Theoretical and experimental analysis of a modular PFRP box beam concept constructed of separate plate elements and mechanical fasteners

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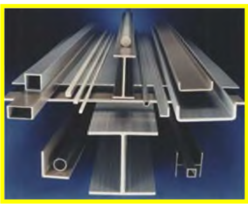
PFRP Structural Beam Profiles

First Generation (Standard)



Open sections

Max. $EI_{xx} = 5.6\times10^{12}$ Nmm^2

Second Generation (Specialized)

Double Web Beams

•Modular bridge decks

Large Closed sections

Max. $EI_{xx} = 1.6\times10^{14}$ Nmm^2

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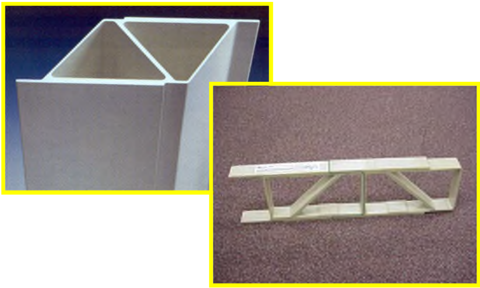
PP-slides available online

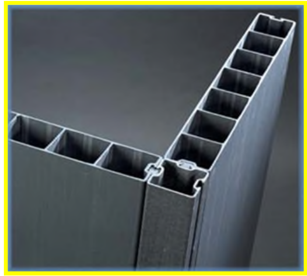
Modularization

Definition : Designed with standardized units or dimensions, as for easy assembly and repair or flexible arrangement and use.

Modular component



Modular systems



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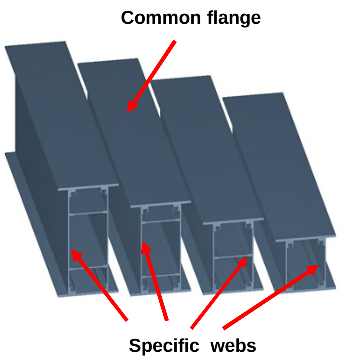
Startlink Modular Beam Assembly

How is it manufactured?

- Constructed from 4 separate PFRP components
- No closed section components
- Modular flanges with family of webs
- Component connected by mechanical fasteners



How does it fit into the market?

Med. sized closed sections with

$EI_{xx} > 8.4 \times 10^{12}$Nmm^2

Lower cost than specialized products

Part of a modular housing building system

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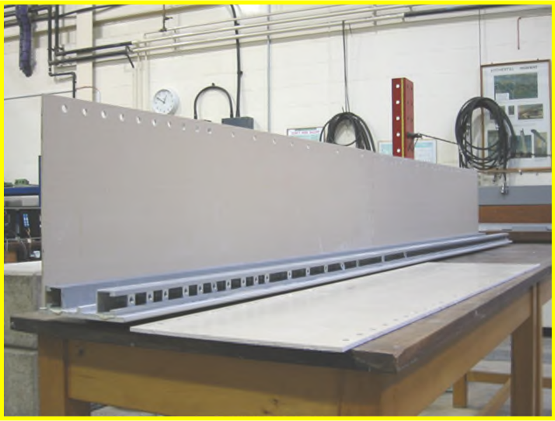
Prototype Beam Assembly



Details:

400 × 200 × 3000 mm

Linear mass 21 kg/m

Design SLS load 88kN

Flexural Rigidity
5.7×10^{12} Nmm^2

Made from available off-the-shelf material

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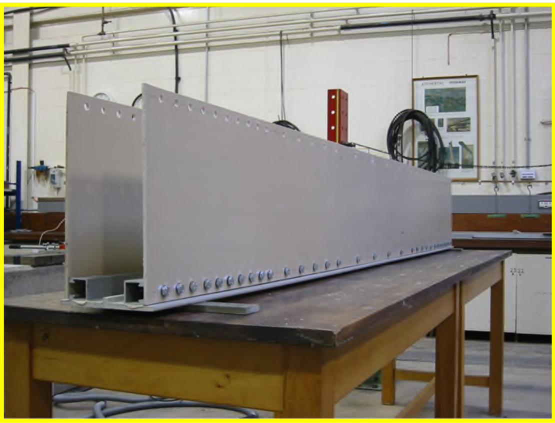
Prototype Beam Assembly



