1

Challenges for the Design of Connections and Joints in All-FRP Construction

Dr J. Toby Mottram MIStrutE CEng
School of Engineering

Costruzioni in Materiale Composito – ALL-FRP CONSTRUCTIONS
Università Iuav di Venezia
18th September 2007

THE UNIVERSITY OF WARWICK

2

Speaker

Academic: 25 years
Chartered: Structural Engineer
Research: "*Modern Methods of Construction*"

- Pultruded FRP shapes and systems for new build
- Lightweight steel framing (for multi-storey buildings)

Publications: 70 on all-FRP constructions
http://www.eng.warwick.ac.uk/staff/jtm/pfrp_latest.pdf
Literature database with > 1500 entries on PFRP R&D

Teaching: Steel design to Eurocodes,
Forensic engineering and FRPs in construction.

WARWICK
PP slide show is available from Personal Web-page
http://www.eng.warwick.ac.uk/staff/jtm/

UK Historical Highlights for FRPs

3

1862	Alexander Parkes showed 'Parkestine' (*an artificial plastic material*)
1929	British Plastics Federation formed
1942	First components used in WWII aircraft
1951	First boat hull built by W. & J. Todd
1957	First Lotus Elite car
1958	Graphite fibres invented
1984	First complete airframe – Avtek 400 (USA)
	and for construction applications --
1988	First bridge enclosure[1] – A19 Tees Viaduct, near Middlesbrough
1992	Two-storey building[1] - Severn Bridges visitors centre (slide 4)
1992	First fully bonded cable stayed bridge[1] – Aberfeldy, Scotland
1994	First firewater caissons on offshore rig
1995	First road bridge[1] – Bonds Mill – (private road)
1995/6	First strengthening of existing structure
1996	Very large structural frame to support electrical equipment (slide 4)
2002	First road bridge[2] – West Mill – (public road) (slide 5)
2006	First "road" bridge over six-lane motorway[2] (Garstang and M6)
2010(?)	First house (STARTLINK®) – for sustainable homes (slide 7)

WARWICK

1. Constructed of the Advanced Composite Construction System (ACCS), (now pultruded by Strongwell).
2. ASSET deck profile (pultruded by Fiberline Composites A/S).

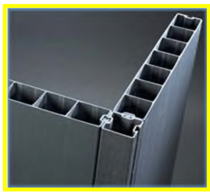
Main All-FRP Structures in UK

4

Stores building, Scott Bader, 70s

Wall system, Crane Composites Ltd., 2007-

Large frame is electrically non-conductive, 1996



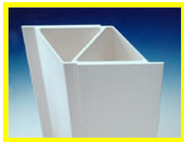
Severn Bridges Visitors centre, executed with (ACCS) Advanced Composite Construction System (now Composolite®), 1992

WARWICK

Observe the differences in the methods of connections

Main “All”-FRP Structures in UK

5



Halgavor Bridge, cycle crossing over A30 close to Bodmin, opened 2001

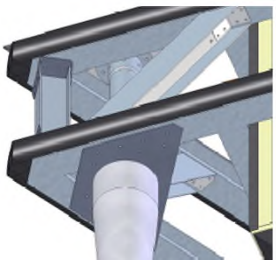
West Mill Bridge, first road crossing using ASSET profile (Fiberline Composites A/S), opened 2002

