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


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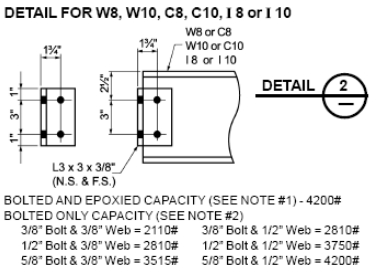
## Pultruded FRP Shapes – ASCE Standard

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

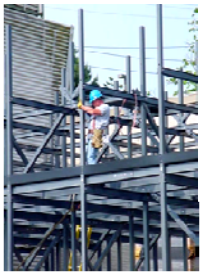
**Simple non-sway frames with bracing**.




BOLTED AND EPOXIED CAPACITY (SEE NOTE #1) - 4200#
BOLTED ONLY CAPACITY (SEE NOTE #2)

| | |
|---|---|
| 3/8" Bolt & 3/8" Web = 2110# | 3/8" Bolt & 1/2" Web = 2810# |
| 1/2" Bolt & 3/8" Web = 2810# | 1/2" Bolt & 1/2" Web = 3750# |
| 5/8" Bolt & 3/8" Web = 3515# | 5/8" Bolt & 1/2" Web = 4200# |

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



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**For buildings to three storeys of height.**

## Pultruded FRP Shapes – ASCE Standard

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**CHAPTERS:**

1. General Provisions
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.**

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

## ASCE Standard – Net Tension Strength

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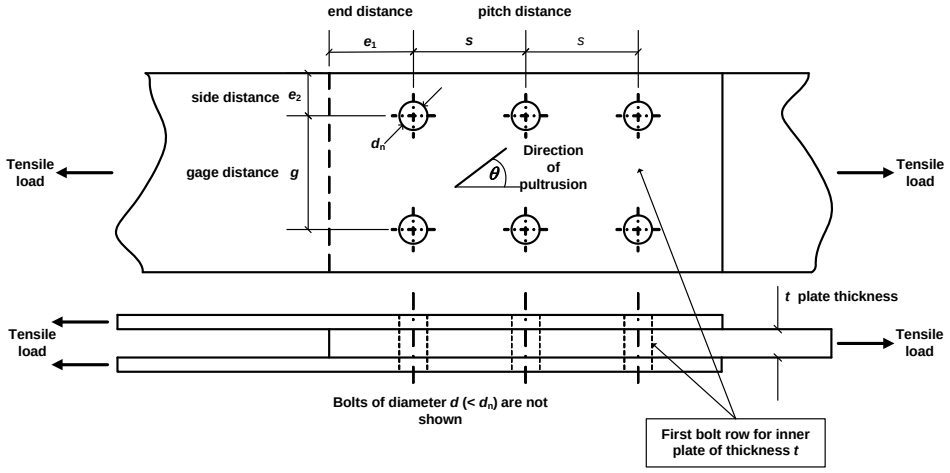
**Net tension resistance of a double lap shear connection with multi-rows of bolts**

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Testing often has outer plates of steel (ASTM and EN standards).

## ASCE Standard – Net tension Strength

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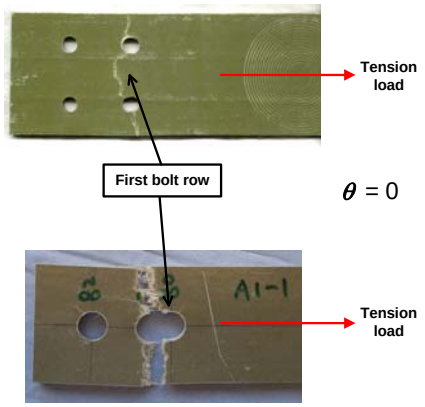
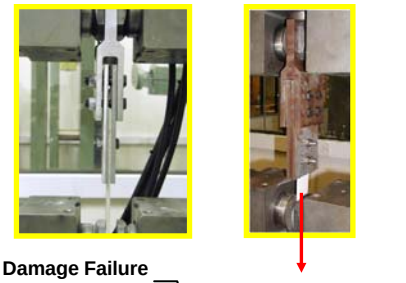
**Net-tension failure for connections with two rows of bolts**




Sources: PhD theses, C. Lutz (2005) & P. Wang (2004)