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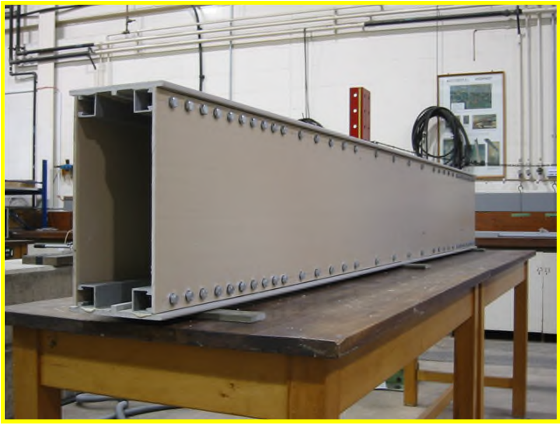

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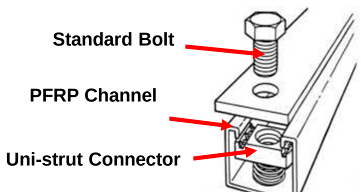
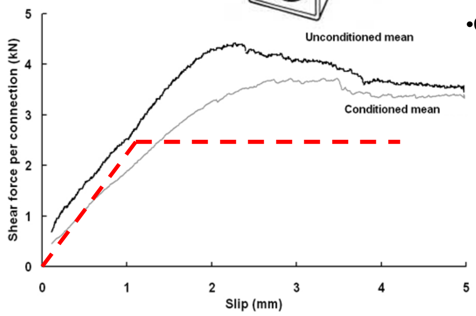
Characterization of Connection Method





Design characteristics (GS2/Standard)

- Recommended bolt torque 20Nm
- Ultimate Resistance 4.4kN
- Working load 2.5kN
- Connection Stiffness 2.5 kN/mm

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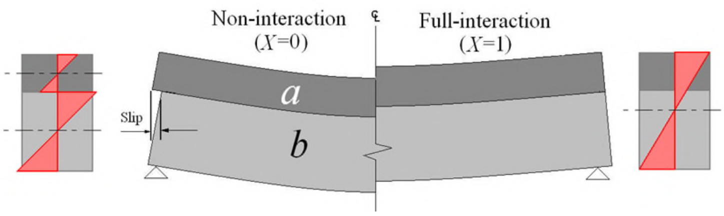
Importance of Shear Connections



Flexural Rigidity (no interaction) 1.1×10^{12} Nmm^2

Flexural Rigidity (full interaction) 5.7×10^{12} Nmm^2

Increase in flexural rigidity of 520%

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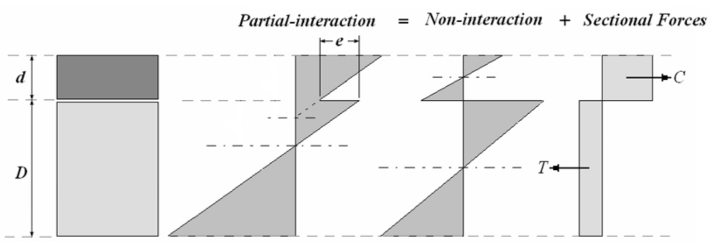
Partial Interaction - Newmark Analysis

2- Layer composite beam in bending:

- **Shear deformation between the components and resulting loss of bending stiffness is taken into account**
- **Bending moment due to sectional forces acting on components in flexure**

Discrete shear connections are replaced by uniform continuous linearly elastic medium
Initially plane sections remain plane
•The components are constant over the length
•There is no vertical separation of the components



$$M = k\sum(EI) + C\left(\frac{D}{2}+\frac{d}{2}\right)$$

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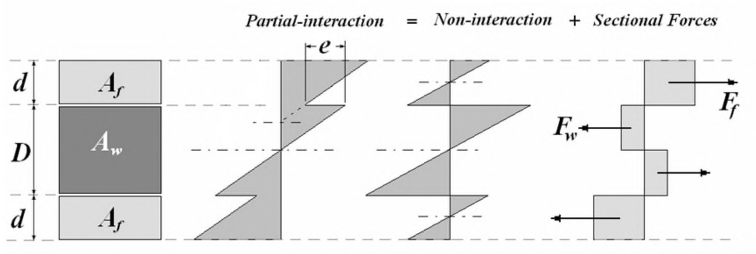
Modified Newmark Analysis

