Probabilistic Fracture Mechanics Based Design of Seismic Column Splices

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Earthquake induced fracture in steel structures (Northridge)

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Earthquake induced fracture in steel structures (Northridge)

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
Where welds are used to make the splice, they shall be complete-joint-penetration groove welds.
Currently required
Inconvenient field weld
Inconvenient field weld
Inconvenient field weld
Inconvenient field weld
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
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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?

Conceptually

\[ \sigma_{\text{fracture}} = f\left( K_{IC}, a, t_{\text{upper}}, t_{\text{lower}} \right) \]

Material Toughness (CVN – \( K_{IC} \))

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

2. Finite Element Simulations
- Allow investigation of many parameter sets
- Not tests!
- Still a bit expensive
  25 simulations = 30-40 weeks
How to determine $\sigma_{\text{fracture}}$ in a general manner?

3. Semi-analytical regressed expressions

$$\text{flange capacity, estimate} = \frac{K_{IC}}{\sqrt{\left(\frac{h}{2}\right)t_{\text{upper}}}}$$

- Can characterize any configuration
- Introduces additional error
Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

\[
\text{capacity estimate}_{\text{flange}} = \frac{K_{IC}}{\sqrt{\left(\frac{h}{2x}\right) t_{\text{upper}}}} \quad \frac{1}{\sqrt{f_1(\quad) f_2(\quad) g_1(\quad) g_2(\quad)}}
\]
Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

- Material toughness
Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

- Material toughness
- CVN is random
- CVN $\rightarrow K_{IC}$
- Conversion error

\[ K_{IC} = \frac{1}{\sqrt{\left( \frac{h}{2x} \right) t_{upper}}} \]

\[ = \frac{1}{\sqrt{f_1( ) f_2( ) g_1( ) g_2( )}} \]
Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

- Material toughness
- CVN is random
- CVN $\rightarrow K_{IC}$
- Conversion error
- Geometry
Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

- Material toughness
- CVN is random
- CVN → $K_{IC}$
- Conversion error

Errors in FE and semi-analytical relationship
Monte Carlo simulations to characterize capacity

Sources of uncertainty (simulated as RVs):

- Material toughness
- CVN is random
- Conversion error
- Geometry

Material toughness:

\[
K_{IC} = \frac{1}{\sqrt{\frac{h}{2x}} t_{upper}}
\]

Geometry:

\[
\sigma_{flange, estimate} = \left( \frac{\sigma_{flange, capacity, true}}{\sigma_{flange, capacity, FEM}} \right) \times \left( \frac{\sigma_{flange, capacity, FEM}}{\sigma_{flange, estimate}} \right) \times \sigma_{flange, capacity, estimate}
\]

Errors in FE and semi-analytical relationship
Application

Toughness

Geometry

\[
flange \ capacity, \ estimate = \frac{K_{IC}}{\sqrt{\left(\frac{h}{2x}\right) t_{upper}}}
\]

\[
\frac{1}{\sqrt{f_1(\ ) \ f_2(\ ) \ g_1(\ ) \ g_2(\ )}}
\]

\[
\sigma_{capacity}
\]
Is this $P_f$ acceptable?

$$flange\ capacity,\ estimate = \frac{K_{IC}}{\sqrt{(h/2)x} \cdot t_{upper}}$$

$$= \frac{1}{\sqrt{f_1(\ ) \cdot f_2(\ ) \cdot g_1(\ ) \cdot g_2(\ )}}$$

Application

Toughness

Geometry

$f$

$\sigma_{capacity}$

$\sigma_{demand}$
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

Is this $P_f$ acceptable?
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 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!