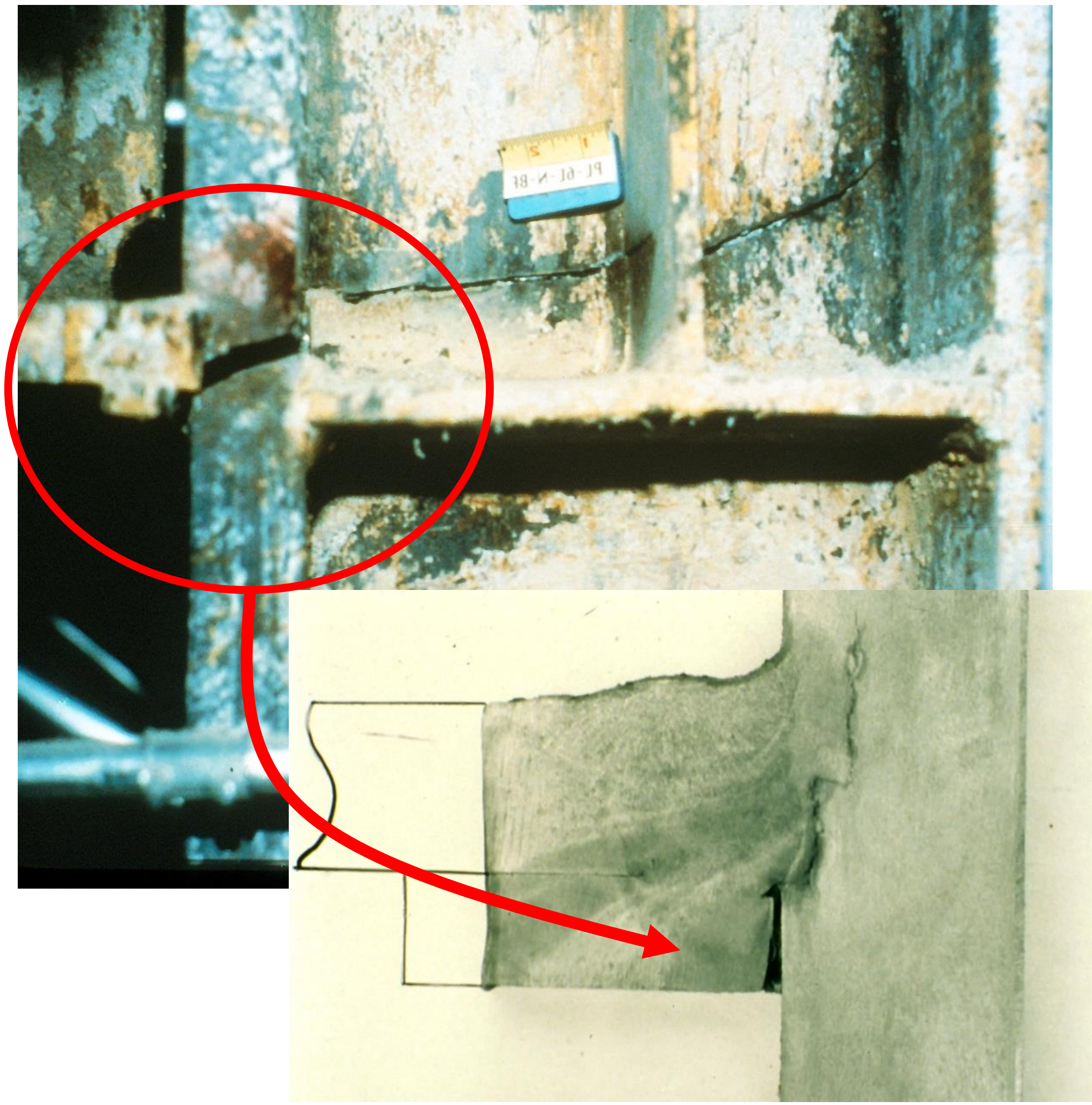
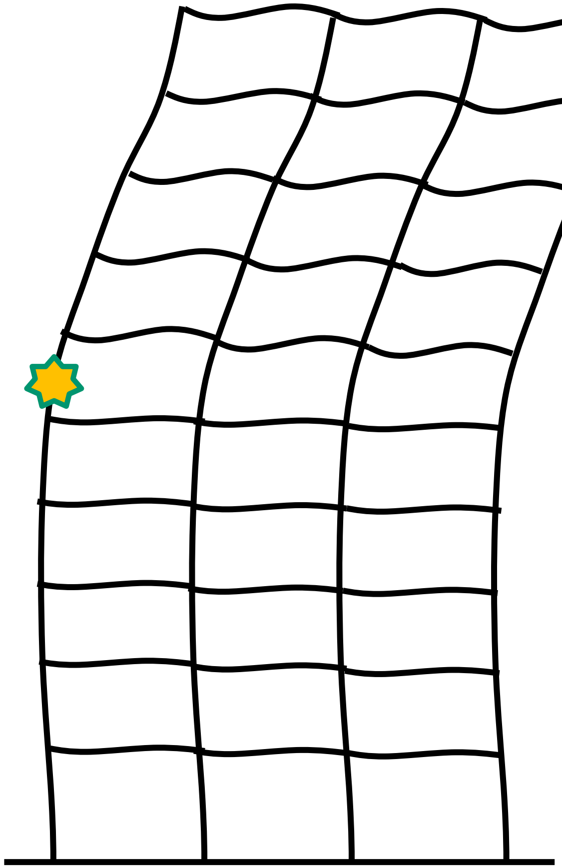
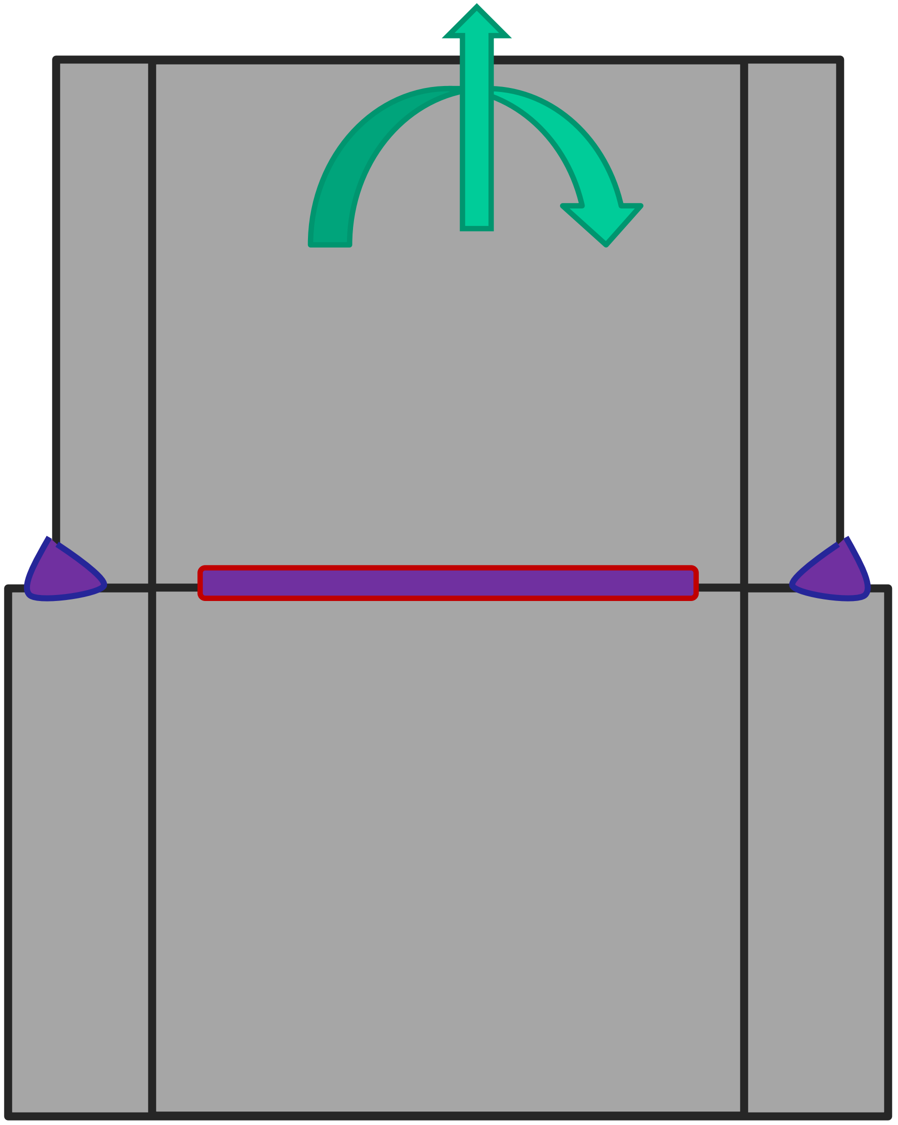




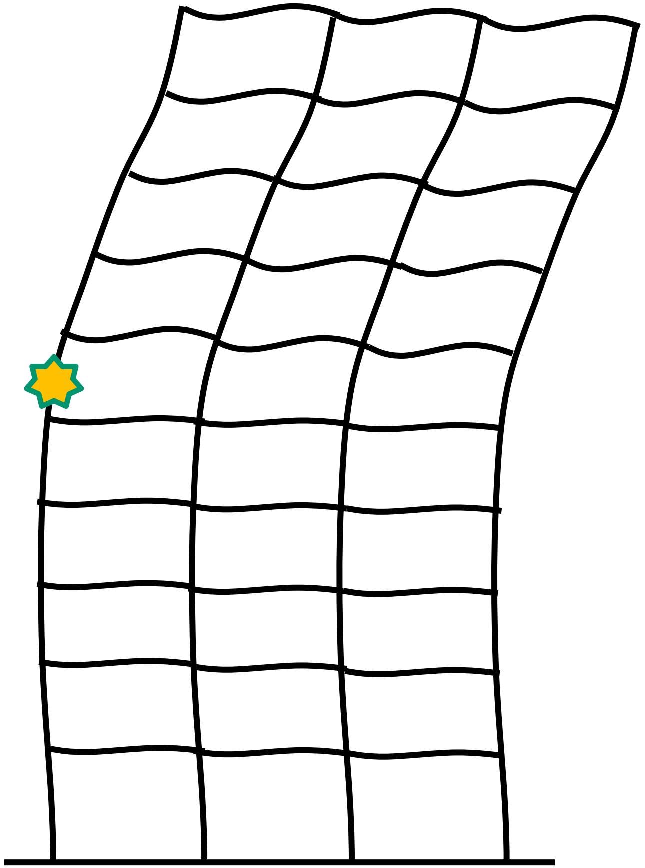
Sharp crack like flaw – resulting in fracture

