Master Graduation Thesis Presentation
By Kalliopi Papangelopoulou

Modular series of FRP pedestrian bridges
The example of Tanthof Delft

Tutors: Joris Smits (main mentor) | Fred Veer (second mentor) | Rafail Gkaidatzis (consultant)

-6th of July 2017-
Problem statement
Problem statement
Background

Maintenance of bridges Overijssel

<table>
<thead>
<tr>
<th>bridge age (yr)</th>
<th>Bridges &lt; 300 m²</th>
<th>Bridges &gt; 300 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td></td>
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</tr>
<tr>
<td>10-15</td>
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<td>15-20</td>
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<td>20-25</td>
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<td>45-50</td>
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<td>50-55</td>
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<td></td>
</tr>
<tr>
<td>55-60</td>
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</tbody>
</table>

source: Klatter H.E., "Societal aspects of bridge management and safety in the Netherlands"
PUBLIC FOOTBRIDGE’S REPLACEMENT

functional life time + aesthetically up-to-date

source: Valbona M., "Bridge decks of reinforced polymer (FRP): A sustainable solution"
Background

CONCRETE, STEEL, WOOD
or
Fiber Reinforced Polymer
as
structural material
Problem statement
Problem statement

<table>
<thead>
<tr>
<th>Depth of element</th>
<th>t</th>
<th>2t</th>
<th>4t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stiffness in bending</td>
<td>1.0</td>
<td>7.0</td>
<td>37.0</td>
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<tr>
<td>Load-carrying capacity in bending</td>
<td>1.0</td>
<td>3.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Weight</td>
<td>1.0</td>
<td>1.03</td>
<td>1.06</td>
</tr>
</tbody>
</table>
Problem statement

Zaha Hadid's Chanel Contemporary Art Container, New York's Central Park (2008)

source: http://www.building.co.uk/
Prove that it is possible to design an all FRP footbridge series and manufacture them via a modular moulding manufacturing process.
Research on:

- FRP raw materials
- FRP mould manufacturing techniques
- bridge design principles
- module matrix
- bridge design
- mould design
Presentation structure

Modular design

Bridge design

Bridge series

Modular mould design

Bridge series manufacturing

Bridge series installation
Bridge population: 64 footbridges
Design principles

- organic/double-curved shape
- monocoque structure
- modular mould
- renewable facade
- no extra supports
- integrated functions on cross-section
Design limitations:

- use of conventional material
- bridge dimensions suitable for Tanthof
- no height difference
- examined on one load case
Modular design

1 mould .......................................................... bridge series

slope

FOUNDATION THICKNESS

DECK

LOWER CURVATURE height

length

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## Modular design

<table>
<thead>
<tr>
<th>CRITERIAS</th>
<th>RESULT</th>
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<tbody>
<tr>
<td>possible length expansion</td>
<td>less modules possible</td>
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<tr>
<td>fixed length</td>
<td>more modules</td>
</tr>
<tr>
<td>fixed length</td>
<td>more modules</td>
</tr>
<tr>
<td>CRITERIAS</td>
<td>RESULT</td>
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<tr>
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<tr>
<td>fixed length</td>
<td></td>
</tr>
<tr>
<td>more modules</td>
<td></td>
</tr>
<tr>
<td>fixed length</td>
<td></td>
</tr>
<tr>
<td>more modules</td>
<td></td>
</tr>
</tbody>
</table>
Modular design

WIDTH 1 - 2M

WIDTH 2 - 3.5M

WIDTH 3 - 5M

Width of Tanthof bridges

1m 1m 1m 0.5m 1m 1m 0.5m 1m
Modular design

Length of Tanthof bridges

LENGTH 1: 4m
LENGTH 2: 8m
LENGTH 3: 12m
LENGTH 4: 16m
<table>
<thead>
<tr>
<th></th>
<th>4m</th>
<th>8m</th>
<th>12m</th>
<th>16m length</th>
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</thead>
<tbody>
<tr>
<td>2m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5m</td>
<td></td>
<td></td>
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</tbody>
</table>

**Parent bridge**

16m x 5m
Proposed Cross-section Length: 6.00m, Width: 3.00m, Clearance Gauge: 2.50m, General Height: +1.50m.
GEOMETRICAL VARIABLES

- plan curve
- side curve
- rotation angle
- flange height
Bridge design

SIDE HEIGHT

DEFLECTION

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2

Plan curve
Rotation angle
Flange height
Bridge design

DEFORMATION OF PLAN SHAPE

DEFORMATION (M)

