# Design Guidance for Bolted Connections in Structures of Pultruded Shapes: Gaps in Knowledge

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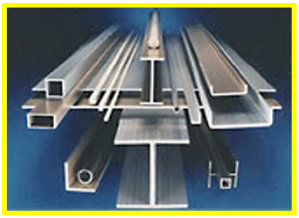
17th International Conference on Composite Materials (ICCM17), Edinburgh, 27-31 July 2009

THE UNIVERSITY OF WARWICK

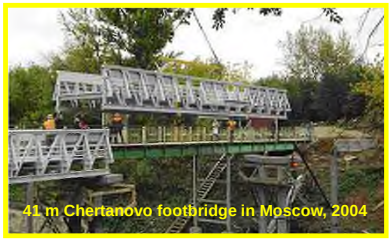


## Applications of Pultruded Shapes in Construction



Standard shapes


Platform with bolted connections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PP slide show is available from Personal Web-page.

## How were Gaps in Knowledge found

**"*Standard for Load and Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures*"** (American Society of Civil Engineers and American Composite Manufacturers Association (Pultrusion Industry Council)).

Eight chapters, we contribute for the "glory of it".

1. GENERAL PROVISIONS
2. DESIGN RESISTANCE
3. TENSION MEMBERS
4. DESIGN OF COMPRESSION MEMBERS
5. DESIGN FOR MEMBERS IN BENDING AND SHEAR
6. MEMBERS UNDER COMBINED FORCES AND TENSION
7. PLATES AND BUILT-UP MEMBERS
8. **BOLTED CONNECTIONS.**



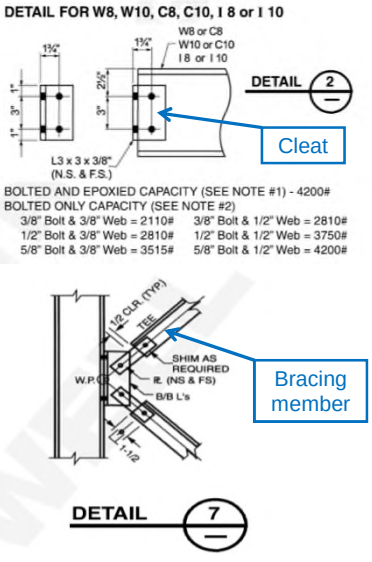
**Expected ASCE publication in 2011**



## Connections and Joints Permitted

LRFD chapter for bolted connections combines design for frame joints, such as the web-cleated type shown on top-right (classify as simple using the principles in BS EN 1993-1-8:2006), with the design of plate-to-plate connections, such as there is in each of the cleat legs and bracing members (bottom-right).

Drafting combined information from researchers and pultruders with design rule provisions found in design standards for other structural materials.



## Reasons for the Gaps in Knowledge

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**Why Research Papers can rarely be used for the basis of design rules:**

- No clear definition of the domain of applicability of the conclusions.
- No critical review of previous research relevant to that domain.
- Conclusions that are recommendations for more research.
- A design method that needs data which will not be available to the designer, or which itself depends on other variables.
- Test results that omit crucial data.
- Test results that exceed proposed design resistance mainly because strength of the materials far exceed the proposed design (i.e., factored) values.
- Theory based on unvalidated assumptions, or that fails to take account of imperfections likely to occur in practice.

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## So Why are there Gaps in Knowledge

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- Conclusions applicable only within a particular environment of specifications and practice.
- An investigation based on literature in one language only, leading to a theory that is not checked against test data reported in another language. It is not sufficient that the theory predicts the author's test results!

Nine reasons can be identified when evaluating what is known from the '200' publications to the bolted connections' chapter.

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## Gaps in Knowledge

**Paper lists 20 questions that need to be addressed, examples are:**

What are to be the recommended details for: connection geometries (e.g. hole clearance, end distance, side distance, pitch, etc.); bolt, nut and washer types; bolt installation torque?

Is it acceptable to have a joint with a single bolt?

What is to be the standard test method that shall be specified to determine pin-bearing strength?

