Deconstruction: A new construction method for prefabricated shells

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Building technology | Structural design

30th of June 2016

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Introduction

A new construction method for prefabricated shells

What are shell structures?
Introduction

Shell construction stagnated over time due to:

- Time consuming fabrication
- High construction material usage (molding)
- High construction material usage (tools)
- Extensive support set up time

Facts:

- € 1000-1200 per m² double curved surface
- € 70 per m² office floor
- Scaffolding 35- 60% of construction cost
Introduction

Shell construction stagnated over time due to:

- Time consuming fabrication
- High construction material usage (molding)
- High construction material usage (tools)
- Extensive support set up time

Fabrication solutions are:

- Prefabrication
- Flexible mold method

Elaborate construction phase costing time and money
Introduction

Elaborate construction phase

1957

2003
Objective

Build shells structures with the least amount of temporary supports during construction
Deconstruction: A new construction method for prefabricated shells

"Removing the least stressed panel(s) based on structural analysis"
Objective

Research question

Can the Deconstruction principle reduce the amount of temporary supports used during the construction of prefabricated shell structures?
Main sub questions:

- What **building methods** are currently used to build shells?
- What influence does the prefab pattern have on **force flow**?
- What are the **advantages of Deconstruction** on prefabricated shell structures?
Main sub questions:

- What building methods are currently used to build shells?
- What influence does the prefab pattern have on force flow?
- What are the advantages of Deconstruction on prefabricated shell structures?

- How do we design a construction method?
- How can we best spread forces over the prefabricated shell pattern?
- What criteria can best be used to select panels in deconstruction?
- What method variations can further reduce the use of temporary supports?
Objective

Restrictions

Shell shape
Generic free form shell

Introduction

Shell structure
Plate shells

Fabrication method
Prefabricated panels

Material
Concrete
Objective

Methods

Literary research:
  Shell construction
  Structural patterning

Designing:
  Patterns for a chosen shell
  Analysis algorithm to find best construction order

Testing:
  Patterns structural integrity
  Algorithm on patterns
  Method variations
Research

Deconstruction: A new *construction method* for prefabricated shells

How are shells constructed?

![Building construction images]
Research

Tile Vaulting
Research

Tile Vaulting

Prototype vault, Block Research Group

- Fast setting mortar
- Small thin bricks
- Multi layered
Research

*Tile Vaulting*

*Prototype vault, Block Research Group*

Igloo method

Cantilevering momentum

Countering momentum
Research

Installation gimmick

sporthall "Lenin"
Research

Installation gimmick

sporthall "Lenin"

Introduction
Objective
Research
Design
Conclusions
Summary
Research

Preassembly

SkilledIn office, RAP studio
Research

Preassembly

Skilled in office, RAP studio
Deconstruction: A new construction method for prefabricated shells

How can we improve prefabricated shells to fit the new construction method?
Research

Structural patterning

Reducing connection margins
"Reducing complexity and margins of error in connections"

6-7 point connection

3 point connection

Nature's design
Research

*Structural patterning*

**Buckling seam**
"A weak folding edge in the pattern where forces are only transferred by connection and not by panel geometry"
Research

*Structural patterning*

Force alignment

"Aligning panel faces with force flow to minimize stress on the connection"
Research

*Structural patterning*

**Force manipulation**

"Force distribution through pattern orientation"
Research

*Structural patterning*

Dynamic relaxation

"Spreading a pattern with set characteristics over a defined geometry to find equilibrium"
Research

Recap

Shell construction
*No suited methods*
*Igloo method*
*Installation gimmick*
*Preassembly*

Structural patterning
*Reducing connections margins*
*Buckling seam*
*Force alignment*
*Detail influence*
*Dynamic relaxation*
Deconstruction: A new construction method for prefabricated shells

How can we find the construction order in a prefabricated shell that needs the least support?
Design

*Deconstruction principle*

Calculated input situation → Removing selected* panel → Recalculation new situation → Removing next panel

---

*LOG*
Design

Deconstruction selection criteria

Normal forces/stresses

Moment forces/stresses

Shear forces

Forces

Deformation

+ - +

- +

Stresses

or
Design

*Deconstruction selection criteria*

Directional stresses not suitable
Design

Deconstruction selection criteria

Addition of stresses (S)