3- Layer composite beam in bending: **Moment equilibrium equation**



From inspection

$$M = k\sum(EI) + \left[F_f(D+d) - F_w\left(\frac{D}{2}\right)\right]$$

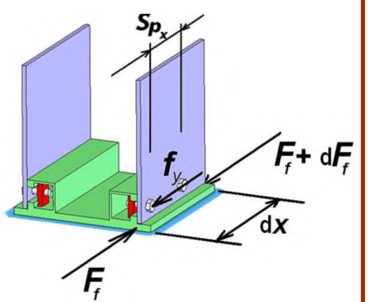
$$M = \left(\frac{2\sum EI}{EA_f(D+d)} - \frac{EA_wD^2}{8EA_f(D+d)} + (D+d)\right)F_f + \left(\frac{2\sum EI}{(D+d)} - \frac{EA_wD^2}{8(D+d)}\right)e$$

Shear deformation of shear connection

Consider an element of flange section in equilibrium

$$f_y dx + dF_f = 0$$

$$K_s = -\frac{f_y Sp_x}{s} \qquad e = \frac{ds}{dx} = \frac{Sp_x df_y}{K_s dx} = \frac{Sp_x}{K}\left(-\frac{d^2F_f}{dx^2}\right)$$



2[nd] differential equation for F_f

$$0 = \frac{d^2F_f}{dx^2} - \psi^2 F_f - \psi^2 \phi x$$

where ψ^2 and ϕ are constants relating to the connection stiffness and flexural rigidity of the components and complete system

Solution for F_f for the case of 4 point bending

$$F_f = \phi\left(x - \frac{\sinh\psi x}{\psi\cosh\psi\frac{L}{2}}\right)$$

Substituting for both k and F_f into the moment equation

$$\left(\sum EI - \frac{EA_w D^2}{16}\right)\frac{d^2v}{dx^2} = Px - \phi\left(x - \frac{\sinh\psi x}{\psi\cosh\psi\frac{L}{2}}\right)(D+d)$$

Integrating twice with respect to x, yields to following linear equation relating the vertical deflection v to the connection stiffness (ψ and ϕ)

$$\left(\sum EI - \frac{EA_w D^2}{16}\right)v = \frac{Pax^2}{2} - \phi\left(a - \frac{\tanh\psi a}{\psi}\right)(D+d)\frac{x^2}{2} + Mx + N$$

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Outline of Experimental Study

Objective: **Determine relationship between degree of shear connection and degree of interaction for the structure**

Method: **Parametric study using 4-point bend tests**

Variable: **Connection spacing , *Spx***

What was measured?

- **Load/deflection behavior**
- **Load/slippage behavior**
- **Strain distribution**

Beam configuration identifier	No. of M10 Unistrut connectors	Theoretical joint shear rigidity, γ N/mm/mm
BA-A50-AP	224	50
BA-A100-AP	112	25
BA-A200-AP	56	12.5
BA-A400-AP	32	6.25

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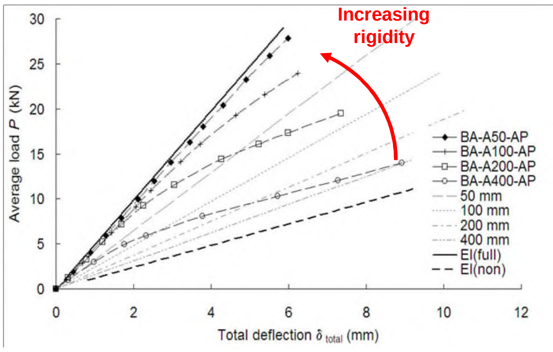
Comparison of Theoretical and Experimental Deflections



- Increasing rigidity with degree of connection
- A high degree of interaction can be achieved
- Non-linear response
- Apparent rigidity influenced by secondary effects (Compression, etc)

- Poor correlation of linear model
- Initial predicted rigidity significantly lower

Unrepresentative connection characterization

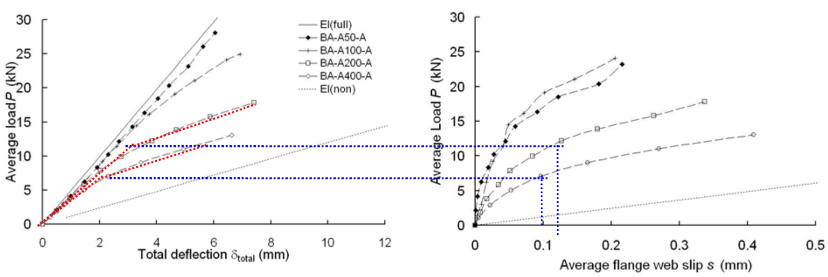
Experimental Load Deflection Behavior

Deflection response

- Non-linear response related to slippage, poor fit with linear models
- Initial rigidity close to EI_{full}
- Final rigidity close to EI_{non}