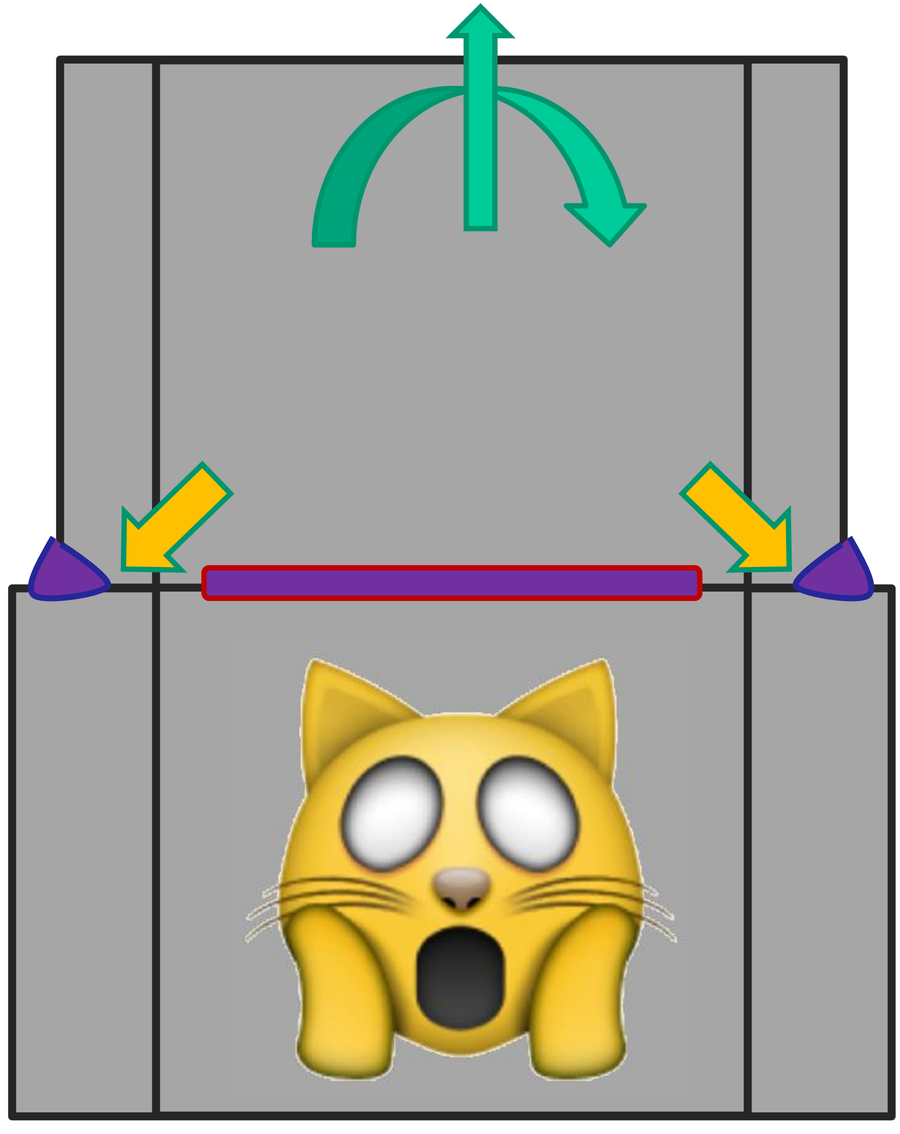
Pre-Northridge column splices



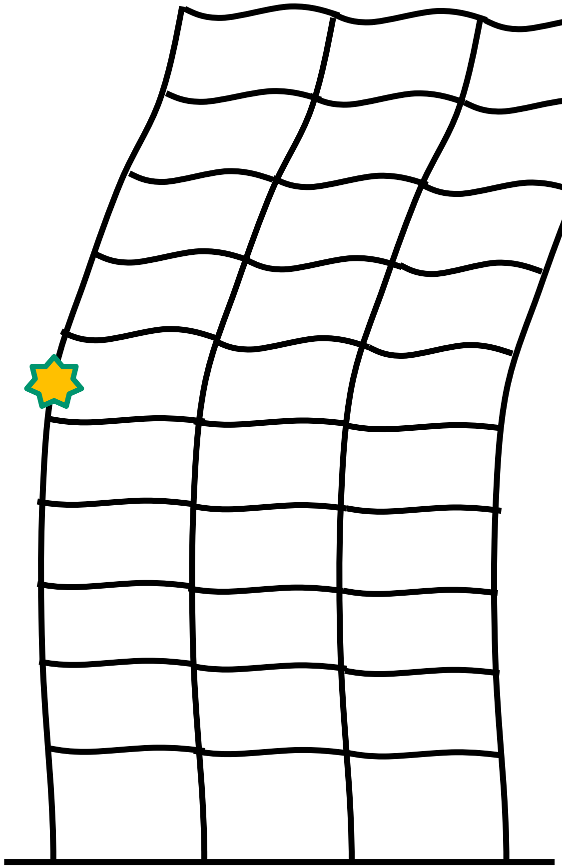


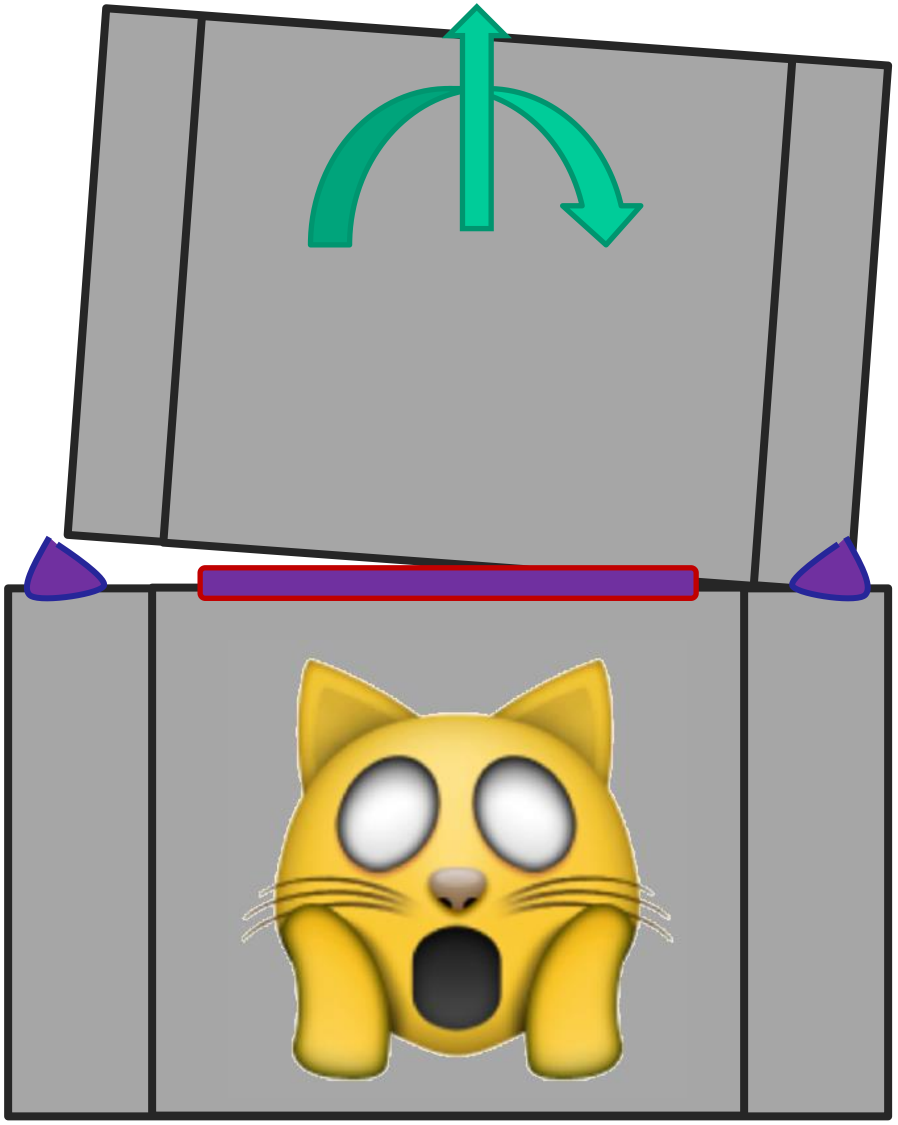
Partial Joint Penetration (PJP) welds





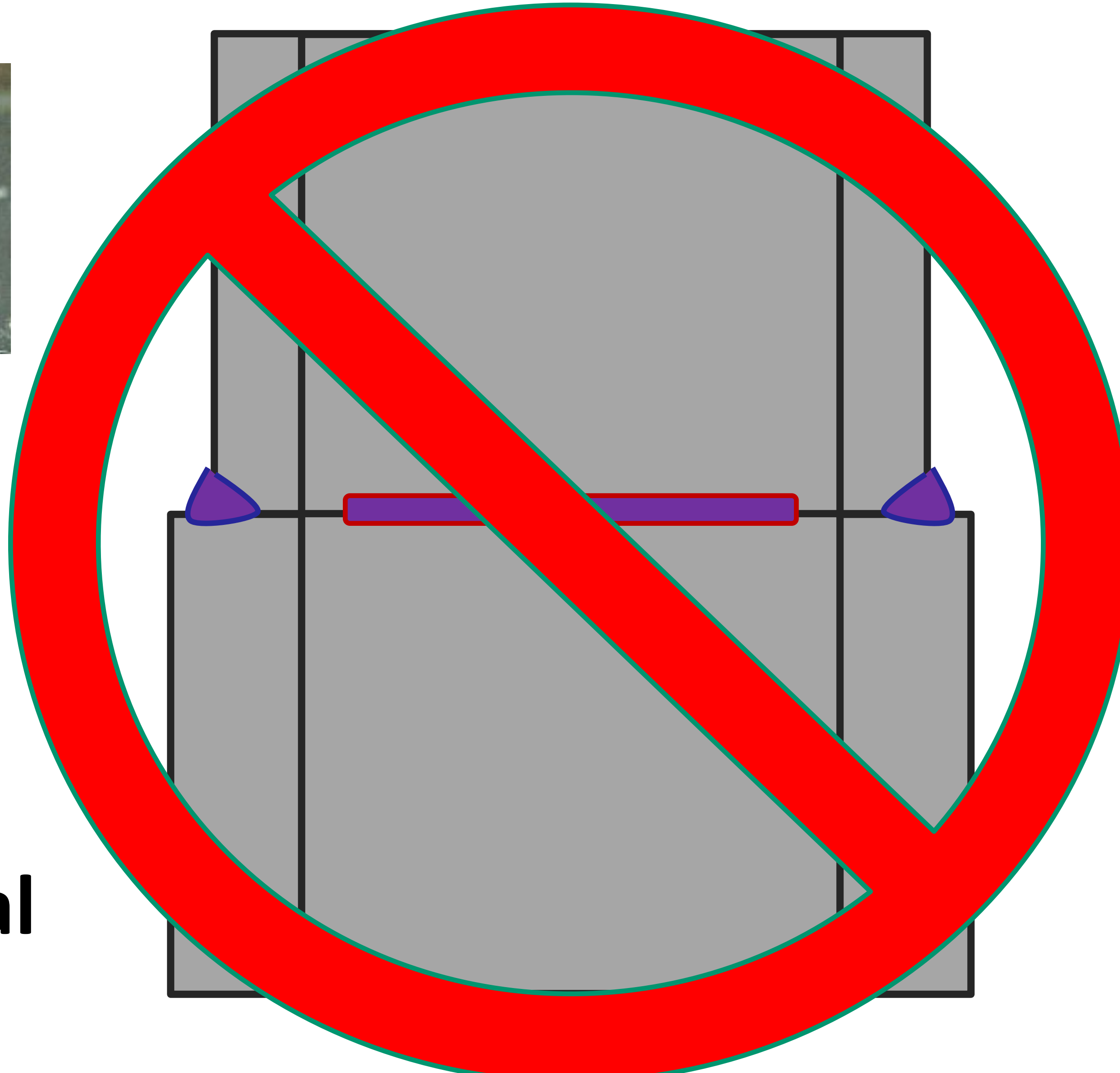
Risk of fracture





Elimination of notch (use only CJP)