Normal stress
Nxx, Nyy, Nxy

Moment stress
Mxx, Myy, Mxy

Resulting stress
Sxx, Syy, Sxy

Top

Middle

Bottom

Normal stresses

Moment stresses

Moment shear stresses

Normal shear stresses
Design

*Deconstruction selection criteria*

Translation to principle stresses

### Selection criteria options

- **Principle stress:**
  - S1 (Top, Middle, Bottom)
  - S2 (Top, Middle, Bottom)
  - S3 (Top, Middle, Bottom)

- **Principal normal stressses:**
  - N1
  - N2

\[
\begin{align*}
S_{xx} &= S_1 \\
S_{yy} &= S_2 \\
\tau_{xy} &= \tau_{yx} = 0
\end{align*}
\]
Design

*Deconstruction selection rules*

Automated vs Manual selection

*Selection needs to be "smart"*

Single vs Multiple selection

*Mirrored selection keeps balance*
Design

Workflow overview

Shell geometry translation & calculation

Establishing prefab pattern

Deconstruction Round 1

Deconstruction Round 2
Test case of the swimming pool in Heimberg

- Heinz Isler
- 32.5 x 32.5 m
- 90 mm thickness
- Free form
- Form found shell
- **Geometry available**
Design

*Pattern guidelines*

- Mirroring edges
- Dynamic relaxation
- Main directions
Design

Pattern primitives

Primitive shapes

Pros
- Simple
- Easily applicable

Cons
- 2 directional
- Continuous seam

- Simple
- Easily applicable
- Multidirectional

- Small coverage
- Continuous seams
- 6-panel connections

- Multidirectional
- Large coverage
- 3-panel connections
- No continuous seams

- Complex geometry adaption

- Multidirectional
- 3-panel connections
- No continuous seams

- Complex geometry adaption
- Tight fit
Design

Pattern stages

Stage 1 - Undirected
- No relation to force flow
- Single mirror axis
- Single panel on supports
Design

Pattern stages

Stage 2 - Directed
- Relation to force flow
- Dual mirror axis
- Hard transitions
Design

Pattern stages

Stage 3 - Relaxed
- Relation to force flow
- Dual mirror axis
- Soft transitions
- Few distorted panels
Design

Mesh design

NURBS panel  Division into quads  Quads to 4 by 4 clockwise!  Mesh welding

- Custom designed mesh
  - Node alignment

- Grasshopper
  - Geometric approximation

- Diana mesh edit
  - UV coordinate based
Design

Detail design

- Detail face
- Detail connection
- Detail Anchoring
Patern results
*Undirected pattern*

First findings
- high peak stress start
- one direction deconstruction
- unstable
- rapid key panel generation
- 168 panels taken out

![Graph showing performance undirected in deconstruction](image)
Pattern results
Directed pattern

First findings
- Stable at start
- Dual axis deconstriction
- Edges out early
- Row selection
- Chanelling force (high average)
- 284 taken out
**Pattern results**

*Relaxed pattern*

**First findings**
- Stable at start
- Good spreading
- Edges out early
- True force flow lines
- Complex deconstruction pattern
- 276 panels taken out

**Performance Relaxed in deconstruction**

![Graph showing performance of relaxed pattern during deconstruction. The graph plots principle stress in N/mm² against the amount of panels removed. The x-axis represents the amount of panels removed, ranging from 0 to 256, while the y-axis represents the principle stress, ranging from -1000 to 11000. The graph includes lines for different stress levels: low end avg, high end avg, low end peak, and high end peak.](image-url)
Pattern results
*Pattern comparison*

Pattern conclusions
- Directed & Relaxed are close
- Relaxed more distributed
- More testing needed
- *Relaxed used for further testing*

Preformance in deconstruction

![Graph showing principle stress in N/mm² against the amount of panels removed.](image)
Method results

*Pure Deconstruction*
Method results

**Pure Deconstruction**

**Pure deconstruction:**
- Runs failed
- Ambitious
- Not realistic for large spans
- Needs foresight
- Presents force flow lines
Method results

