A Filament Wound Pillar for a Pedestrian Bridge
Research question

What aesthetic value and structural capacity can be achieved by manufacturing a loadbearing column using the filament winding composite forming technique?
Research methodology

» Part one:
  Literature study
  Geometry

» Part two:
  Structural analysis
  Calculations

» Part three:
  Physical testing
  Aesthetics
  Conclusions and further research
Part one

Literature study

Geometry
Composite

» Fibres
Composite
» Fibres
» Resins
1. Creel
2. Alignment device
3. Tension controller
4. Alignment device
5. Resin bath
6. Wiper system or,
7. Nip roller
9. Mandrel
10. Spindle
Part one

Literature study

Geometry
Geometry
Physical modelling
Geometry

Digital modelling
- \( P_{nx} = 1 \)
- \( P_{nx} \text{ to } P_n \text{ ratio} = 0.05 \)
- 1 intersection
Geometry

- $P_{nx} = 2$
- $P_{nx} \text{ to } P_{n} \text{ ratio } = 0.09$
- 3 intersections

![Graph showing bundle length vs. $P_{nx}$]
Geometry

- $P_{nx} = 3$
- $P_{nx} \text{ to } P_{n} \text{ ratio } = 0.13$
- 5 intersections
» $P_{nx} = 4$
» $P_{nx}$ to $P_n$ ratio = 0.17
» 7 intersections
- \( P_{nx} = 5 \)
- \( P_{nx} \) to \( P_n \) ratio = 0.22
- 9 intersections
Geometry

- $P_{nx} = 6$
- $P_{nx}$ to $P_n$ ratio $= 0.26$
- 11 intersections
- \( P_{nx} = 7 \)
- \( P_{nx} \) to \( P_n \) ratio = 0.30
- 13 intersections
Geometry

- $P_{nx} = 8$
- $P_{nx}$ to $P_n$ ratio = 0.34
- 15 intersections
- $P_{nx} = 9$
- $P_{nx}$ to $P_n$ ratio = 0.39
- 17 intersections
- $P_{nx} = 10$
- $P_{nx} \text{ to } P_{n} \text{ ratio} = 0.43$
- 19 intersections
Geometry

- $P_{nx} = 11$
- $P_{nx}$ to $P_n$ ratio = 0.47
- 21 intersections
Geometry

Height

4 m 2,8 m
Part two:
Structural analysis
Calculations
Structural analysis

Static behaviour

Surface

F

F'

F

Wireframe
Circular reinforcements

» Stiff horizontal ring
» Part of winding path
» Additional mould structure
Circular reinforcements

» Stiff horizontal ring
» Part of winding path
» Additional mould structure
Part two:
Structural analysis
Calculations
Calculations

External forces

\( F_Z \)

» 175 \( kN \) total live load

» 25 \( kN \) total dead load

» 1,2 & 1,5 safety factors

» 292 \( kN \) total load
Geometrical input

- **Pillar height** = 2800 mm
- **Bottom radius** = 700 mm
- **Top radius** = 420 mm
- **Connection points** = 19
- **Point shift per crossing** = 6
Calculations

Geometrical input
- Pillar height = 2800 mm
- Bottom radius = 700 mm
- Top radius = 420 mm
- Connection points = 19
- Point shift per crossing = 6

Geometrical output
- Max length bundle = 409 mm
- Intersection layers = 11
Calculations
Hand calculations

Input
» \( F = 292 \text{ kN} \)
» Only one section between two intersections
» \( K = 1,0 \)
Calculations

**Input**

- $F = 292\, \text{kN}$
- *Only one section between two intersections*
- $K = 1,0$

**Output**

- *Buckling is primary cause of failure*
- *Polar bundle thickness* = $\phi 18\, \text{mm}$
- *Hoop bundle thickness* = $\phi 10\, \text{mm}$
Output type A

» Buckling is primary cause of failure
» Polar bundle thickness = 26 mm
Output type B

» Buckling is primary cause of failure
» Polar bundle thickness  =  Ø 18 mm
» (Hoop bundle thickness  =  Ø 13 mm)
Requirements of the pillar

Supports

Circular reinforcement
Through winding

Resulting force
Part three:
Physical testing
Aesthetics
Conclusions and further research
Physical testing

Mould type A
Physical testing

Mould type B
<table>
<thead>
<tr>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Height</strong></td>
<td><strong>Height</strong></td>
</tr>
<tr>
<td>514 mm</td>
<td>495 mm</td>
</tr>
<tr>
<td>78 mm</td>
<td>78 mm</td>
</tr>
<tr>
<td>129 mm</td>
<td>129 mm</td>
</tr>
<tr>
<td>80 mm</td>
<td>80 mm</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0</td>
<td>2 x 2</td>
</tr>
<tr>
<td><strong>Top radius</strong></td>
<td><strong>Longest bundle</strong></td>
</tr>
<tr>
<td><strong>Bottom radius</strong></td>
<td><strong>Bottom radius</strong></td>
</tr>
<tr>
<td><strong>Longest bundle</strong></td>
<td><strong>Polar layers</strong></td>
</tr>
<tr>
<td><strong>Polar layers</strong></td>
<td><strong>Hoop layers</strong></td>
</tr>
<tr>
<td><strong>Hoop layers</strong></td>
<td><strong>Hoop layers</strong></td>
</tr>
<tr>
<td><strong>Winding time</strong></td>
<td><strong>Winding time</strong></td>
</tr>
<tr>
<td>30 / 15 min</td>
<td>60 / 25 min</td>
</tr>
</tbody>
</table>
## Physical testing: Comparison