Use of notch tough weld filler material and base metal

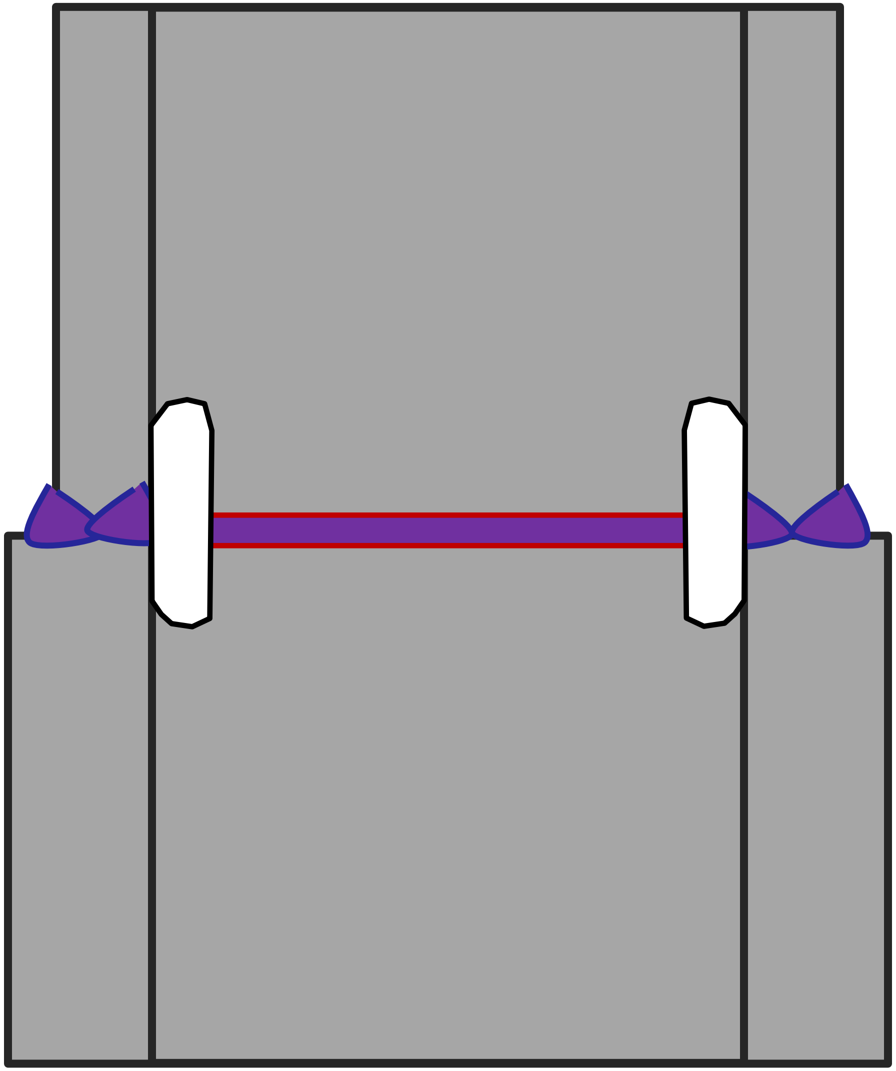


2010 AISC Seismic Provisions

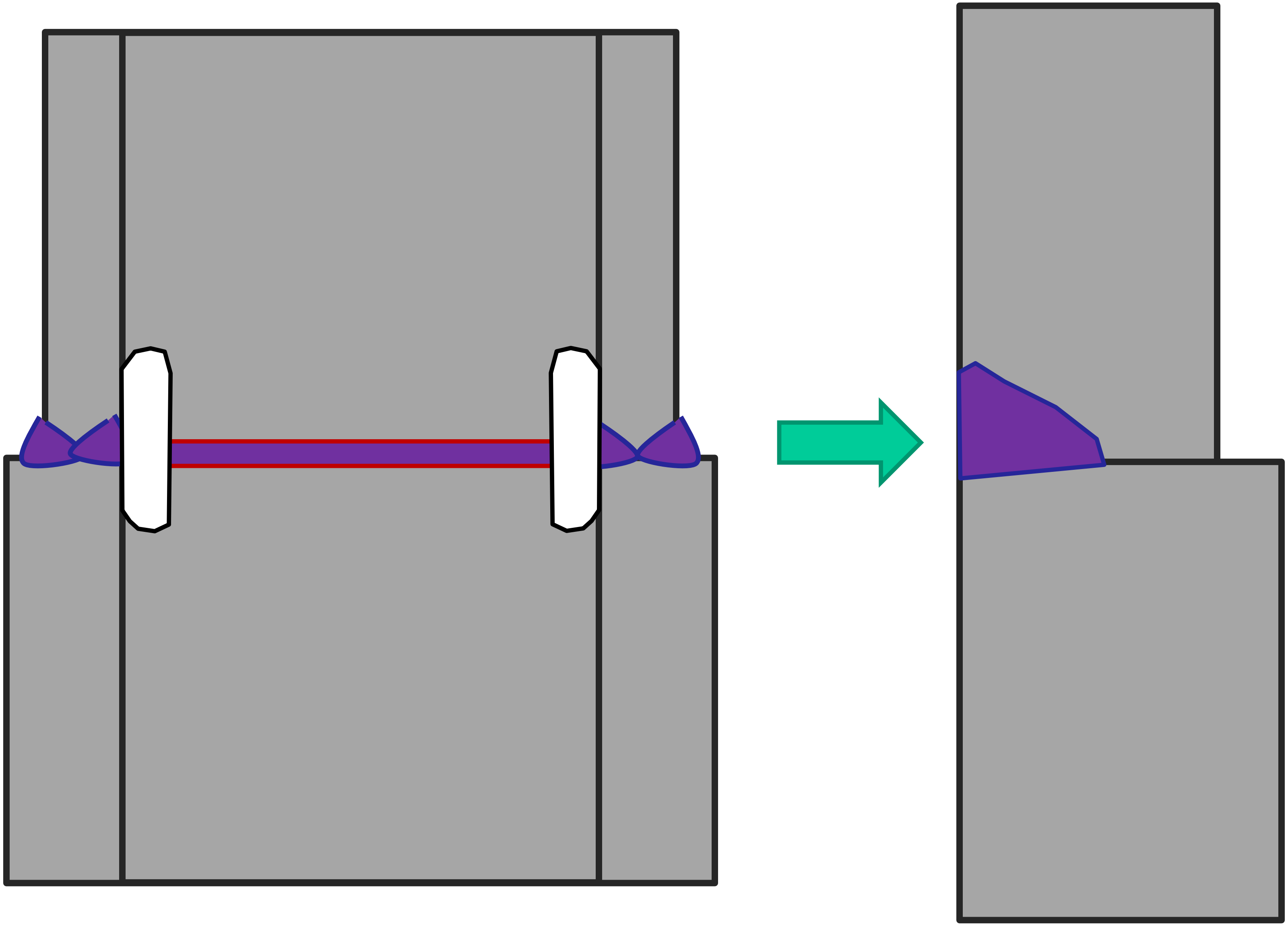
For Intermediate Moment Frames and Special Moment Frames

“Where welds are used to make the splice, they shall be complete-joint-penetration groove welds.”