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

## ASCE Standard – Net tension Strength

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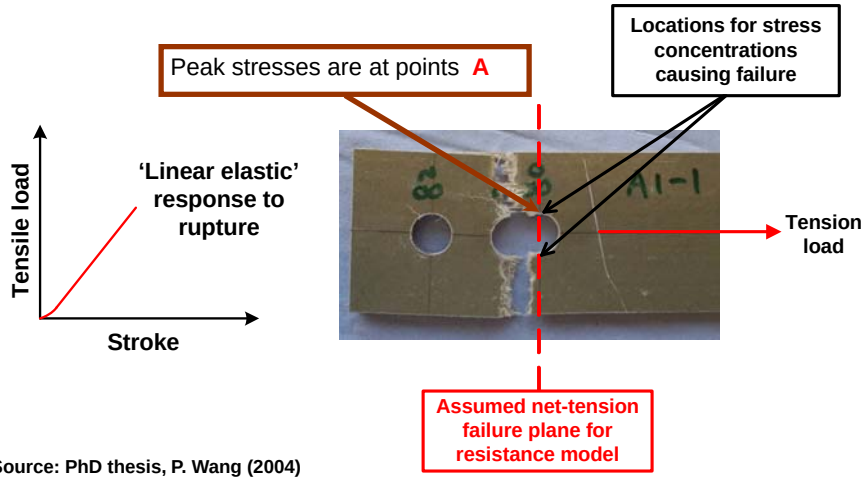
**Net-tension failure for connections with two rows of bolts**




Source: PhD thesis, P. Wang (2004)

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# ASCE Standard – Net tension Strength

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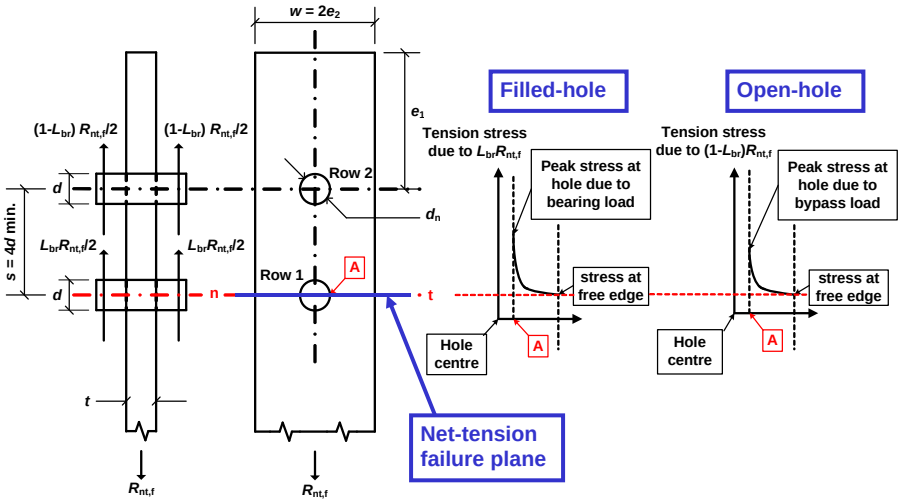
**Model for net-tension resistance, this is $R_{nt,f}$**

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# ASCE Standard – Net tension Strength

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**Semi-empirical model by Hart-Smith (1987)**

**Term in brackets is a reduction factor**

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

$w$ 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 (?))

$F_L^t$ is Longitudinal tensile strength of the pultruded material.

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

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

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**Model for case when loading direction and orientation of pultruded material are aligned ($\theta$ = 0).**

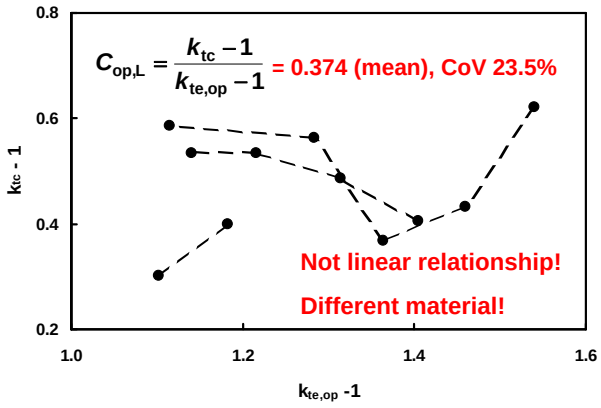
# ASCE Standard – Net tension Strength



**Evaluation of semi-empirical model by Hart-Smith (1987)**

**Not time to discuss all issues for evaluation!!**

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




$$k_{te,op} = 2 + \left(1 - \frac{d_n}{w}\right)^3$$

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.

Test results from G. J. Turvey and P. Wang, 'Open-hole strength of pultruded plate,' *Structures & Buildings*, 156 1, 2003, 93-101.

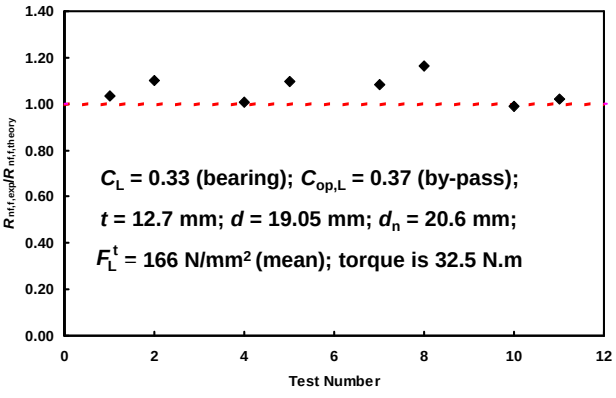
# ASCE Standard – Net tension Strength



**Net-tension failure for connections with two rows of bolts.**

**Plotted Longitudinal connection results required three studies.**

RT with as-received material




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.**

J . T. Mottram, 'Prediction of net–tension strength for multi-rowed bolted connections of pultruded material using the Hart-Smith semi-empirical modeling approach,' *Composites for Construction*, **(14)1**, (2010),105-114.