Revision force flow lines
Method results

Preassembly configurations
Method results

*Preassembly configurations*

![Graph of Deformation](image1)

![Graph of Amount of Panels](image2)

![Graph of S1 Top panel average](image3)

![Graph of S3 bottom panel average](image4)
Method results

Preassembly configurations
Method results

Preassembly 14
Method results

**Preassembly 14**

**Preassembly in Deconstruction:**
- Runs failed
- Preassemblies stable on their own but not with additions
- Different points of stability
- Large cantilevers

**Introduction**

**Objective**

**Design**

**Conclusions**

**Summary**
<table>
<thead>
<tr>
<th>Method results</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Automated support placement</em></td>
</tr>
</tbody>
</table>
Method results

*Automated support placement*
Method results

Automated support placement:
- Runs succeed
- Minimal deformation
- 60 supports needed
- 48 supports vital, 12 for further deconstruction
Method results

Combination external
Method results

Combination external

Preassembly & ASP:
- Runs semi succeeded
- Long period around 5 N/mm² at generated supports
- 12 supports + 232 panels preassembled
Method results
Combination Internal
Method results

*Combination Internal*

**Supported preassembly:**
- Runs succeed
- 12 supports + 184 panels preassembled
- Peak in iteration 41 designers mistake
Method results

Results comparison

Normal

ASP

Preassembly & ASP

Supported preassembly

252 supports

60 supports

12 supports
232 panels

12 supports
184 panels
Conclusions

On structural patterning

*Hexagon pattern best suited*

*Directional patterning improves force flow*

*Relaxation distributes stress*

*Implement force alignment*

*Force flow lines fluent*
Conclusions

**On selection criteria**

*S1,3 Middle or N1,2*

*Multiple selection (in mirrored geometry)*

*Manual towards automated selection*

*Needs "smart" selection rules*
On Deconstruction

*Pure Deconstruction is ambitious/not realistic*

*Preassembly disputable*

*Automated support placement a succes*

*Preassembly & ASP disputable*

*Supported preassembly a succes*
Conclusions

Further research

On Deconstruction algorithm

*Stress based selection*

"Smart" selection rules

Implement force alignment

Testing on different shell types
Conclusions

*Further research*

**Related research**

*Structural patterning*

*Installation gimmick design*

*Fabrication of structural elements with flex mold*

*Panel design for deconstruction*

*Deconstruction on grid shells*

*Deconstruction on asymmetric shells*
Introduction

Construction of shell structures is too expensive and time consuming.

Objective

How can we optimize force flow, maintain stability and counter deformation during the construction of prefabricated shells so that there is no need for, or a maximum reduction of, scaffolding and temporary supports?

Design

Conclusions

Summary

**Problem statement:**

Construction of shell structures is too expensive and time consuming.

**Research question:**

How can we optimize force flow, maintain stability and counter deformation during the construction of prefabricated shells so that there is no need for, or a maximum reduction of, scaffolding and temporary supports?