Currently required



Inconvenient field weld



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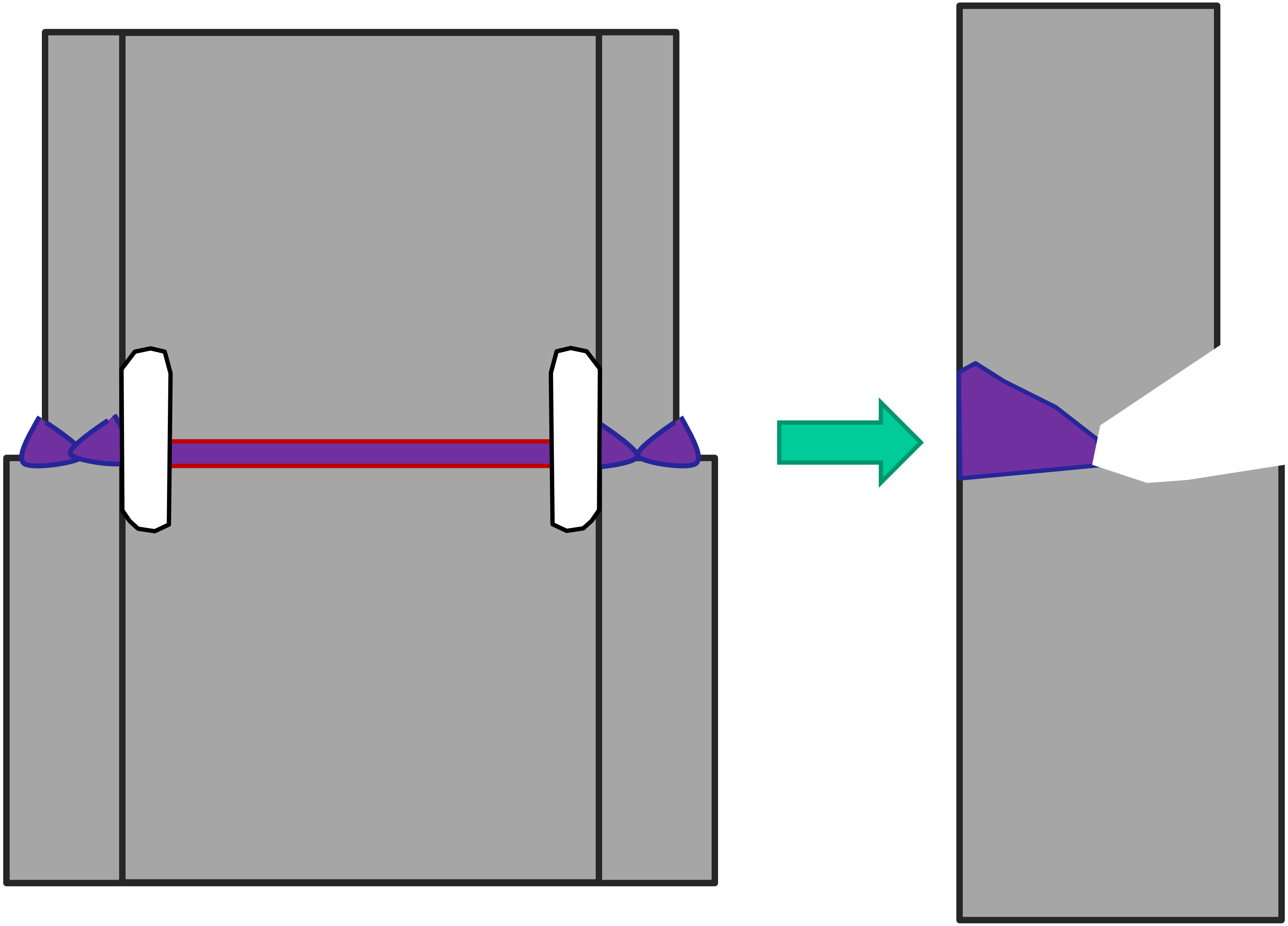

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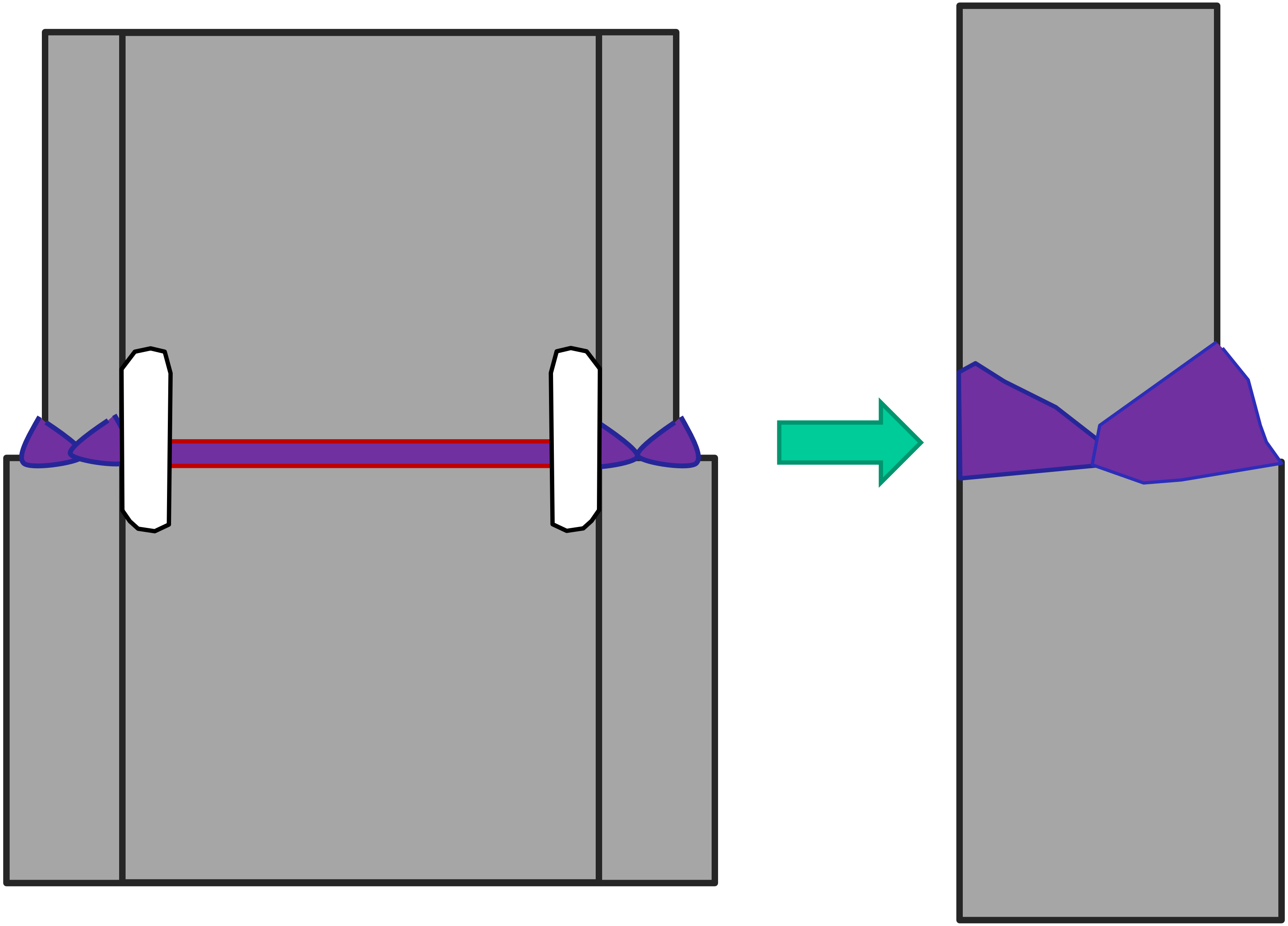