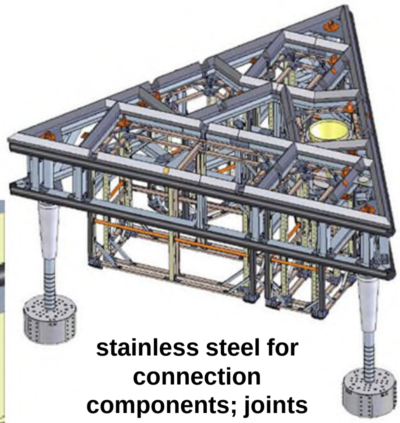
WARWICK

Main “All”-FRP Structures in UK

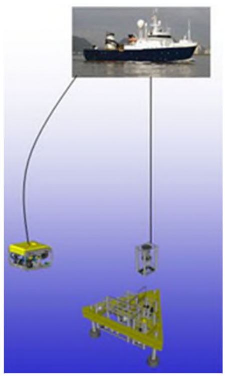
6

8 by 7 m plan PFRP docking station





stainless steel for connection components; joints bolted and bonded



6-monthly service over 20 years at depth of 1400 m

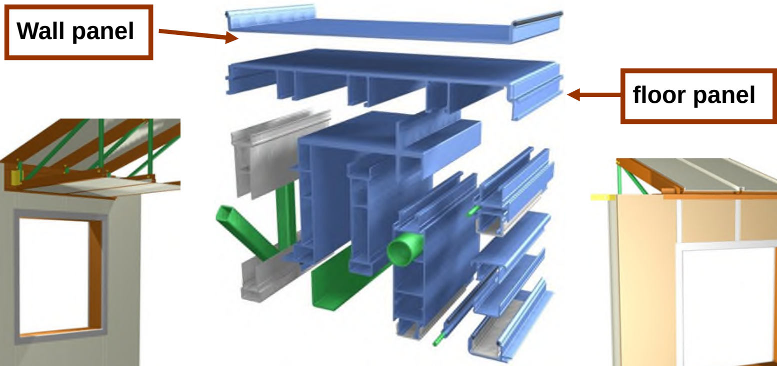
DELOS project – Deep-ocean Environment Long-term Observatory System

WARWICK

Engineered by 2H Offshore, UK, and fabricated by Fibreforce Composites, UK, in 2007.

7

Main All-FRP Structures in UK



Range of integrated pultruded shapes;

joined by snap-fit and dowelled connections.

STARTLINK® system for buildings (housing) and other structures

WARWICK Exciting development for the future.

8

Why is Design of Connections and Joints a Challenge for us?

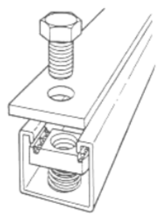
- Many joint configurations and details.
- Design manuals guidance (for pultuded shapes) can be different, and is often NOT based on 'rigorous' physical testing.
- Lack of material 'ductility'.
- Failure can be sudden and 'brittle'.
- Need for accurate stress and failure analysis.
- Lack of knowledge on durability and long-term structural integrity.
- Need for physical testing to verify new designs.

WARWICK

9

Focus on Mechanical Fastening and Bolting

- **Bolts (FRP or steel)**
- **Rivets**
- **Screws**
- **Unistrut connectors (blind fixing)**
- **Embedded fasteners (Big Head)**
- **Dowels or pegs**
- **Mechanical interlocking (keyed, hooked, toggled, snap-fitted)**



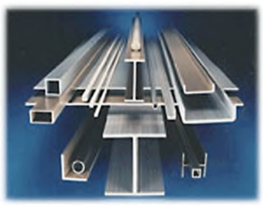
Methods of connection found in timber and steel construction

WARWICK

10

Code of Practice for Pultruded FRP Structures

New American Project – "*Standard for Load Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures*" (ASCE and ACMA).



Three years, starting Sept. 07.

Limited funds; none for new physical tests.

Drafters contributing for the "glory of it".

CHAPTERS

1. **GENERAL PROVISIONS;**
2. **DESIGN RESISTANCE;**
3. **TENSION MEMBERS;**
4. **COMPRESSION MEMBERS AND BEARING;**
5. **MEMBERS IN BENDING AND SHEAR[1];**
6. **MEMBERS UNDER COMBINED LOADS;**
7. **PLATES (Girders);**
8. **JOINTS AND CONNECTIONS[1].**

"Connections and Joints" in Europe

WARWICK

Note 1. Speaker to lead drafting of Chapter 8. Working with Profs. Larry Bank, Carol Shield and Russell Gentry.

Why Guidance for Bolting only

11

Advantages are:

1. Field or shop assembly.
2. Fabrication of parts simple.
3. Inspection easy.
4. Tooling unsophisticated.
5. Familiarity.
6. Low cost.
7. Fast.
8. Forces carried immediately.
9. Structure can be disassembled.
10. Historical precedence.
11. Most R&D results (but not necessarily for code calibration).

WARWICK

Why Guidance for Bolting only

12

Disadvantages are:

1. FRP fasteners (recommend stainless steel).
2. Stress concentrations (very difficult to achieve 50% strength of base PFRP material).
3. Inefficient because two or more bolts in a column configuration do not take an equal share of the action.
4. Lack of recognised design guidance.