## ASCE Standard – Net tension Strength



**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



$$R_{nf,t} = rf\, w\, t\, F_L^t$$

$$rf = \left[ \left( K_{nt,L} L_{br} \left( \frac{w}{nd} \right) \right) + \left( \frac{K_{op,L}(1 - L_{br})}{\left( 1 - n\left( \frac{d_n}{w} \right) \right)} \right) \right]^{-1} \qquad \text{Equ. (3)}$$

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

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

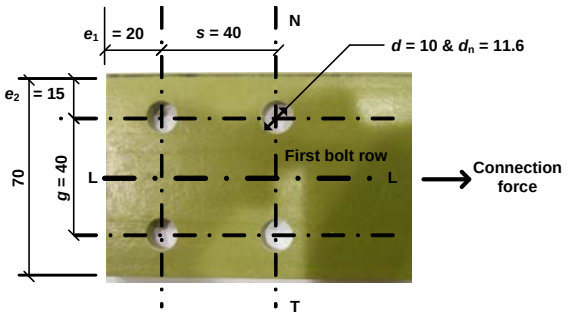
The **minimum value** will provide a simple formula for practitioners to use.

# Resolution – Net tension Multi-bolt Rows



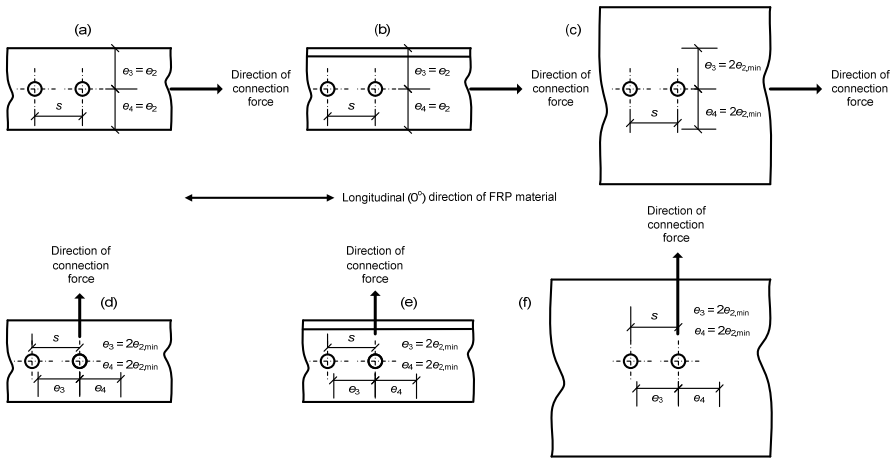
**Minimum requirements for bolted connection geometries for multi-row configurations without bolt stagger**

| Notation | Definition | Minimum required spacing (or distance in terms of nominal bolt diameters) Tension or compression load |
|---|---|---|
| $e_{1,min}$ | End distance | 2*d* |
| $e_{2,min}$ | Edge distance | 1.5*d* |
| $s_{min}$ | Pitch spacing | 4*d* |
| $g_{min}$ | Gage spacing | 4*d* |




# Resolution – Net tension Multi-bolt Rows






Many geometries are **NOT** simple plate-to-plate connections.

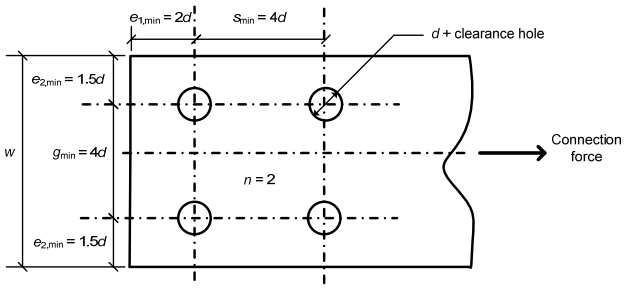
## Resolution – Net tension Multi-bolt Rows



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

| $e_2/d$ | $g/d$ | $w/d$ | $rf$ |
|---|---|---|---|
| 1.5 | 4 | 7 | 0.34 |
| 1.5 | 8 | 11 | 0.26 |
| 1.5 | 12 | 15 | 0.20 |
| 3 | 4 | 10 | 0.38 |
| 4 | 4 | 12 | 0.39 |

smallest *rf*




## 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 $R_{nf,t} = 0.2\, w\, t\, F_L^t$.
- 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.