**How does pin-bearing strength vary with environmental conditioning, bolt shaft flexure, position of bolt in clearance hole, orientation of 'bearing' force to the orientation of the FRP material?**

What is the strength reduction factor when loading is for the single-lap plate-to-plate configuration and the basic resistance formulae are based on a double-lap test arrangement?

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## Gaps in Knowledge

**How do we predict strength when there are two or more rows of bolting (i.e. when the by-pass loading exists and there is a requirement to know the open-hole stress concentration factor)?**

What is the distribution of the connection force between the bolts in multi-rows?

How is the strength of connections affected by a combination of in- and out-of-plane actions (as found in frame joints)?

What is the strength of connections for bracing members with eccentric loading?

What is the moment-rotation response of 'prescriptive' web-cleated ('pinned') connections that fail by the prying action causing the FRP cleats or columns to delaminate?

Can the rotational and in-plane stiffnesses be characterized such that analysis can be used to check if frame deformation satisfies a serviceability limit state?

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## ASCE Standard- Bearing Strength Formula



$$R_{br} = t\,d\,F_{\theta}^{br}$$

$t$ is thickness of FRP.

$d$ is diameter of bolt.

$F_{\theta}^{br}$ is the specified pin-bearing strength for the orientation of the resultant force at the bolt/FRP contact with respect to the direction of pultrusion.

**Is there an expression for $F_{\theta}^{br}$, given that we use a standard test method to determine $F_0^{br}$ and $F_{90}^{br}$ ?**

From ASCE-16-95 the expression (Hankinson-type) for interpolating between parallel (0º) and perpendicular (90º) to wood grain loading is

$$F_{\theta}^{br} = \frac{F_0^{br} F_{90}^{br}}{F_0^{br}\sin^2\theta + F_{90}^{br}\cos^2\theta}\,.$$

**Is this expression what we require?**

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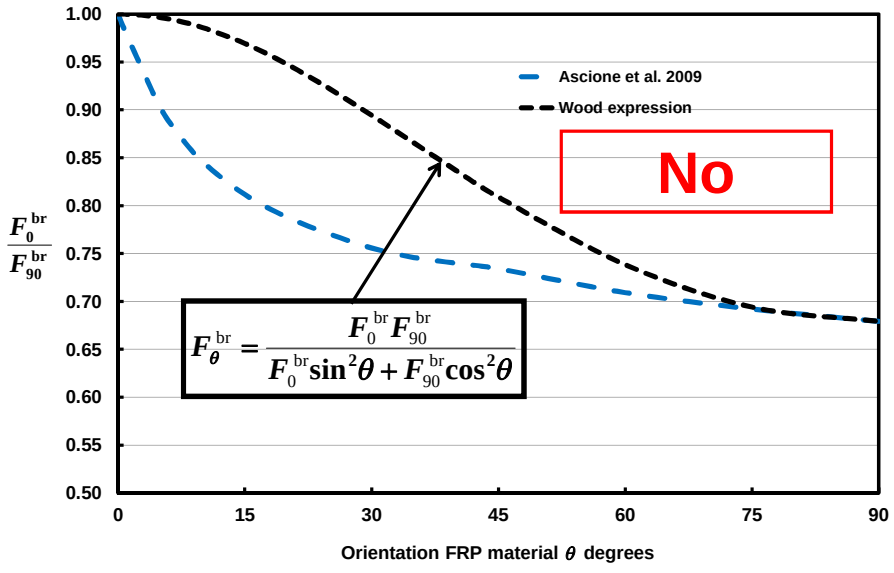
## ASCE Standard- Bearing Strength Formula



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**This is a gap in our knowledge**