WARWICK

General Philosophy to the Approach

13

Drafting will be to combine aspects of the concepts from:

1. ASCE 16 standard for wood.
2. AISC specification for bolted connections in steel trusses or simple steel frames (braced with no sway)
3. AISC specification for connections in cold formed steel members.
4. RCSC Specification for Structural Joints Using ASTM A325 or A490 Bolts.
5. code and background chapters “Connection Design” in the EUROCOMP Design Code and Handbook.
6. design guidance on connections in the pultruders’ Design Manuals.

WARWICK Structural Eurocodes do provide equivalent concepts found in 1 to 3 above.

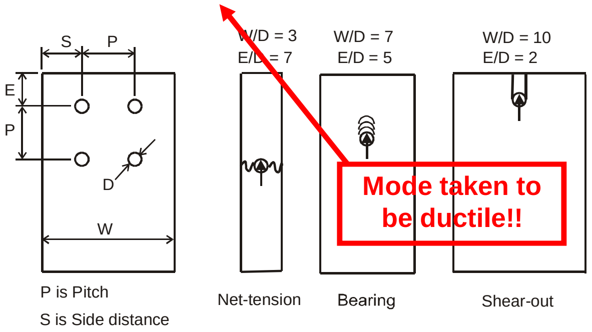
Types of Bolted Joints and Connections

14

Single-bolted single-lap and double-lap joints with loading in longitudinal or transverse direction based on 5 failure modes of:

Net tension Shear out Bearing Cleavage Splitting

Load test



Geometries for distinct failure modes are for EXTREN 500 ¼ inch plate with tension in longitudinal direction. M10 steel bolt with 0.2 mm clearance and “finger” tight torque. RT loading @ 10 kN/min (from Dr Geoff Turvey, Lancaster Univ., UK).

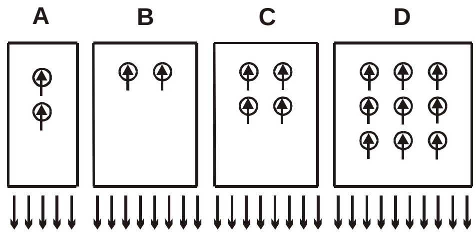
WARWICK W is width, E is end distance, S is side distance and P is pitch (for multi-bolted joints)

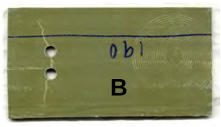
Types of Bolted Joints and Connections 15

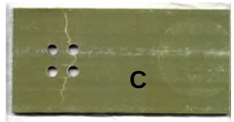
Multi-bolted single-lap and double-lap joints with loading in longitudinal or transverse direction based on single bolt failure modes. (block shear and by-pass load)

Effect of Geometry:[1]

- Resistance influenced more by the number of bolts in a row than in a column (A < B).
- Failure is at the first row of bolts when there are more than one row (A, C, & D).
- Small difference in max. load for joint types B and C show that a second row of bolts has little additional effect on strength.





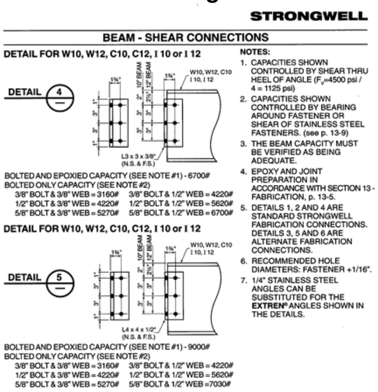


WARWICK **Note: 1. From SI project at Lancaster & Warwick Univs. (2000-02) (SI is for Structural Integrity)**

Types of Bolted Joints and Connections 16

Simple shear beam-to-column and beam-to-beam connections based on single bolt failure modes in the members or connecting elements.

Web cleat design details



From Dr Geoff Turvey

Moment-resistant with steel flange cleats

WARWICK **Standard not to scope moment resistant connections – semi-rigid action is attractive for PFRP structures.**

Joints and Connections Chapter

17

Provide design formulae and design guidance for both serviceability and strength limit states.

Determine professional factors for the formulae proposed for the different failure modes based on available test data.

Provide detailing guidelines for end/edge distances and spacing as a function of fastener diameter. Recommendations will be given on bolt torque, clearance hole size, washer type and sizes, etc. Detailing guidelines will be provided for joints and connections that are "bearing" failure controlled since slip-critical load transfer is not practical.