PLAN DISTANCE (M)

side curve

plan curve

rotation angle

flange height

Bridge design

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Bridge design

DEFORMATION OF ROTATION ANGLE

ANGLE OF ROTATION (°)

DEFORMATION (M)

-60 -40 -20 0 40 60 80 100

0.000000

0.200000

0.400000

0.600000

0.800000

1.000000

1.200000

1.400000

1.600000

Bridge design

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Bridge design

FLANGE HEIGHT

DEFLECTION vs HEIGHT

- Side curve
- Plan curve
- Rotation angle
- Flange height
CONCLUSIONS

Important aspects of the shape:
- Curved side shape
- Negative plan curvature
- Existence of flange
- Flange height
CONCLUSIONS

Important aspects of the shape:
- Curved side shape
- Negative plan curvature
- Existence of flange
- Flange height
EQUIVALENT STRUCTURAL HEIGHT

$I = \frac{1}{12}bh^3$
Bridge design

Sandwich FRP Deck
non-slippery flooring

Sandwich FRP shell structure

FRP modular railing

Rain water gutter

LED Lighting
Bridge design

\[ I_i = \left( \frac{1}{12} \right) \times \left( \omega_i \times (h_i^3) \right) + (A_i \times d_i^2) \]

\[ E_0 \times I_0 = E \times I \]

\[ E_0 = E \times \frac{I}{I_0} \]

\[ G_0 = \frac{E_0}{2 \times (1 + \nu_0)} \]

Resin epoxy polymer +
E-glass fibres +
PVC cross-linked foam =
new sandwich FRP material

\( I = 0.019 \text{ m}^4 \)
\( E = 15.86 \text{ GPa} \)
\( G = 6.95 \text{ GPa} \)
Bridge design

maximum deformation:
7mm < 53mm (l/300)

Pedestrian Bridges Tanthof Delft
Structural simulation

Bridge series deformation

<table>
<thead>
<tr>
<th>Length (m)</th>
<th>Width 2m</th>
<th>Width 3.5m</th>
<th>Width 5m</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.4</td>
<td>0.6</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>2.3</td>
<td>2.2</td>
<td>2.5</td>
</tr>
<tr>
<td>12</td>
<td>4.4</td>
<td>4.5</td>
<td>4.6</td>
</tr>
<tr>
<td>16</td>
<td>5.1</td>
<td>5.8</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Bridge design

- modular elements
- easy replacement
- max. opening 0.5m diameter
- railing height 1.00 m
• modular elements
• easy replacement
• max. opening 0.5m diameter
• railing height 1.00 m
Bridge series
Bridge section:

- FRP Composite modular railing 1040x2000mm (+1000mm from walking level)
- FRP Composite parapet height 500mm with integrated LED light (+450mm from walking level)
- FRP Composite Bridge Deck 466mm with integrated rain water gutter
- FRP Composite Bridge structure 105mm
- FRP Composite angle foundation connection 30mm with additional web support

Final cross-section with railing
Bridge series

Detail 1 (all dimensions in mm)

Tapered FRP Composite railing
- hand-railing 70x40x30mm
- railing element 50x15x30mm
- railing element 60x25x30mm
- lower railing element 60x25x30mm
Bridge series

Detail 2 (all dimensions in mm)

FRP Composite ply 8mm
Epoxy resin, E-glass fibres, UD lay-up

FRP Composite core 90mm
PVC cross-linked foam, rigid, DH 0.030

Exterior LED light, white colour, 80lm/W
8.5x17.2x1900mm

Optional embedded wooden mould element in order to create the LED light cavity
22x11/16x1900mm
Bridge series

Detail 3 (all dimensions in mm)

- Embedded wooden mould element in order to create the gutter cavity, 33/50x20
- FRP Composite ply 8mm
  - Epoxy resin, E-glass fibres, UD lay-up
- FRP Composite core 90mm
  - PVC cross-linked foam, rigid, DH 0.030
- FRP Composite water rain gutter 20x33mm
- FRP Composite deck ply 5mm
  - Epoxy resin, E-glass fibres, UD lay-up
- FRP Composite deck core 20-500mm
  - PVC cross-linked foam, rigid, DH 0.015
- Non-slippery flooring 3mm
  - Gravel stones, epoxy resin

Mould seam

FRP Composite deck core 20-500mm
- PVC cross-linked foam, rigid, DH 0.015
Foundation system

Ground section:
- Concrete pavers with sand filled joints 60x200x75mm
- Bedding sand nominal 200mm
- Compacted soil sub-grade min. 300mm
- Steel "kick-pate" - protection from uneven ground settlement - 25x2000x800
- Reinforced concrete foundation 1500x1500mm
Embedded wooden mould element in order to create the connection cavity max. 95x165