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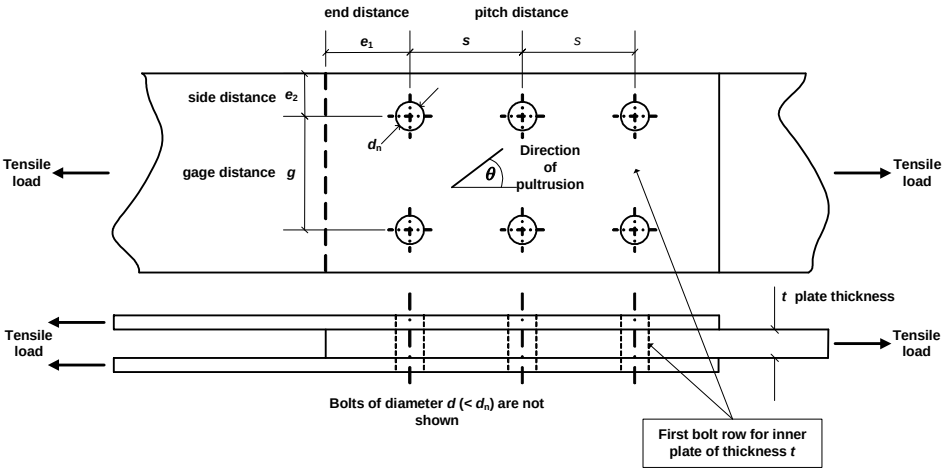
# ASCE Standard – Net-tension

**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)

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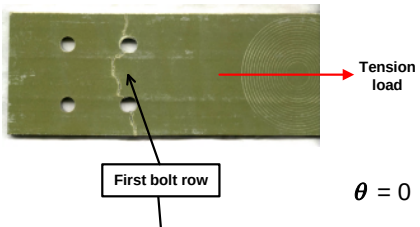
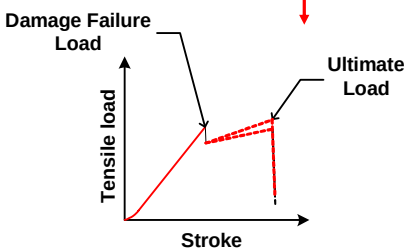
# ASCE Standard – Net tension

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




First bolt row

$\theta = 0$


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

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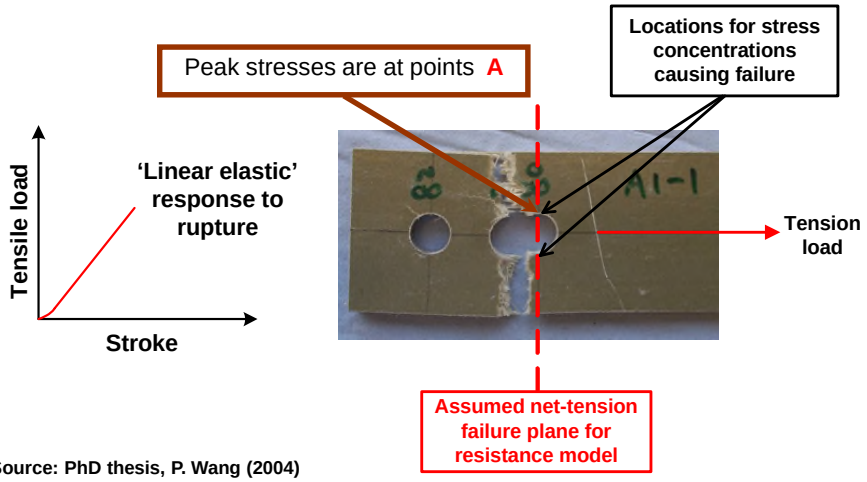
For this failure mode the damage and ultimate loads can be the same.

# ASCE Standard – Net-tension

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




Source: PhD thesis, P. Wang (2004)