Adhesive bonding will not be considered

WARWICK

Joints and Connections Chapter

18

Commentary to Chapter 8 will:

- provide rationale and citations for design formulae proposed.
- provide details and dimension limits for the connected members and connecting elements for typical connections.
- give known limitations of the test data. (Approach will be to define specific joint and connection types and to prepare design guidelines for these standard types. A reference test procedure to characterize standard connections may be proposed.)
- propose a reference test procedure for a non-standard connection types.
- provide detailing guidance for bonded fillers and bonded bearing plates (or stiffeners) for local secondary strengthening in connections.

WARWICK

Joints and Connections Chapter

19

To scope design currently found in three types of structures:

Trusses

Lattice frames

Braced frames (no sway)

For braced frame structures the scope of Chapter 8 will be for the design of:

Primary beam-to-column simple connections (slide 16).

Continuous beam over column top connections.

Secondary beam to primary beam connections.

Continuous beam bearing on continuous beam connections.

Vertical and horizontal bracing members to primary members (to involve gusset plates or other connecting elements).

Splice connections for column and beam members.

WARWICK

Joints and Connections Chapter

20

Challenge: ***Suggested and experimentally-determined minimum joint geometry ratios*** **(at RT and no environmental ageing)**

Source	Plate thickness t (mm)	Bolt diameter / Plate thickness D/t	Edge distance / Bolt diameter E/D	Side distance / Bolt diameter S/D	Width distance / Bolt diameter W/D	Clearance hole size (mm)	Washer diameter / Bolt diameter
Strongwell (1989)	6.35 to 19.05	1.0 to 3.0	2.0 to 4.5 (3)[1]	1.5 to 3.5 (2)[1]	4 to 5 (5)[1]	1.6	-
Fiberline (1995)	3 to 20	0.5 to 16.0	2.5 & 3.5	2.0	4	1.0	2
EUROCOMP[2] (1996)	Unspeci-fied	1.0 to 1.5	≥ 3	≥ 0.5W/D	≥ 3	≤ 0.05D	>2
Creative Pultrusions (1999)	6.35 to 12.7	Unspeci-fied	2.0 to 4.5 (3.0)[1]	1.5 to 3.5 (2.0)[1]	4 to 5 (5.0)[1]	1.6	2.5
Rosner & Rizkalla (1995)	9.53 to 19.05	0.5 to 1.0	5[3]	Single-bolt	5[3]	1.6	-
Cooper and Turvey[4] (1995)	6.35	1.6	3	Single-bolt	4	Close fit (0.1 to .3)	-

Notes: 1. Recommended minimum design value. 2. General glass fibre reinforced plastics (including PFRPs). 3. D is hole diameter (bolt diameter and hole clearance). 4. From joint tests with tensile load in direction of pultrusion.

WARWICK For sources refer to literature database at http://www.eng.warwick.ac.uk/staff/jtm/pfrp_latest.pdf

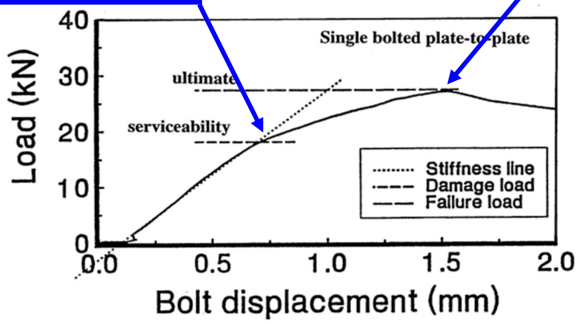
Joints and Connections Chapter

21

Challenge: *What defines failure for SLS and ULS?*

SLS – based on change in stiffness?

ULS – based on maximum load value



Slide 14 has test details

Plot reproduced from Cooper, C. and Turvey, G.J., Composite Structures, 32, 1-4, 1995, 217-226.

Joints and Connections Chapter

22

Challenge: *Failure modes for different testing conditions*

Longitudinal flat sheet PFRP

From Lancaster Univ. (Drs Turvey and Wang)

Net tension

Maximum recommended operating temperature is 65°C.