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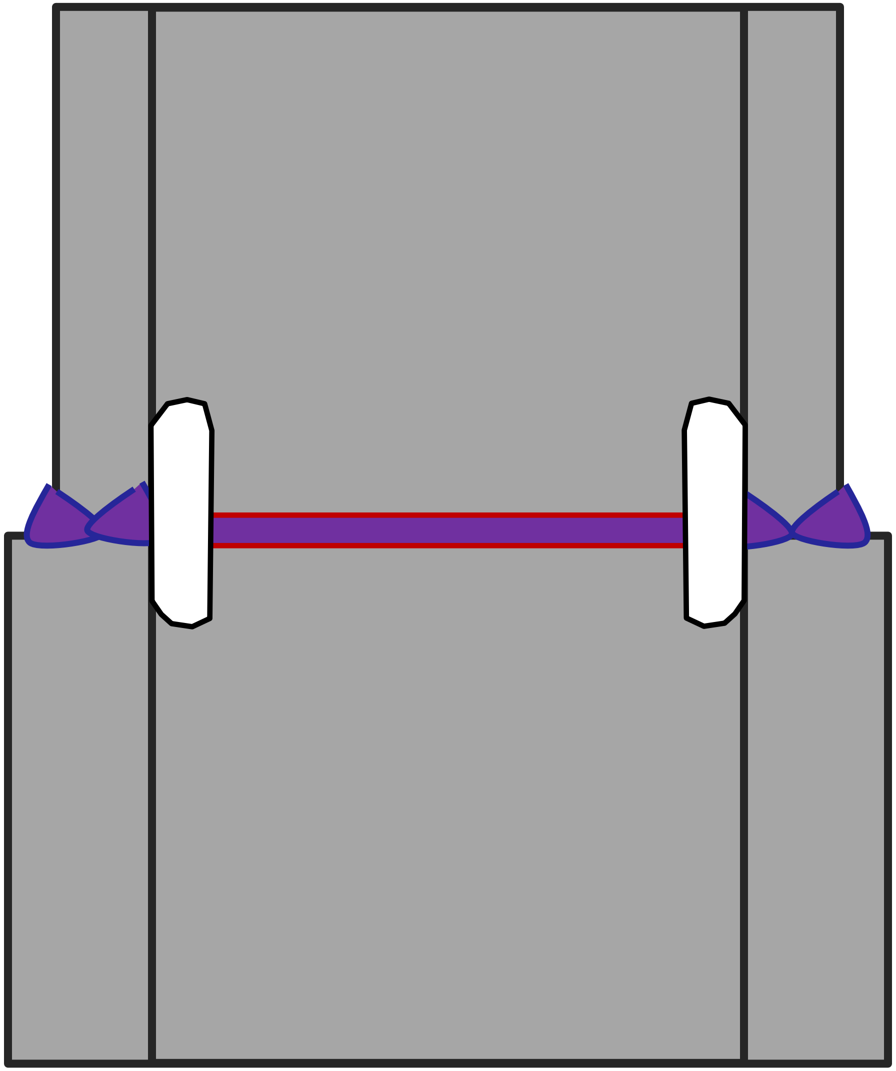
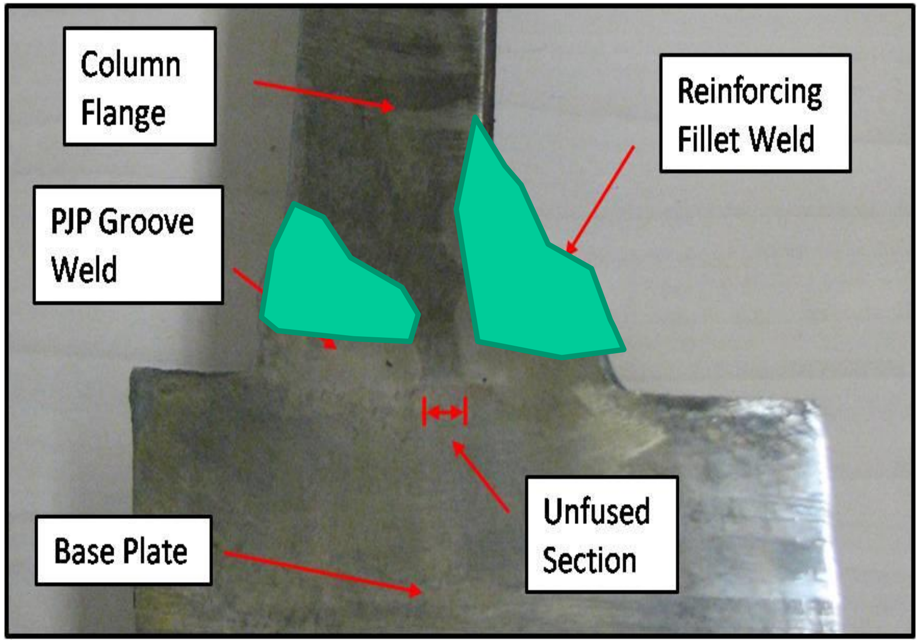
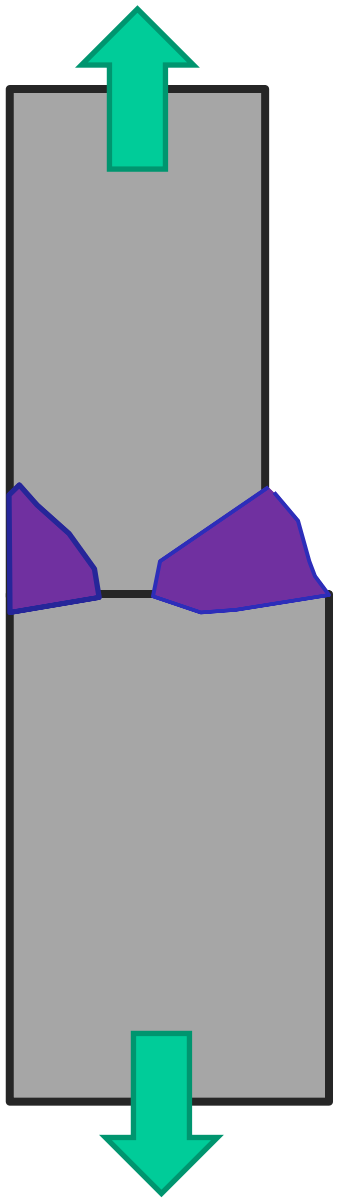


Excellent performance of tough, PJP welded base plates and other details



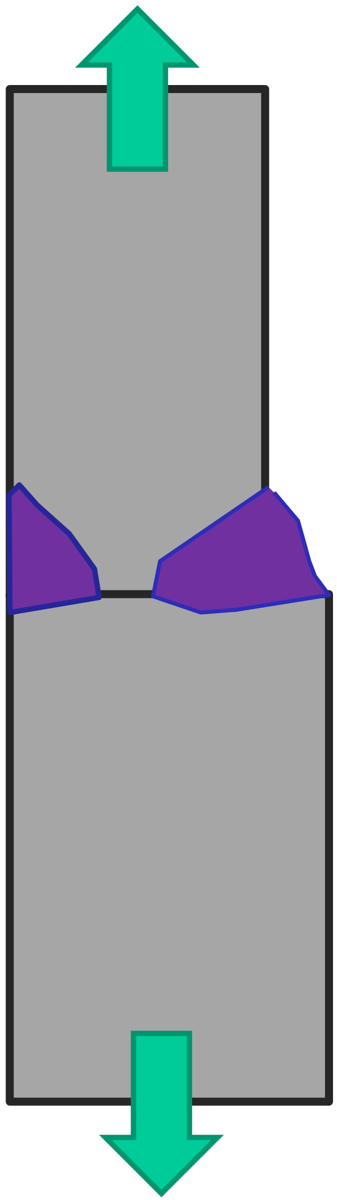
Can we use PJPs in splices?
If so, under what conditions?

The aim – a safe and reliable PJP welded splice



Understanding of seismic stress demands and uncertainty

The aim – a safe and reliable PJP welded splice



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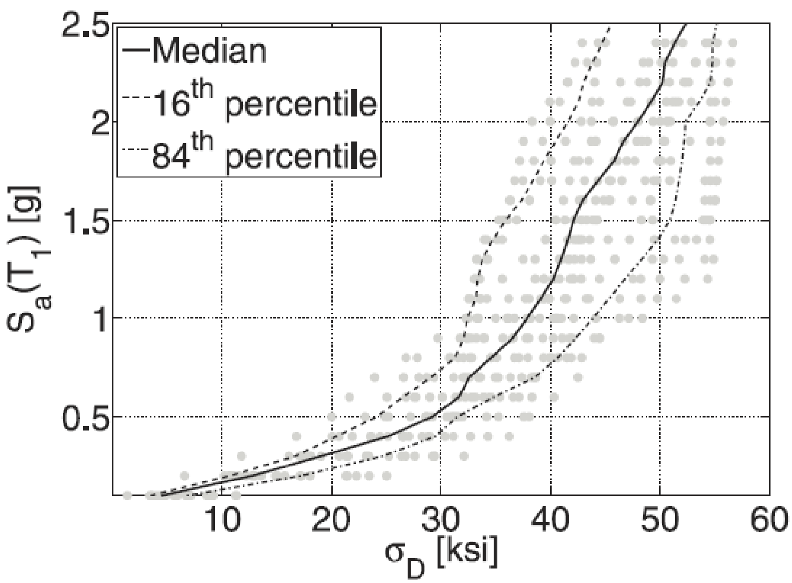

