FRP Structures
A canopy in Kotzia square

by Rutger Stefan Oor

Mentors: Ir. Joris Smits / Ir. Arie Bergsma / Ir. Peter Eigenraam

Sustainable Design Graduation Studio / Structural Design & Innovative Materials
Master Graduation Thesis / 06-2016
More Cladding than Loadbearing Composites

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Objectives

**Main Objective:**
- Prove that it is possible to design a self-supported FRP shell canopy structure with large spans between the support points

**Sub-objectives:**
- Finding the most suitable fibre type that has the mechanical strength that is needed and it cost-effective
- Finding the proper polymer type that has the mechanical strength that is needed, it is cost effective and it is resistant to different types of corrosion
- Defining which is the most suitable type of structure for the design
- Specifying which production technique is the most rapid, accurate and cost-effective from those that can be used for the production of the roof structure
- Finding which are the benefits of using FRP compared to other materials

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Constraints

- Canopy structure entirely made out of FRP
- No external support is allowed/Self-supported structural canopy
- Structural analysis only in FEM software
Kontzia Square

- Introduction -

Archaiki Odos & Cemetery, 480 BC

- Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Literature Review

- Introduction
- Materials
- Fibre-reinforced Polymers
- Shell Structures

Chapter 2
Materials
Polymers
Fibres
Foam Cores

Chapter 3
Fibre-reinforced Polymers
Production Techniques
Moulds
Detailing

Chapter 4
Shell Structures
What is a Shell?
Form Finding
Steering of Form

Design - Manufacturing & Installation - Conclusions -
A Canopy in Kontziaz Square

- Introduction
- Materials
- Fibre-reinforced Polymers
- Shell Structures
- Design
- Manufacturing & Installation
- Conclusions
Kontzia Square

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - **Design** - Manufacturing & Installation - Conclusions -
Canopy Typologies

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Most Efficient Typology

- Shell Thickness: 100mm
- Laminate Thickness: 10mm
- Maximum displacement: 0.021311 m
- Utilization: -1.9 % / 0.9 %
- Cost of Materials: 447556 euro
Canopy Design

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - **Design** - Manufacturing & Installation - Conclusions -
Canopy Design

Location of Support Points on the Site

Canopy Sections

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Form Finding Process

Form Finding Result
Sandwich Mechanical Properties

FRP: Polyester/E-glass fiber
(woven fabric composite, quasi-isotropic laminate)

Density: 1710-1890 kg/m³
Young’s modulus: 16.5-18.1 GPa
Yield strength: 183-201 MPa
Shear modulus: 6.58-7.24 GPa
Price: 1.61-1.77 EUR/kg

Foam Core: PVC cross-linked foam
(rigid, closed cell, DH 0.030)

Density: 36-44 kg/m³
Young’s modulus: 0.023-0.029 GPa
Yield strength: 0.37-0.43 MPa
Shear modulus: 0.06-0.016 GPa
Price: 11.5-12.6 EUR/kg.
Structural Comparison of the Three Geometries

- Shell Thickness: 100mm
- Laminate Thickness: 5mm
- Maximum displacement: 0.0573110 m
- Utilization: -2.9% / 1.6%
- Cost of Materials: 195545 euro
- Weight: 62954 kg
Redesigning the Outline of the Canopy

- Shell Thickness: 100mm
- Laminate Thickness: 5mm
- Maximum displacement: 0.052239 m
- Utilization: -2.5% / 1.4%
- Cost of Materials: 177058 euro
- Weight: 45703 kg

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Canopy Geometry

Axonometric Drawing
Side Support Elements

Perspective View

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Central Support Element

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - **Design** - Manufacturing & Installation - Conclusions -
The Canopy with the Supports

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - **Design** - Manufacturing & Installation - Conclusions -
The Canopy with the Supports

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
The Canopy with the Supports

Perspective Drawing
The Canopy with the Supports

Perspective Drawing
Perforations on Canopy

- Shell Thickness: 100mm
- Laminate Thickness: 5mm
- Max. displacement: 0.051545 m
- Utilization: -2.3 % / 1.1 %
- Cost of Materials: 105685 euro
- Weight: 34024 kg

Change from Previous Edition
- Max. Displacement: -1.32%
- Costs & Weight: -40.31%

Change from Original Edition
- Max. Displacement: -10.05%
- Costs & Weight: -45.95%
Panel Division

1. Panel Division
2. Original Panel Division & Refined Panel Division
3. Refined Panel Division Overlapping with Perforations
4. Adjusted Perforations

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Number of Panes

- 100 Panels
- 42 Types of Panel
- 2 x Panels 3-42
- 4 x Panel 2
- 6 x Panel 1
- 42 Mould are Needed
• Shell Thickness: 100mm
• Laminate Thickness: 5mm
• Maximum displacement: 0.062108 m
• Utilization: -1.4% / 1.0%
• Cost of Materials: 101921 euro
• Weight: 32813 kg