Bearing

Net tension design (E/D = 7 and W/D = 3)

(From left-to-right: RT, 40°C, 60°C and 80°C)

Results are with matrix of polyester resin; from SI project

Joints and Connections Chapter

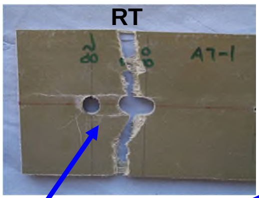
23

Challenge: ***Failure modes for different testing conditions***

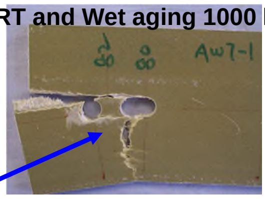
Longitudinal flat sheet PFRP

From Lancaster Univ. (Drs Turvey and Wang)

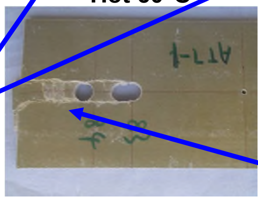
RT



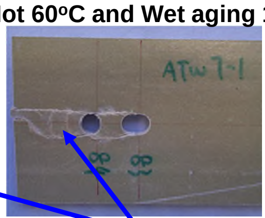
RT and Wet aging 1000 hrs



Hot 60^{o}C



Hot 60^{o}C and Wet aging 1000 hrs



Net tension/ cleavage

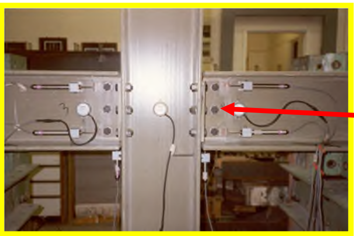
Shear-out

WARWICK

From SI project

Joints and Connections Chapter

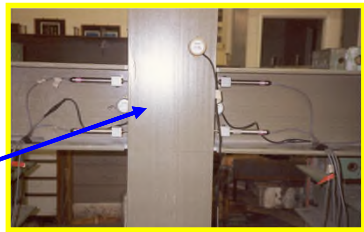
24

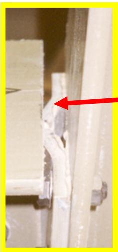


Simple joints;

Major

Minor





PFRP failure due to prying action

Challenge: ***Lack of formulae to design for web cleat prying action***

WARWICK

Joints and Connections

25

Design Approaches - SIMPLISTIC LEVEL

Ultimate joint resistance:

- Minimum joint geometry (for "bearing" failure; RT). (slide 20)
- Load Tables (Fiberline Composites (SF = 3) and
  Creative Pultrusions Inc. (Cleated beam connections – (SF = 4)).
- Knock-down factors (for hot/wet conditioning, etc.).
- EUROCOMP Simplified Design Method (has shortcomings).

Knock-down factors can allow for environmental and long-term durability effects (current approaches do NOT)

Simplistic Level approaches lead to high Factors for Safety

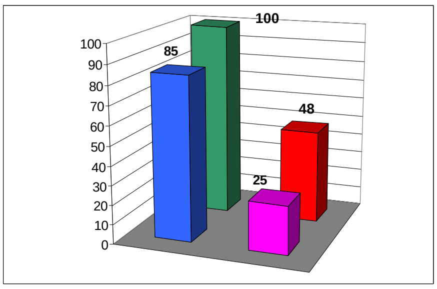
WARWICK

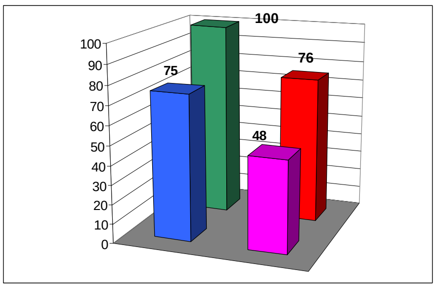
American standard to have a level between the two bounds presented in slides 25 to 29.

Joints and Connections

26

Knock-down Factors – SIMPLISTIC LEVEL





■ Room Temperature ■ Wet conditioning (1000 hrs under water)
■ Hot conditioning (60°C) ■ Hot & Wet conditioning

WARWICK

From actual test results; SI project

Joints and Connections

27

Design Approaches - STRUCTURAL INTEGRITY LEVEL

Accounts for progressive damage growth and a higher resistance than given by initial damage load (see slide 21). Approaches are semi-empirical and require a lot of information! Reduces Factors of Safety.

From 1970s – Hart-Smith – Concentric loading only – Correlation coefficient to convert isotropic stress concentration factors to fit test data for bolted connections with orthotropic plates – Curve fitting. Requires FEA for by-pass load distribution.