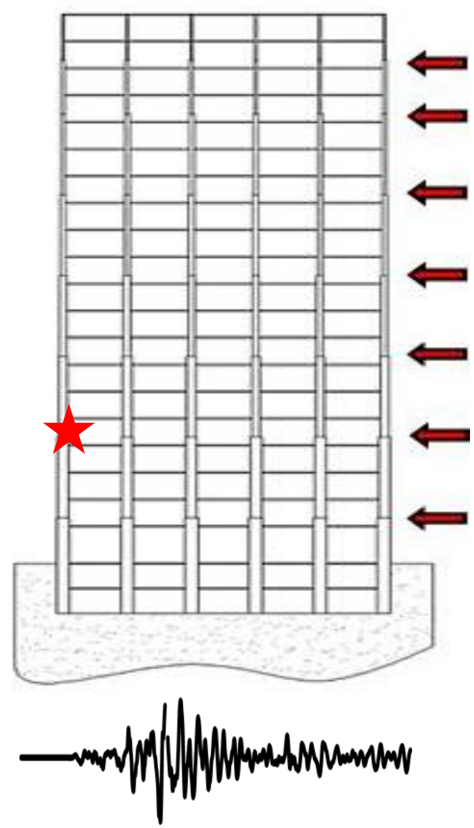

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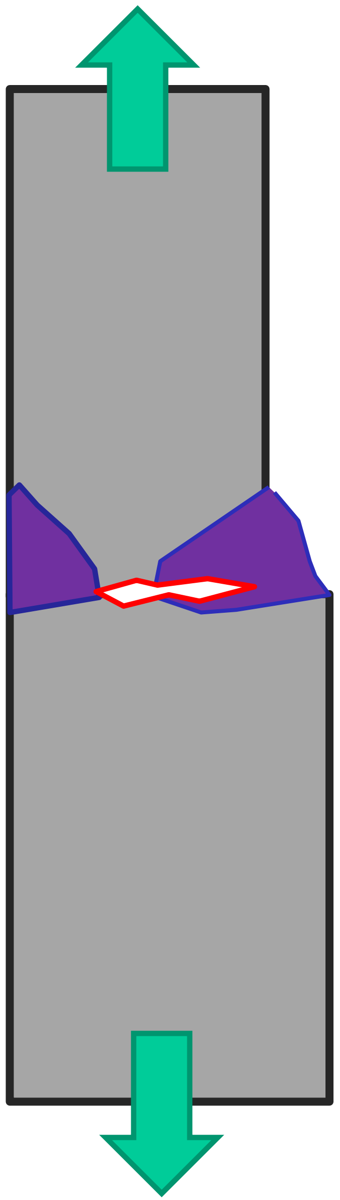
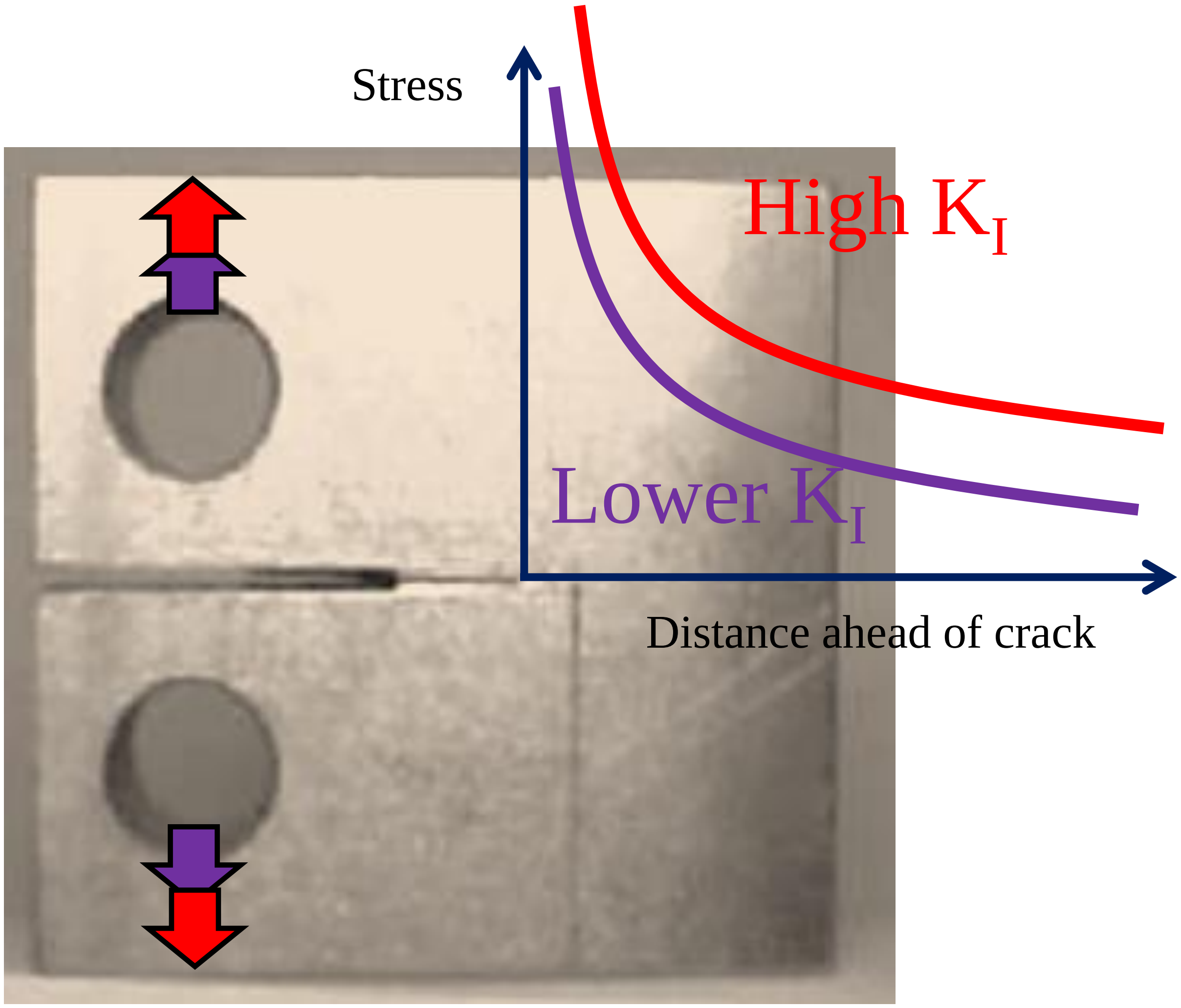


Understanding of seismic stress demands and uncertainty

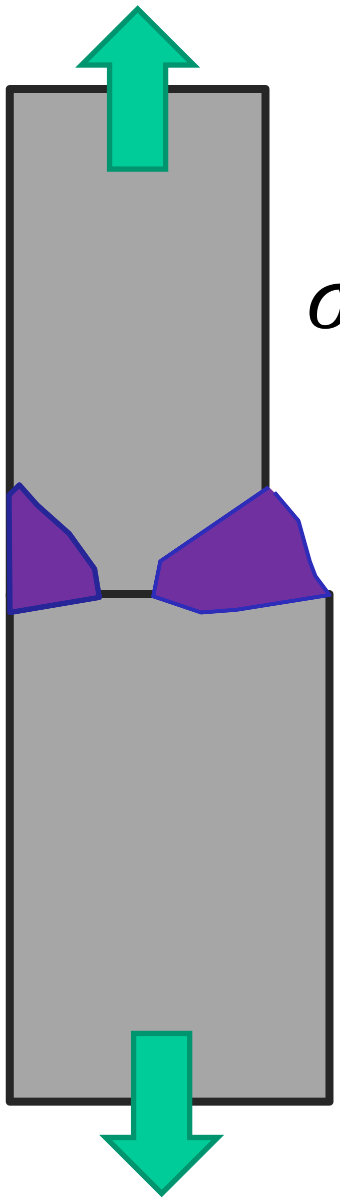
Understanding of fracture stress capacity and uncertainty

To understand capacity, fracture mechanics is necessary



Fracture occurs if K_I (which characterizes the stress field) exceeds K_{IC} (a material property)

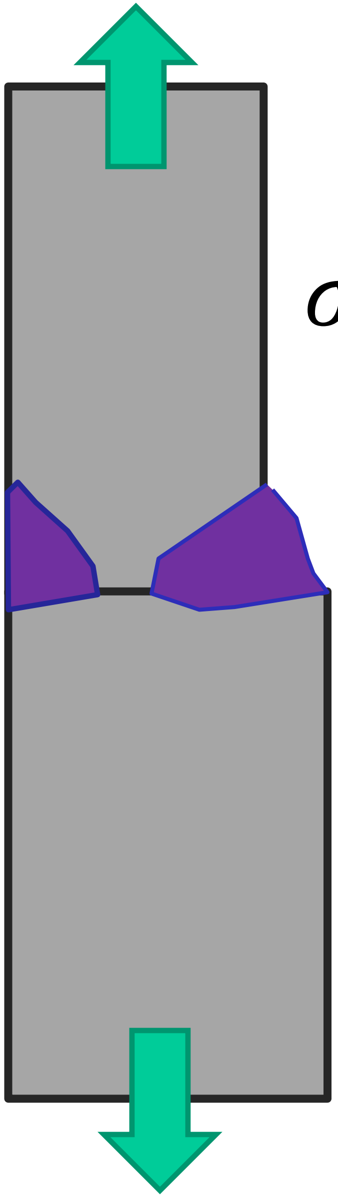
What stress does the splice fracture at?



Conceptually

$$\sigma_{fracture} = f(K_{IC}, a, t_{upper}, t_{lower})$$

What stress does the splice fracture at?



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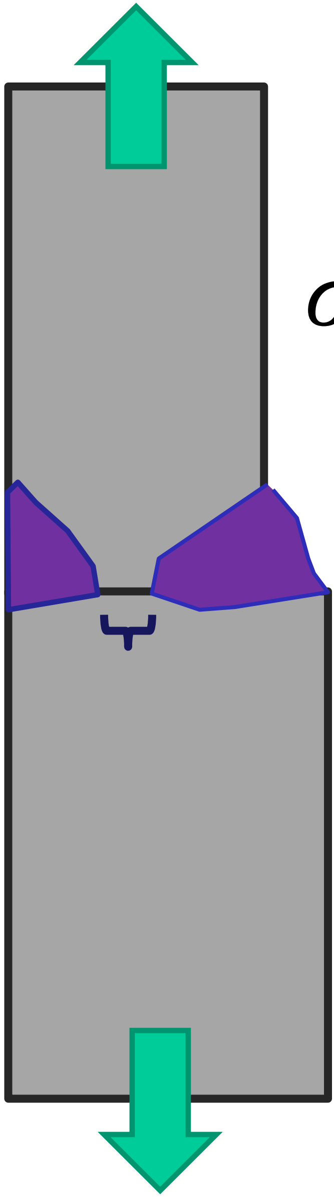
Material Toughness (CVN – K_{IC})

What stress does the splice fracture at?



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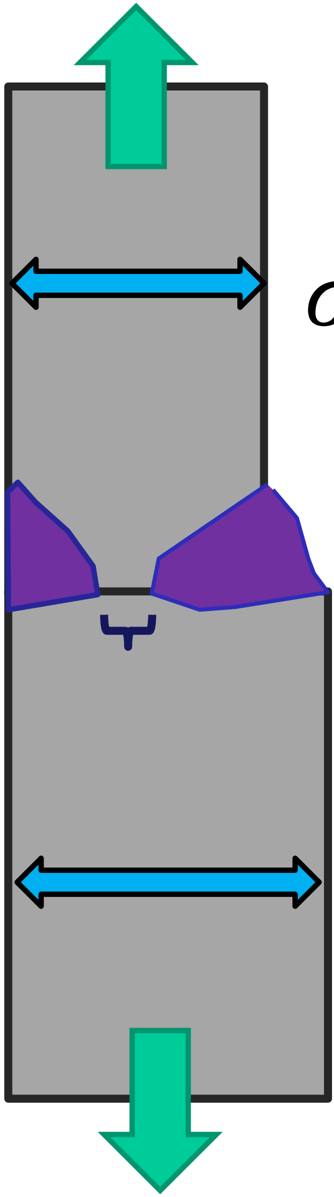
Crack Length

What stress does the splice fracture at?



Conceptually

$$\sigma_{fracture} = f(\, K_{IC,}\, a, t_{upper}, t_{lower})$$

Material Toughness (CVN – K_{IC})

Crack Length

Geometry

How to determine $\sigma_{fracture}$ in a general manner?

1. Experiments

- Expensive
- Limited data set in terms of geometry, material properties
- 5 full scale experiments
  = 1 PhD + $200K

How to determine $\sigma_{fracture}$ in a general manner?