Axonometric Diagram, Maximum Displacement

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
The Canopy with the Perforations

Transverse Section

Longitudinal Section

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - **Design** - Manufacturing & Installation - Conclusions -
The Canopy with the Perforations

Plan of the Canopy

Plan/Top View of the Canopy
Water Drainage

Rain Path, Plan Diagram
Water Drainage

Stream of waters and falling distance

Support element and landing location of the water

Grill drainage

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
## Thickness Optimization

<table>
<thead>
<tr>
<th>Shell Thickness</th>
<th>Laminate Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td></td>
<td>6 mm</td>
</tr>
<tr>
<td>60 mm</td>
<td>7 mm</td>
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<td>8 mm</td>
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<tr>
<td>70 mm</td>
<td>9 mm</td>
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<td>10 mm</td>
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<tr>
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<tr>
<td>90 mm</td>
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<tr>
<td>100 mm</td>
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<td></td>
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</tr>
<tr>
<td>110 mm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>120 mm</td>
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</table>
## Thickness Optimization

<table>
<thead>
<tr>
<th>Max. Dis. Utilization</th>
<th>Laminate Thickness 5 mm</th>
<th>Laminate Thickness 6 mm</th>
<th>Laminate Thickness 7 mm</th>
<th>Laminate Thickness 8 mm</th>
<th>Laminate Thickness 9 mm</th>
<th>Laminate Thickness 10 mm</th>
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<tbody>
<tr>
<td>Shell Thickness 50 mm</td>
<td>0.117372</td>
<td>0.102961</td>
<td>0.092922</td>
<td>0.085633</td>
<td>0.080194</td>
<td>0.076065</td>
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<tr>
<td></td>
<td>-3.5 / +2.3</td>
<td>-3.5 / +2.3</td>
<td>-3.5 / +2.3</td>
<td>-3.5 / +2.3</td>
<td>-3.6 / +2.4</td>
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<td>Shell Thickness 60 mm</td>
<td>0.099349</td>
<td>0.086537</td>
<td>0.075535</td>
<td>0.070926</td>
<td>0.065920</td>
<td>0.062045</td>
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<tr>
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<td>-2.8 / +1.9</td>
<td>-2.8 / +1.9</td>
<td>-2.8 / +1.9</td>
<td>-2.8 / +1.9</td>
<td>-2.9 / +2.0</td>
<td>-2.9 / +2.0</td>
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<tr>
<td>Shell Thickness 70 mm</td>
<td>0.086251</td>
<td>0.074759</td>
<td>0.066645</td>
<td>0.060651</td>
<td>0.056075</td>
<td>0.052497</td>
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<tr>
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<td>-2.3 / +1.6</td>
<td>-2.3 / +1.6</td>
<td>-2.3 / +1.6</td>
<td>-2.3 / +1.6</td>
<td>-2.4 / +1.6</td>
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<tr>
<td>Shell Thickness 80 mm</td>
<td>0.076356</td>
<td>0.065942</td>
<td>0.058569</td>
<td>0.0531</td>
<td>0.048906</td>
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<td>-1.9 / +1.3</td>
<td>-1.9 / +1.3</td>
<td>-1.9 / +1.3</td>
<td>-2.0 / +1.4</td>
<td>-2.0 / +1.4</td>
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<td>Shell Thickness 90 mm</td>
<td>0.068451</td>
<td>0.058953</td>
<td>0.052213</td>
<td>0.047203</td>
<td>0.043348</td>
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<td>-1.7 / +1.1</td>
<td>-1.7 / +1.2</td>
<td>-1.7 / +1.2</td>
<td>-1.7 / +1.2</td>
<td>-1.7 / +1.2</td>
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<tr>
<td>Shell Thickness 100 mm</td>
<td>0.062108</td>
<td>0.053357</td>
<td>0.047139</td>
<td>0.042507</td>
<td>0.038936</td>
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<td>-1.4 / +1.0</td>
<td>-1.4 / +1.0</td>
<td>-1.4 / +1.0</td>
<td>-1.5 / +1.0</td>
<td>-1.5 / +1.0</td>
<td>-1.5 / +1.0</td>
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<tr>
<td>Shell Thickness 110 mm</td>
<td>0.056796</td>
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<td>0.042956</td>
<td>0.038665</td>
<td>0.035351</td>
<td>0.032723</td>
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<td>-1.3 / +0.9</td>
<td>-1.3 / +0.9</td>
<td>-1.3 / +0.9</td>
<td>-1.3 / +0.9</td>
<td>-1.3 / +0.9</td>
<td>-1.3 / +0.9</td>
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<tr>
<td>Shell Thickness 120 mm</td>
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<td>0.044786</td>
<td>0.039449</td>
<td>0.035447</td>
<td>0.03236</td>
<td>0.029908</td>
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<tr>
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<td>-1.1 / +0.8</td>
<td>-1.1 / +0.8</td>
<td>-1.1 / +0.8</td>
<td>-1.1 / +0.8</td>
<td>-1.1 / +0.8</td>
<td>-1.1 / +0.8</td>
</tr>
</tbody>
</table>