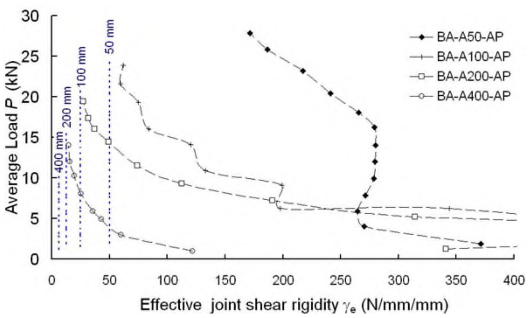
Slippage response

- Non-linear response above that of non-interaction
- Small slippage (>0.2mm) results in significant loss of composite action



Determination of Effective Joint Shear Rigidity

Comparison of individual connection behaviour with group connection behaviour



Joint shear rigidity directly related to degree of shear connection

Initial effective joint shear rigidity much greater than expected

Final effective joint rigidity approximately twice estimated value

- **Indicating the design connection stiffness of 2.5kN/mm is an underestimate**

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Assessing the performance of the system

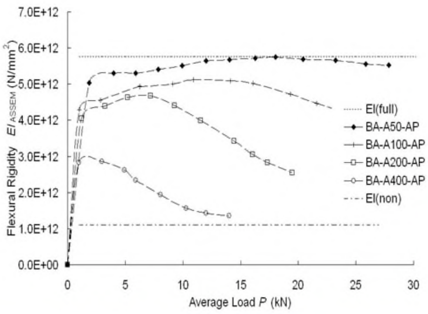
Determining the Flexural Rigidity

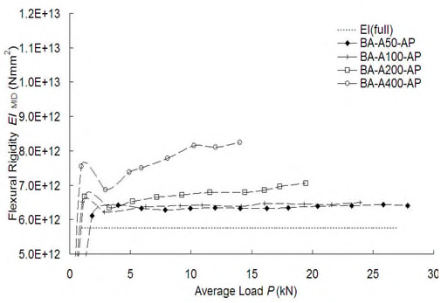
Total deflection analysis

- **Full shear connection assuming rigid connectors doesn't provide full interaction**
- **40% increase in interaction with 100% increase in shear connection**
- **Sensitive to deflection accuracy**

Linear elastic strain analysis

- **Over estimate of flexural rigidity, *EI*MID**
- **Degree of connection influences mid-span behavior**
- **Global Influence of outer-span flange strains reducing the strain at mid-span**





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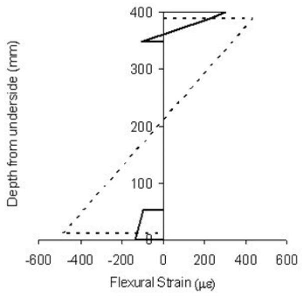
Assessing the performance of the system

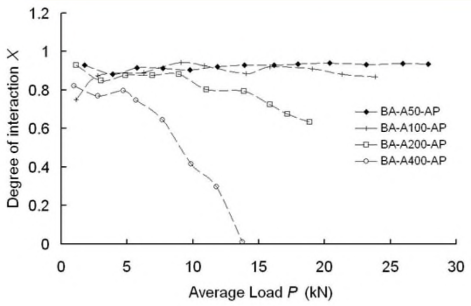
Determination of Degree of Interaction (M_{EXP}/ M_{THEORY})

Methodology:

- Calculation of moment carried by flanges $M_{EXP\ flange}$
- Comparison with Theoretical moment in flanges $M_{THEORY\ flange}$

- Spacing ≤ 100mm provide approximately full interaction
- SLS of Span /400 is only just possible
- High degrees of interaction are achieved during the initial loading





Conclusions

The modular beam assembly

- Concept is valid, a high degree of interaction is achievable
- Limit on interaction is governed by the stiffness of connection
- No direct relationship between degree of interaction and shear connection

Application of connector characterization to modular beam assembly

- A more representative and accurate characterisation of required (group behaviour)

Evaluation of the modified Newmark Analysis

- Poor correlation between linear theoretical model and the non-linear experimental results
    - Recommend use of effective joint shear rigidity, over characterization data.

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