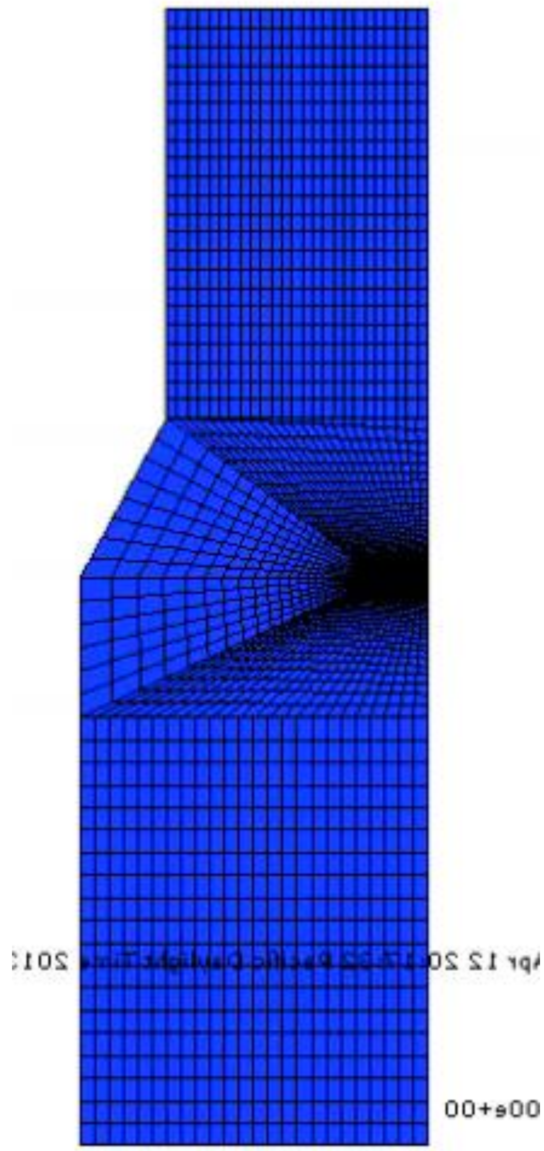
2. Finite Element Simulations

- Allow investigation of many parameter sets

But,

- Not tests!
- Still a bit expensive

  25 simulations = 30-40 weeks



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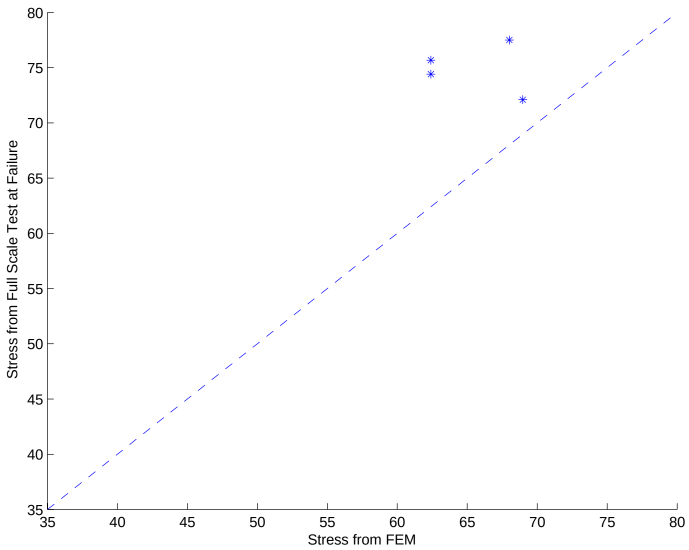
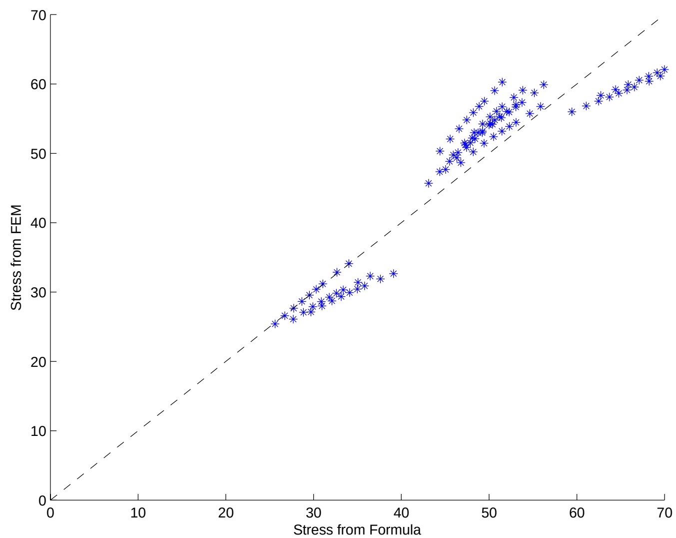


How to determine $\sigma_{fracture}$ in a general manner?

3. Semi-analytical regressed expressions

$$\sigma^{flange}_{capacity,estimate} = \frac{K_{IC}}{\sqrt{\pi \times (h/2x) \times t_{upper}}} \times \frac{1}{x\sqrt{a} \times f_1(h) \times f_2(x) \times g_1(h) \times g_2(x)}$$

- **Can characterize any configuration**
- **Introduces additional error**



Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

$$s^{flange}_{capacity,estimate} = \frac{K_{IC}}{\sqrt{p \times (h/2x) \times t_{upper}}} \times \frac{1}{x\sqrt{a} \times f_1(h) \times f_2(x) \times g_1(h) \times g_2(x)}$$

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Material toughness

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Material toughness

CVN is random

CVN → K_{IC} conversion error

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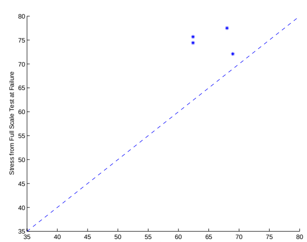
Material toughness

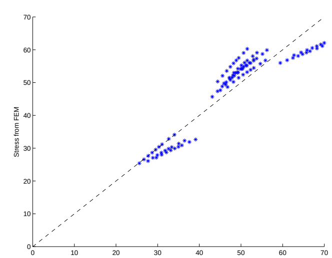
Geometry

CVN is random

CVN → K_{IC} conversion error

$$\sigma^{flange}_{capacity,true} = \left(\frac{\sigma^{flange}_{capacity,true}}{\sigma^{flange}_{capacity,FEM}}\right) \times \left(\frac{\sigma^{flange}_{capacity,FEM}}{\sigma^{flange}_{capacity,estimate}}\right) \times \sigma^{flange}_{capacity,estimate}$$





Errors in FE and semi-analytical relationship

Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

$$\sigma^{flange}_{capacity,estimate} = \frac{K_{IC}}{\sqrt{\pi \times (h/2x) \times t_{upper}}} \times \frac{1}{x\sqrt{a} \times f_1(h) \times f_2(x) \times g_1(h) \times g_2(x)}$$

Material toughness

Geometry

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CVN → K_{IC} conversion error

$$\sigma^{flange}_{capacity,true} = \left(\frac{\sigma^{flange}_{capacity,true}}{\sigma^{flange}_{capacity,FEM}} \right) \times \left(\frac{\sigma^{flange}_{capacity,FEM}}{\sigma^{flange}_{capacity,estimate}} \right) \times \sigma^{flange}_{capacity,estimate}$$

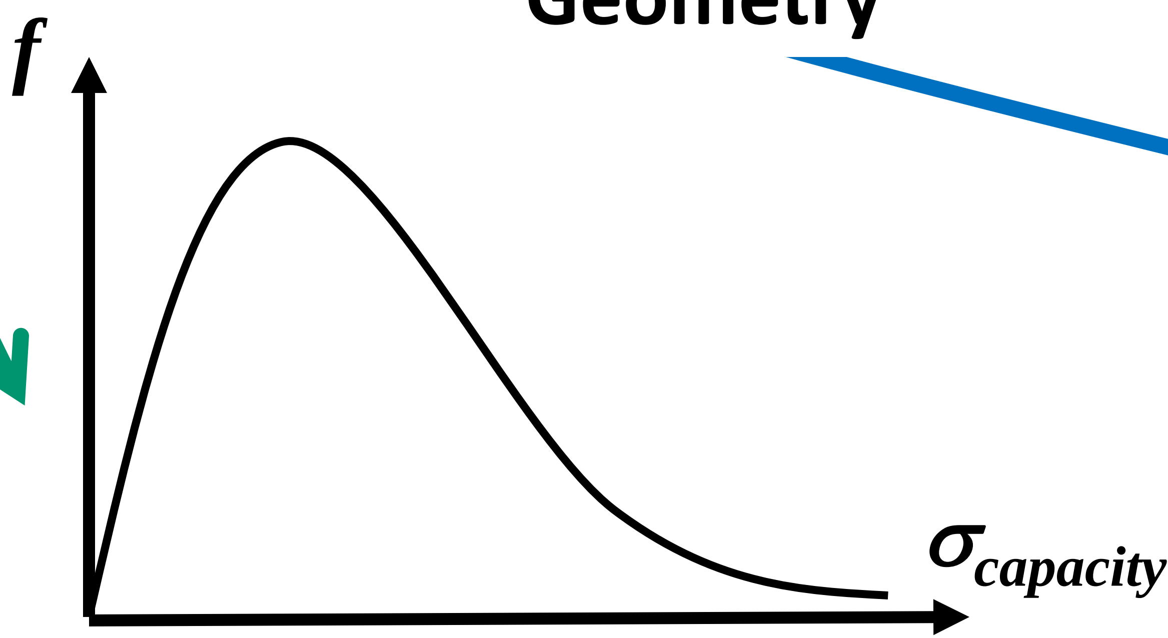
Errors in FE and semi-analytical relationship

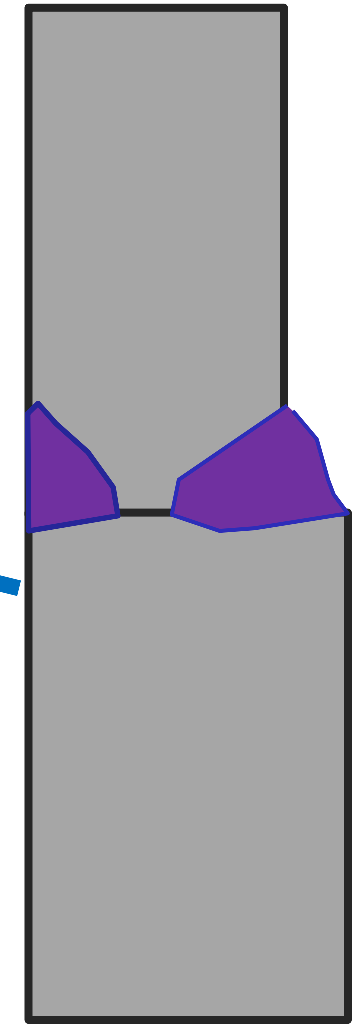
Application

Toughness

$$\sigma^{flange}_{capacity,estimate} = \frac{K_{IC}}{\sqrt{\pi \times (h/2x) \times t_{upper}}} \times \frac{1}{x\sqrt{a} \times f_1(h) \times f_2(x) \times g_1(h) \times g_2(x)}$$