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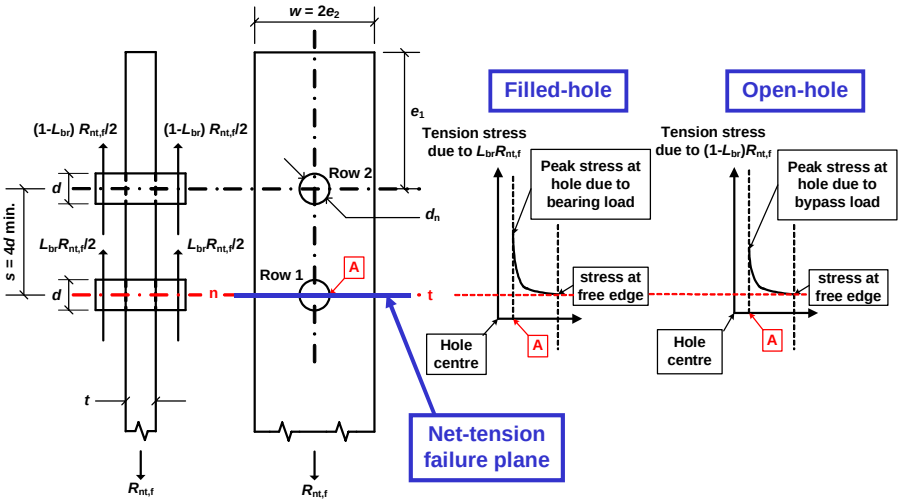
# ASCE Standard – Net-tension

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

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## ASCE Standard – Net-tension



**Semi-empirical model by Hart-Smith (1987)**
**Developed for aircraft and aerospace structures of laminated FRPs**

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

$w$ 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 (A gap!))

$F_L^t$ is Longitudinal tensile strength of the pultruded material. **(L ≅ 0 degrees)**

$K_{nt,L}$ 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).**

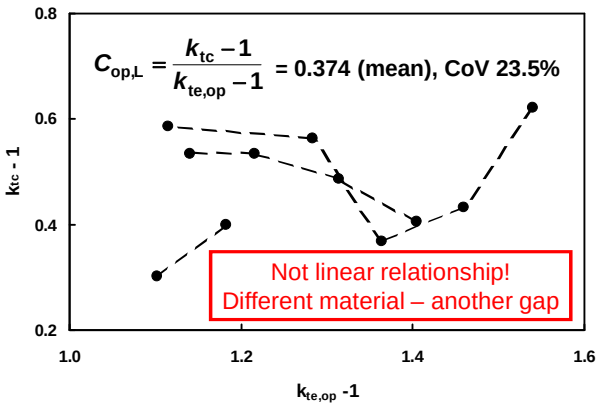
## ASCE Standard – Net-tension



**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.

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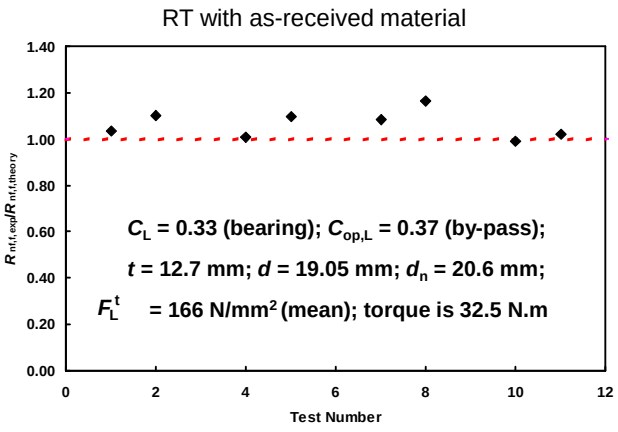
**Test results from G. J. Turvey and P. Wang, 'Open-hole strength of pultruded plate,' *Structures & Buildings*, 156 1, 2003, 93-101.**

## ASCE Standard – Net-tension



**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.

Only 8 test results, without duplication – yet another gap. Need more test results that correspond to what the design standard is to permit.

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J . T. Mottram, 'Prediction of net–tension strength for multi-row bolted connections of pultruded material using the Hart-Smith semi-empirical modeling approach,' *Composites for Construction*.

## Concluding Remarks



- If research is to be 'useful' for the basic of design rules it is essential for the work to be planned to correspond to what the standard is to permit.
- Because there are 'no' rules for the design of pultruded FRP frames with bolted connections it is unsurprising that many research papers fail to report all information necessary for code writing.
- By drafting a chapter for the design of bolted connections we have identified 20 questions that specify our gaps in knowledge (others may follow).
- These questions provide a framework for further targeted research whose deliverables will enable code writers to refine and improve proposed design provisions (based on what is known and understood today).

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Thank you for your attention.
Any questions?
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