Rationale for Simplifying the Strength Formulae for the Design of Multi-row Bolted Connections Failing in Net Tension

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Pultruded FRP Shapes – ASCE Standard

“Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures”

Simple non-sway frames with bracing.

Beam-to-column web-cleated connection
from Strongwell Design Manual

For buildings to three storeys of height.
Pultruded FRP Shapes – ASCE Standard

CHAPTERS:
2. Design Requirements
3. Tension Members
4. Design of Compression Members
5. Design for Flexure and Shear
6. Members Under Combined Forces and Torsion
7. Plates and Built-up Members
8. BOLTED CONNECTIONS.
   Project to write draft 2008-10.
   Published in 2014.

Note that in the USA the word connection is our word joint, and vice versa.

ASCE Standard – Net Tension Strength

Net tension resistance of a double lap shear connection with multi-rows of bolts

Testing often has outer plates of steel (ASTM and EN standards).
Net-tension failure for connections with two rows of bolts

For this failure mode the damage and ultimate loads can be the same.

Peak stresses are at points A

Locations for stress concentrations causing failure

‘Linear elastic’ response to rupture

Assumed net-tension failure plane for resistance model

Model for net-tension resistance, this is $R_{nt,f}$

Filled-hole

Open-hole

Net-tension failure plane

ASCE Standard – Net tension Strength

Semi-empirical model by Hart-Smith (1987)

Term in brackets is a reduction factor

$R_{nt,f} = \left[ \frac{1}{K_{nt,L}L_{br}\left(\frac{w}{d}\right) + K_{op,L}\left(1-L_{br}\right)\left(1-\frac{d_n}{w}\right)} \right] \times wt F^1$

- $w$ is width
- $t$ is thickness
- $d$ is bolt diameter
- $d_n$ is hole diameter
- $L_{br}$ proportion of tension load taken in bearing by first bolt row (steel and FRP $L_{br} = 0.6$)

$F^1_L$ is longitudinal tensile strength of the pultruded material.

$K_{nt,L}$ depends on geometry and a filled-hole correlation coefficient ($C_f$).

$K_{op,L}$ depends on geometry and an open-hole correlation coefficient ($C_{op,L}$).

Model for case when loading direction and orientation of pultruded material are aligned ($\theta = 0$).
Evaluation of semi-empirical model by Hart-Smith (1987)

Not time to discuss all issues for evaluation!!

Open hole correlation coefficient, $C_{op,L}$

$$C_{op} = \frac{k_{tc} - 1}{k_{te,op} - 1} = 0.374 \text{ (mean), CoV 23.5\%}$$

$k_{te,op} = 2 + \left(1 - \frac{d_n}{w}\right)^3$ is the isotropic stress concentration factor.

$k_{tc}$ is the orthotropic stress concentration determined by experiment using open hole specimens with different $d_n/w$ ratios.


Net-tension failure for connections with two rows of bolts. Plotted Longitudinal connection results required three studies.

Each test number is for a different connection geometry, having constant bolt diameter and type, plate thickness and tightening torque.

Resistance ratios are for conservative design.

$C_L = 0.33$ (bearing); $C_{op,L} = 0.37$ (by-pass);

$t = 12.7$ mm; $d = 19.05$ mm; $d_n = 20.6$ mm;

$F_{L}^0 = 166$ N/mm$^2$ (mean); torque is 32.5 N.m
Findings from evaluation exercise:

- Comparison between experimental and predicted strengths for 17 different connection geometries show that the simple modelling approach has potential to give safe and reliable net-tension strength predictions.
- For the two connections that did not give a safe prediction it is observed that their same geometry would not be designed for.

Practitioners on the ASCE/SEI Fiber Composites And Polymers Standards committee (FCAPS), said that they would NOT use the Hart-Smith design method as it is too complicated.

Resolution – Net tension Multi-bolt Rows

\[ R_{nt,\text{f}} = rf \cdot w \cdot F_L' \]

\[ rf = \left[ K_{\text{nl,br}} \cdot \left( \frac{w}{nd} \right) + \left( K_{\text{op,br}} \cdot \left( 1 - \frac{L_{\text{br}}}{d_n} \right) \right) \right]^{-1} \]

Equ. (3)

*rf* is reduction factor to gross cross-sectional strength

What is the range for *rf* for connection details permitted by the ASCE standard?

The minimum value will provide a simple formula for practitioners to use.
Resolution – Net tension Multi-bolt Rows

Minimum requirements for bolted connection geometries for multi-row configurations without bolt stagger

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
<th>Minimum required spacing (or distance in terms of nominal bolt diameters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{1,\text{min}}$</td>
<td>End distance</td>
<td>$2d$</td>
</tr>
<tr>
<td>$e_{2,\text{min}}$</td>
<td>Edge distance</td>
<td>$1.5d$</td>
</tr>
<tr>
<td>$s_{\text{min}}$</td>
<td>Pitch spacing</td>
<td>$4d$</td>
</tr>
<tr>
<td>$g_{\text{min}}$</td>
<td>Gage spacing</td>
<td>$4d$</td>
</tr>
</tbody>
</table>

**Equations:**

$e_1 = 20 \quad s = 40 \quad d = 10 \quad d_e = 11.6$

**Diagram:**

Connection force

Resolution – Net tension Multi-bolt Rows

Many geometries are NOT simple plate-to-plate connections.
Resolution – Net tension Multi-bolt Rows

Values of the reduction factor (rf) from Equ. (3) for the multi-row configuration of two rows of two bolts per row illustrated.

<table>
<thead>
<tr>
<th>e/d</th>
<th>g/d</th>
<th>w/d</th>
<th>rf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>4</td>
<td>7</td>
<td>0.34</td>
</tr>
<tr>
<td>1.5</td>
<td>8</td>
<td>11</td>
<td>0.26</td>
</tr>
<tr>
<td>1.5</td>
<td>12</td>
<td>15</td>
<td>0.20</td>
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<tr>
<td>3</td>
<td>4</td>
<td>10</td>
<td>0.38</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>12</td>
<td>0.39</td>
</tr>
</tbody>
</table>

**smallest rf**

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Resolution – Net tension Multi-bolt Rows

- An EXCEL spreadsheet can be used to apply the Hart-Smith formulae (and accompanying design parameters).
- An analytical parametric study allows reduction to a single formula.
- It is $R_{nf,t} = 0.2 \, w \, t \, F'$. 
- This lower bound strength is for the range of connections that are practical and permitted in the LRFD standard to be published by ASCE. (It is not known if the geometry for reduction factor 0.2 provides the net tension mode of failure.)
- Because the lower bound strength can be half the actual design strength the full set of formulae are made available in an appendix with the commentary.
- When applying the ‘simplified’ formula it is to be recognize that there can be a maximum limit on the effective (or actual) width (w) of the connected component for the strength $R_{nf,t}$ to be valid.

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