From 1990s – EUROCOMP Rigorous Design Method[1] - Characteristic distance concept to characterise additional resistance due to damage tolerance – Requires FEA for source (load distribution to bolts) and target (local stress distributions around bolt-hole).

WARWICK Note: 1. Complex and not shown to be practical.

Joints and Connections

28

Hart-Smith Design Method STRUCTURAL INTEGRITY LEVEL

Method does not account for different P/D or E/D ratios

Use conservative property data to construct design charts.

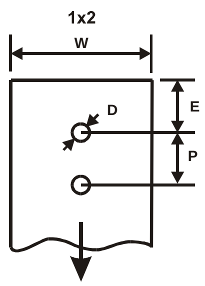
For RT (dry material, as received) there are independent joint type A test results from Canada (plate material, bolt diameter, bolt torque, clearance hole size are all different.

Joint Type A (slide 15)

One column with two rows (1x2)

Longitudinal orientation

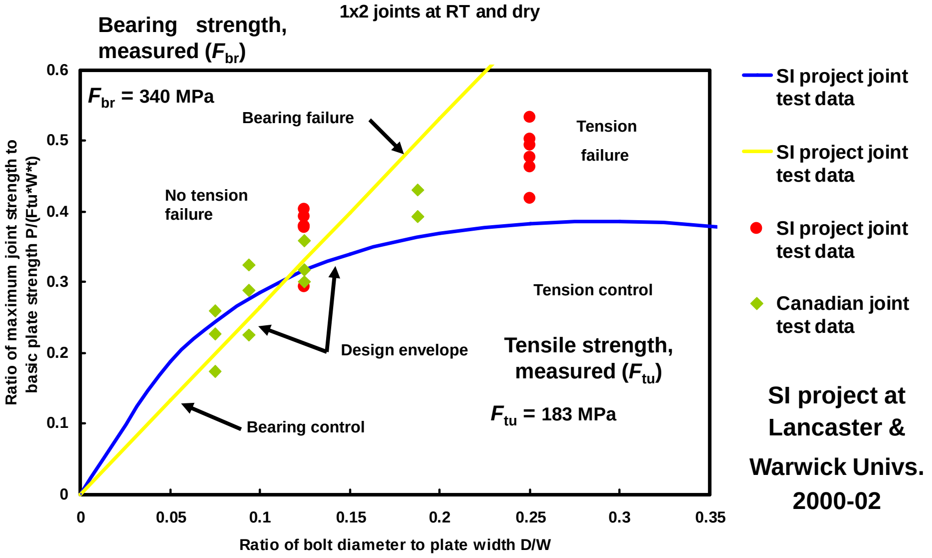
Mean joint strengths for 12 geometries



WARWICK From SI project; work not published.

Joints and Connections

29



WARWICK ◆ from Hassan, N. K., Mohamedien, M. A. and Rizkalla, S. H., J. Composites for Construction, 1 1, 1997, 3-6.

To Meet Challenges Research Needs to

30

- provide more tests results with parameters that correspond to practice.
- establish worthiness of design guidance for connections (bolted and, later, other methods).
- establish scope and limitations of design methodologies for timber and steel construction; calibrate design formulae (slide 13).
- develop understanding and know-how for design of bolted connections to become generalised.
- prepare draft for an approved design guidance (slide 10).
- improve confidence for the execution of bolted connections in primary load bearing all-FRP structures.

WARWICK

Concluding Remarks

31

- UK has seen a steady progress in the execution of novel and innovative structures of FRP structural materials, and this progress can be expected to grow as technologies mature and we seek sustainable solutions for buildings and bridges.
- Knowing how to design safe and reliable connections and joints remains the biggest challenge for those wanting to exploit FRPs in construction.
- For pultruded shapes bolting is the primary connection method (it provides flexibility and is familiar).
- There is a need for standard connection details giving easy to assemble structures that are safe, reliable and cost-effective.

WARWICK

Concluding Remarks

32

- With the American Society of Civil Engineers and American Composites Manufacturers Association we are preparing a "*Standard for Load Resistance Factor Design (LRFD) of Pultruded Fiber-Reinforced Polymer (FRP) Structures*". To be successful a concerted effort is needed to transfer R&D into practice.

Strongwell, USA

Creative Pultrusions Inc., USA

Fiberline Composites, Denmark

WARWICK


33
Thank you for your attention.
Any questions?
WARWICK
Email: J.T.Mottram@warwick.ac.uk
2007©