- Shell Thickness: 70mm
- Laminate Thickness: 5mm
- Maximum displacement: 0.086251 m
- Utilization: -2.3% / 1.6%
- Cost of Materials: 84854 euro
- Weight: 31396 kg

**Change from Previous Edition:**
- Max Displacement: +38.87%
- Costs & Weight: -16.74%

**Change from Original Edition:**
- Max Displacement: +50.49%
- Costs & Weight: -56.60%
Insolation

UV Radiation Analysis Diagram

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - **Design** - Manufacturing & Installation - Conclusions -
Insolation

Volume of Different Materials

Weight of Different Materials

Price of Different Materials

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Installation - Conclusions -
Photorealistic Picture
Manufacturing & Assembly
Thickness Optimization

27 Trucks are needed
Canopy Cost Estimation

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
Joint Between Panels

1. Male to Female
2. Splice plate and nut
3. Tighten the nut
4. Close the cover
Assembled joint
Joint Between Panels

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - **Manufacturing & Assembly** - Conclusions -
Panel Joints and Assembly

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
Panel Production Steps

Step 01: Creation of the Master Mould
Panel Production Steps

Step 02: Creation of the Cover of the Perforations
Panel Production Steps

Step 03: Vacuum Injection of the Cover
Panel Production Steps

Step 04: The Cover is cured
Panel Production Steps

Step 05: Cleaning the Master Mould
Panel Production Steps

Step 06: Adjustments on the Master Mould
Panel Production Steps

Step 07: Adding the first color of the Panel
Panel Production Steps

Step 08: Placing the Fibres
Panel Production Steps

Step 09: Placing the Foam Blocks
Step 10: Placing the Joints
Step 11: Closing the Cavity of the Joints
Panel Production Steps

Step 12: Placing the Fibres
Step 13: Adding the Second Color of the Panel
Step 14: Closing the Mould
Panel Production Steps

Step 15: Vacuum Injection
Panel Production Steps

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -

Step 16: The Panel is Cured
Panel Production Steps

Step 17: Removing the Panel from the Mould
Panel Production Steps

Step 18: Store the Panel
Step 19: Apply the Adhesive for the cover
Step 20: Attaching the Cover to the Panel
Panel Production Steps

Step 21: Store the Panel
Section of the Mould and Produced Panel

01 GFRP cap of the female part of the joint
02 Female part of the joint, Steel
03 Male part of the joint, Steel
04 Translucent GFRP cover of the perforation, 3mm
05 Structural Adhesive
06 Steel rod M10, 100mm length
07 Neoprene sealant
08 5mm Composite, Polyester, E-glass fiber, woven fabric composite, quasi-isotropic laminate
09 Polycarbonate Foam, PC (copolymer, high-heat)
10 Lower part of the master mould
11 Color coating
12 Middle upper part of the master mould
13 Part of the master mould
14 Cover of the female part of the joint during the panel production
15 Upper part of the master mould

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
Details 01, 02, 03, 04

01 5mm Composite, Polyester, E-glass fiber, woven fabric composite, quasi-isotropic laminate
02 Polycarbonate Foam, PC (copolymer, high-heat)
03 5mm Composite of the cover panel, Polyester, E-glass fiber, woven fabric composite, quasi-isotropic laminate
04 Polycarbonate Foam of the cover panel, PC (copolymer, high-heat)
05 Silicon sealant
06 Reinforced concrete support element
07 Double-curved steel plate, 10mm
08 Steel reinforcement anchors with treads
09 Steel rods welded to the steel plate, M10
10 Steel spacer embedded in the composite panel
11 Web of the cover panel, 2mm
12 Web of the support panel, 2mm

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
Central Support Element Cross Section

01  GFRP sandwich panel, 70mm thickness
02  Steel spacer embedded in the composite panel
03  GFRP sandwich panel, cover of the support panel
04  Drainage pipe Ø180mm
05  Male part of the joint, Steel
06  Female part of the joint, Steel
07  Reinforced concrete support element
08  Steel reinforcement anchors with treads
09  Locations of the steel spacers on the support element
Details 05, 06, 07

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
Details 08, 09

- Introduction - Materials - Fibre-reinforced Polymers - Shell Structures - Design - Manufacturing & Assembly - Conclusions -
Conclusions & Recommendations

Conclusions:
• Importance of form finding process
• Displacement problem of the structure
• Large mould-making costs

Recommendations:
• Research on bio-resins and bio-based polymers
• Research on new and cheaper mould-making techniques
• Research on alternative types of core
• Research on panel division techniques that benefit the structural efficiency of the structure
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