<table>
<thead>
<tr>
<th></th>
<th>Type A</th>
<th>Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total weight</td>
<td>305 g</td>
<td>410 g</td>
</tr>
<tr>
<td>Fibre length</td>
<td>64 m</td>
<td>77 m</td>
</tr>
<tr>
<td>Fibre weight</td>
<td>153 g</td>
<td>185 g</td>
</tr>
<tr>
<td>Matrix weight</td>
<td>145 g</td>
<td>220 g</td>
</tr>
<tr>
<td>Fibre weight fraction</td>
<td>52 %</td>
<td>46 %</td>
</tr>
<tr>
<td>Fibre volume fraction</td>
<td>32 %</td>
<td>28 %</td>
</tr>
<tr>
<td>Theoretical E-modulus</td>
<td>28 GPa</td>
<td>25 GPa</td>
</tr>
</tbody>
</table>
Physical testing

Testing equipment
Physical testing

Testing
Physical testing

Testing
Physical testing
Physical testing

Testing type A
Physical testing

Testing type A

Delamination of intersection

Fracture next to intersection

Bending moment contrained $K=0.699$

No interaction of bundle
Physical testing

Results type A
Physical testing

Testing type B
Physical testing

Testing type B

- Constrained connection
- Fracture by bending
- Fracture next to intersection
- Deformation of circular reinforcement
- Delamination of intersection by bending
- No interaction of bundle
Physical testing

Results type B
Physical testing

Results

Normal top support

B4 top support after test
Physical testing

Results

- Type A: 13.10 N/g
- Type B: 24.68 N/g
- Factor: 1.88

![Structural efficiency graph](image)

Type A: 13.10 N/g
Type B: 24.68 N/g
Factor: 1.88
Specific strength [N/g]

- **Type A**
  - Standard deviation (σ): 1.97

- **Type B**
  - Standard deviation (σ): 1.41

» *Standard deviation (σ) type A: 1.97*
» *Standard deviation (σ) type B: 1.41*
Scaling

» Buckling is primary cause of failure
» Circular bundle section

\[ F = \frac{\pi^2 EI}{(KL)^2} \]

\[ I = \frac{\pi}{4} r^4 \]

» \( F \) = Critical Force
» \( E \) = Elastic modulus
» \( K \) = Effective length factor
» \( L \) = Bundle length
» \( I \) = Moment of inertia
» \( r \) = Bundle section radius
**Scaling**

- *Buckling is primary cause of failure*
- *Circular bundle section*

\[
F = \frac{\pi^3 E}{4K^2} \cdot \frac{r^4}{L^2}
\]
Physical testing

Results

Scaling

» *Buckling is primary cause of failure*

» *Circular bundle section*

\[
F = \frac{\pi^3 E}{4K^2} \cdot \frac{r^4}{L^2}
\]

» \( E = 17.500 \text{ MPa} \)

» \( K = 1 \)

» \( C_1 = 135.652 \)
1 to 5 testing values

- \( F_{t,\text{total}} = 10.000 \, N \)
- \( F_{t,\text{bundle}} = 265 \, N \)
- \( L_{t,\text{max}} = 80 \, mm \)
- \( r_t = 1.9 \, mm \)

\[
F = C_1 \cdot \frac{r^4}{L^2}
\]

\[
r = \sqrt[4]{\frac{FL^2}{C_1}}
\]
1 to 1 pillar values

- $L_{\text{scaled}} = 400 \text{ mm}$
- $r_{\text{scaled}} = 9.4 \text{ mm}$
- $F_{\text{bundle}} = 6879 \text{ N}$
- $F_{\text{total}} = 250 \text{ kN}$

$$F = C_1 \cdot \frac{r^4}{L^2}$$
1 to 1 pillar values

- \( L_{\text{scaled}} = 400 \, \text{mm} \)
- \( r_{\text{scaled}} = 9.4 \, \text{mm} \)
- \( F_{\text{bundle}} = 6879 \, \text{N} \)
- \( F_{\text{total}} = 250 \, \text{kN} \)

Conclusion

- \( 250 \, \text{kN} < 292 \, \text{kN} \)
- *Structural potential*

\[
F = C_1 \cdot \frac{r^4}{L^2}
\]
Part three:
Physical testing
Aesthetics
Conclusions and further research
Part three:
Physical testing
Aesthetics
Conclusions and further research
The design of the support elements

» Manufacturing

» Effect of movement
The design of the support elements
» Manufacturing
» Effect of movement

Structural effect of the stacked layers
» Interaction of the bundles
» Winding strand thickness
The design of the support elements
» Manufacturing
» Effect of movement

Structural effect of the stacked layers
» Interaction of the bundles
» Winding strand thickness

Optimal winding path
» Thickness of the circular reinforcements
The design of the support elements
- Manufacturing
- Effect of movement

Structural effect of the stacked layers
- Interaction of the bundles
- Winding strand thickness

Optimal winding path
- Thickness of the circular reinforcements

Construction
- Winding on site
End of P5
Thank you
Parameters

» \( Pn \) = 14 to 26
» \( Pnx \) = 7