Geometry





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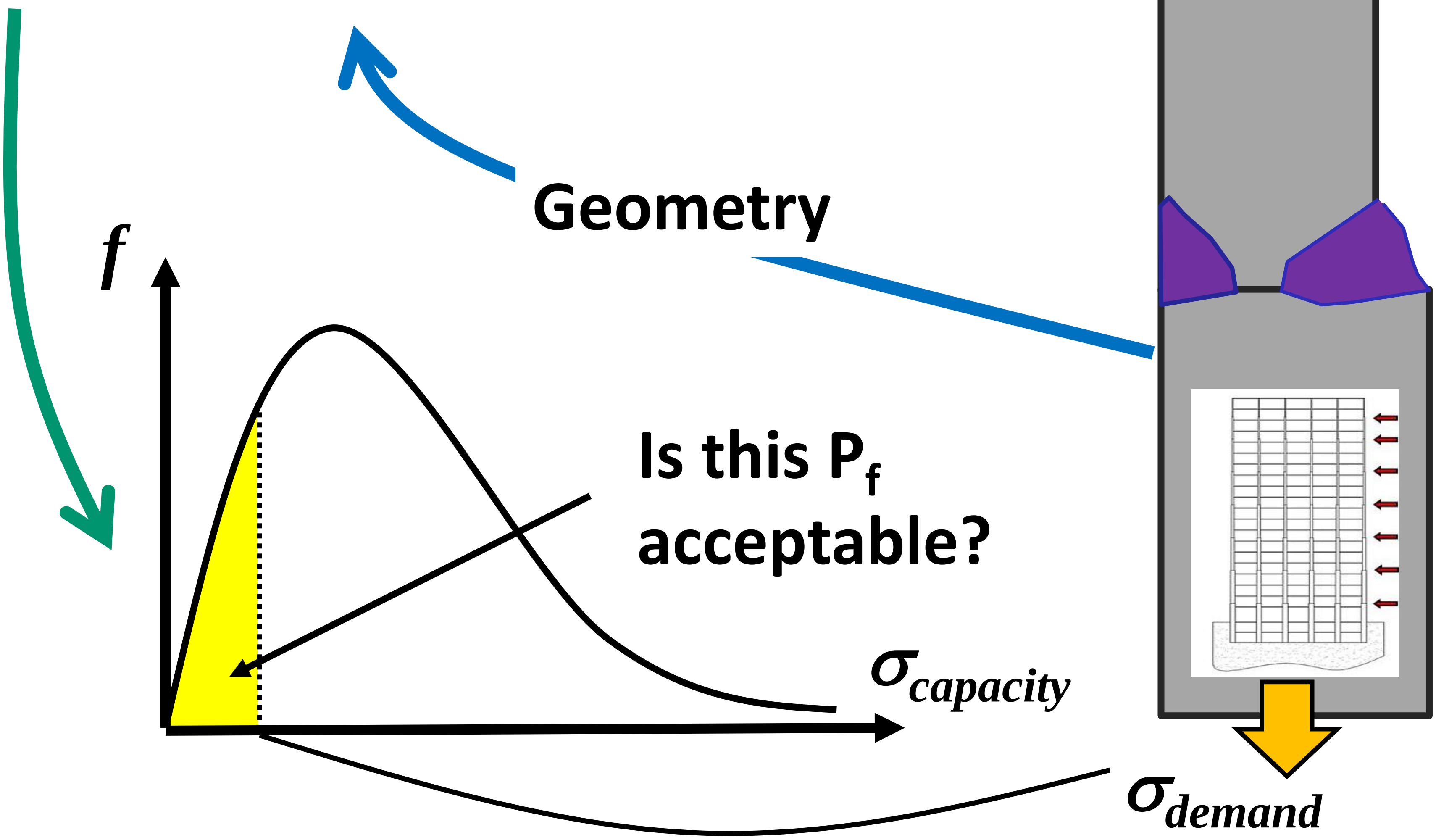
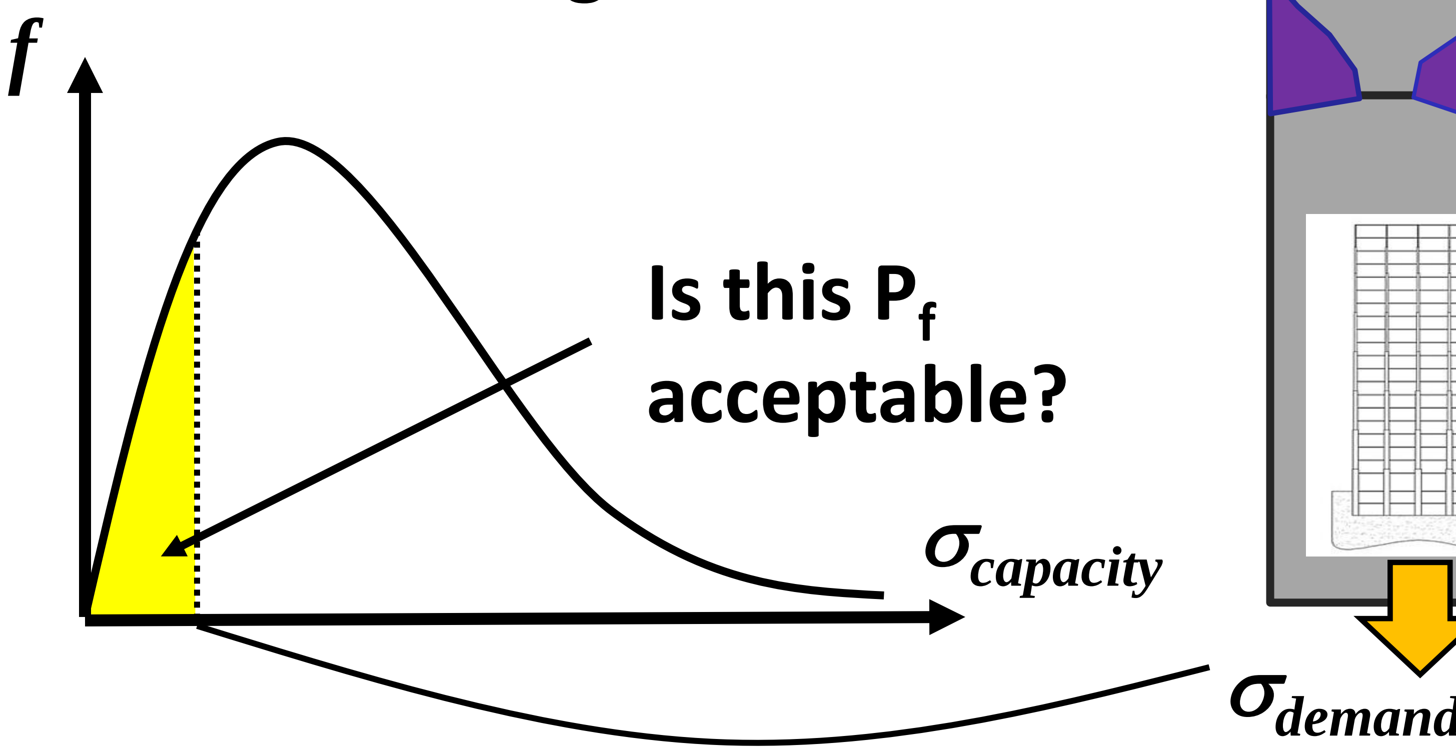
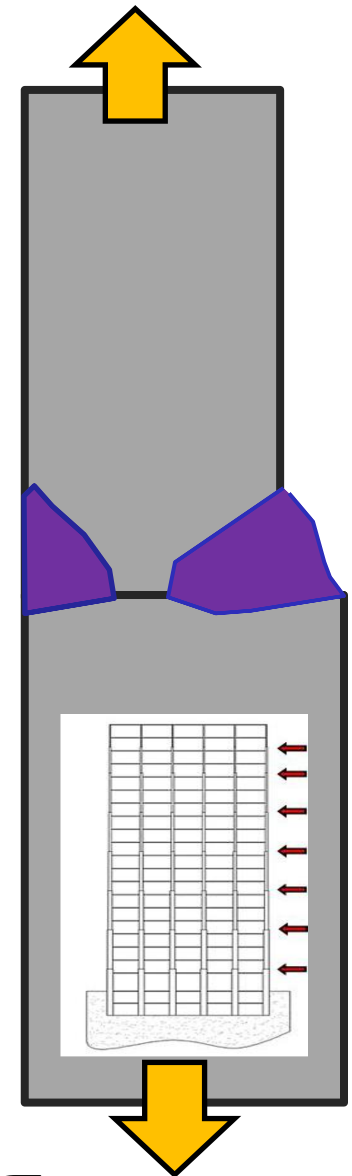


Assessment of splice safety

P_f is acceptable if

- 85% Penetration is maintained
- Thicker flange is 15% thicker than thinner flange
- Some other detailing considerations





Summary

- NLTHA to determine demands
- Full scale experiments
- Fracture mechanics simulations
- Reliability analysis
- Determination of acceptable geometries
- For the first time since 1994, cracks are explicitly allowed in demand critical welds in seismic steel structures in the USA

6g. Column Splices

Column splices shall comply with the requirements of Section D2.5. Where welds are used to make the flange splices, they shall be complete-joint-penetration groove welds.

Exception: For ~~Grade 50 and Grade 60 columns~~columns with minimum yield stress not exceeding 60 ksi, partial-penetration groove welds are permitted under the following conditions:

(a) The thicker flange is at least 15% thicker than the thinner flange.
(b) The partial-penetration welds have a minimum ~~size~~ effective throat of 85% of the thickness of the smaller column flange.

Thank you for your attention!