**Methods:**

**Literary research:**
- Shells
- Shell construction
- Structural patterning

**Designing:**
- 3 Patterns for Heimberg swimming pool
- Deconstruction algorithm

**Testing:**
- 3 patterns
- Pure, Preassembly & ASP
- Variations

**Conclusions:**

**On structural patterning**
- Structural patterning is improved by direction & relaxation

**On selection criteria**
- Needs "smart" selection rules

**On Deconstruction**
- Shows promise but needs further development
Thank you
## Research
### Method comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>Amount of manual labour</th>
<th>Supports</th>
<th>Amount of supports</th>
<th>Cost</th>
<th>Construction speed</th>
<th>Freeform</th>
<th>Amount of Waste material</th>
<th>Application to large span</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timber Formwork</td>
<td>Large, on-site</td>
<td>Scaffolding</td>
<td>Large</td>
<td>High</td>
<td>Low</td>
<td>Yes</td>
<td>High</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>Prefabrication (CNC-milling)</td>
<td>Average</td>
<td>Scaffolding</td>
<td>Large</td>
<td>High</td>
<td>Medium</td>
<td>Yes</td>
<td>High</td>
<td>Yes, Exponential growth cost</td>
<td>High</td>
</tr>
<tr>
<td>Tile Vaulting</td>
<td>Large, on-site</td>
<td>Guiding wood or cardboard</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Yes</td>
<td>Medium</td>
<td>No, Exponential growth labour</td>
<td>Low</td>
</tr>
<tr>
<td>Post-stressing (Utzon 40)</td>
<td>Average</td>
<td>Guiding wood or cardboard</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Yes</td>
<td>Low</td>
<td>No, Exponential growth labour</td>
<td>Medium</td>
</tr>
<tr>
<td>Temp Post stressling (Lenin)</td>
<td>Average</td>
<td>Installation gimmick</td>
<td>Very low</td>
<td>Unknown</td>
<td>High</td>
<td>No, Domes only</td>
<td>Low</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>Reusable Formwork (CNIT)</td>
<td>Large, on-site</td>
<td>Scaffolding</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>No, Leaning arches only</td>
<td>Average</td>
<td>Yes</td>
<td>High</td>
</tr>
<tr>
<td>Pneumatic Formwork</td>
<td>Limited</td>
<td>Inflatable cushion</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>No, Controllable pneumatic only</td>
<td>Low</td>
<td>Yes</td>
<td>Low</td>
</tr>
<tr>
<td>Pre-assembly</td>
<td>Average</td>
<td>Scaffolding</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Yes</td>
<td>Medium</td>
<td>Yes, Exponential growth cost</td>
<td>High</td>
</tr>
<tr>
<td>3D printing</td>
<td>Limited</td>
<td>Scaffolding</td>
<td>Large</td>
<td>High</td>
<td>Low</td>
<td>Yes</td>
<td>High</td>
<td>Yes, Exponential growth time</td>
<td>Medium</td>
</tr>
</tbody>
</table>
**Ideal computational workflow**

1. **Goal:**
   1. Establishing a fast automatic communication between modelspace & Finite element program
   2. Determining base stress results for later comparisson

   **Methods:**
   1. Translating geometry to FE input format
   2. Linking FE output to right position on shell
   3. Applying geometrical transformation based on FE output
   4. Automating 3 previous steps

   **Products:**
   - Base values for monolithic shell
   - Automated calculation loops for optimization

2. **Goal:**
   1. Conducting a variant study on possible patterns
   2. Calculating patterns for further selection and base values
   3. Determining the impact of panel size

   **Methods:**
   1. Variant study of pattern primitives and variation in orientation
   2. Calculating 5 relevant patterns
   3. Calculating different sizes patterns
   4. Selecting 2 patterns for further optimization

   **Products:**
   - 2 panel patterns usable for optimization & production
   - Base stress values for chosen patterns
   - Preferred size of panel

3. **Goal:**
   1. Determining peak stress points in critical deconstruction path
   2. Determining max stress value for detail design
   3. Testing first deconstruction "designs"

   **Methods:**
   1. Testing 2 patterns with reverse deconstruction algorithm
   2. Testing best pattern with first deconstruction "designs"

   **Products:**
   - 1 pattern for pattern optimization
   - Peak stress values for comparison after optimization
   - Draft deconstruction design (pre-assembly/struts)

4. **Goal:**
   1. Optimizing pattern/forceflow in shell
   2. Reducing peak stresses in intact shell
   3. Maintaining producable dimensions

   **Methods:**
   1. Alligning panel edges perpendicular to force flow vectors
   2. Checking new panel stress results with previous stress results & implementing return for stress increase
   3. Comparing panel with producable dimensions & implementing return for excessive panels

   **Products:**
   - Verdict if force alignment improves force flow and/or reduces peak stresses
   - A customized pattern based on the force flow through the shell shape

5. **Goal:**
   1. Finding the most suitable construction order
   2. Finding detail and panel design values
   3. Finding deformation values to compensate during construction

   **Methods:**
   1. Basic reverse deconstruction for new peak stress values for comparisson
   2. Designed reverse deconstruction to see effects of pre-assembly/struts
   3. Final reverse deconstruction for design values

   **Products:**
   - Final building order
   - Final Detail design force values
   - Final Panel design force values
   - Deformation values during construction