M6 screw (x2) 10mm
FRP Composite cover 5mm
Stainless steel case 2mm
Perforated stainless steel plate 3mm
M10 bolt(x2) welded on steel plate 25mm
FRP Composite ply 8mm
Epoxy resin, E-glass fibres, UD lay-up
FRP Composite core 90mm
PVC cross-linked foam, rigid, DH 0.030
FRP Composite modular railing 2000mm

deck side
canal side
Non-slippery flooring 3mm, mixed gravel stones/epoxy resin
FRP Composite deck ply 5mm, Epoxy resin, E-glass fibres, UD lay-up

FRP Composite deck shear web 2mm
Epoxy resin, E-glass fibres, UD lay-up

FRP Composite deck core 90mm
PVC cross-linked foam, rigid, DH 0.015, 20-500mm

FRP Composite ply with embedded steel plate 11mm
Epoxy resin, E-glass fibres, UD lay-up

Concrete pavers with sand filled joints 60x200x75mm

Perforated stainless steel plate 3mm

FRP Composite angle foundation connection 30mm

M10 bolt welded on perforated steel plate
Detail 6 (all dimensions in mm)

- M10 bolt welded on perforated steel plate 25mm
- FRP Composite angle foundation connection 30mm
- FRP Composite ply with embedded steel plate 11mm
  - Epoxy resin, E-glass fibres, UD lay-up
- Perforated stainless-steel plate 3mm
- FRP Composite deck core 90mm
- PVC cross-linked foam, rigid, DH 0.015, 20-500mm
- FRP Composite deck shear web 2mm
  - Epoxy resin, E-glass fibres, UD lay-up
- FRP Composite ply 8mm
  - Epoxy resin, E-glass fibres, UD lay-up
- M10 bolt welded on perforated steel plate 25mm
- FRP Composite shear web 2mm
  - Epoxy resin, E-glass fibres, UD lay-up
- FRP Composite ply 8mm
  - Epoxy resin, E-glass fibres, UD lay-up
- FRP Composite core 90mm
  - PVC cross-linked foam, rigid, DH 0.030
  - M10 bolt ending 25mm
- L-Anchor for uplifting forces
- Stainless steel base plate 10mm
  - Reinforced concrete foundation 1500x1500mm
- FRP Composite angle foundation connection 30mm
- FRP Composite ply with embedded steel plate 11mm
  - Epoxy resin, E-glass fibres, UD lay-up
- Perforated stainless-steel plate 3mm
- FRP Composite deck core 90mm
- PVC cross-linked foam, rigid, DH 0.015, 20-500mm
- FRP Composite deck shear web 2mm
  - Epoxy resin, E-glass fibres, UD lay-up
- FRP Composite ply 8mm
  - Epoxy resin, E-glass fibres, UD lay-up
- M10 bolt ending 25mm
- L-Anchor for uplifting forces
- Stainless steel base plate 10mm
  - Reinforced concrete foundation 1500x1500mm
Bridge series

Tanthof area—small housing context

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Bridge series

Tanthof area - urban context
Bridge series

Delftse Hout area - natural context
Voorhof area - Multiplex housing context
How is the bridge series manufactured?
Modular mould design

Male mould
- FRP sheet

Product
- FRP sandwich

Female mould
- FRP sandwich
Modular mould design

Width: 7 modules
Length: 7 modules
Edge part: 2 modules
Modular mould design

- Male interlocking connection
- Female interlocking connection
- Champhed corners / designed seams
- Rubber seal strips

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Bridge series manufacturing
Bridge series manufacturing

- Edge module
- Width 5m module
- Width 3.5m module
- Centre module
- Width 3.5m module
- Width 5m module
- Edge module

(x, y)

桥系列制造

- 边缘模块
- 宽度5m模块
- 宽度3.5m模块
- 中心模块
- 宽度3.5m模块
- 宽度5m模块
- 边缘模块

(x, y)
Bridge series manufacturing
railing connections

protective coating

PVC foam core + glass fibres

protective coating

female mould
Bridge series manufacturing
Bridge series manufacturing

male mould

final product

female mould

vacuum connection/flange

resin outlet

resin injection

resin outlet

resin gates
Bridge series manufacturing
Bridge series installation

length 4m  9 bridges
length 8m  9 bridges
length 12m 30 bridges
length 16m 15 bridges

54 bridges / 4
14 trucks

63 bridges
Bridge series installation
Bridge series installation
Conclusions

• combination of multiple research topics
• free-form design appropriate for large structures or individual elements
• Light RTM is not appropriate for bio-resins
• modularity in connections for larger structures