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&

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Arches and Shells in Timber

Tallinn
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The Design and Construction Process

Concept ➔ Scheme ➔ Solution ➔ Concept

- Concept
- Scheme
- Solution
The Design and Construction Process

Idea → Design → Construction → Idea
The Use of Roundwood

a basic material
The Use of Roundwood

low grade timber

low environmental impact
Background - The Timber Production Process

low cost material
The Client Brief

1. For improved quality and early added value, at 20 years thin to one tree per 11 m².
   - This releases value to be used in better management

2. At 30-35 years: - Clear fell
   - Use trees not suitable for sawn timber
The Material – Norway Spruce

Thinned/poor quality trees:
• small diameter
• 180-220 mm at 1 metre
• 75-100mm at 10-15 metres
The Advantages of Roundwood

THE EFFECT OF SHRINKAGE

Tangential Shrinkage = 2 x Radial Shrinkage
Radial Shrinkage

Very Little Longitudinal Shrinkage
Mechanical properties:

- same strength wood as sawn timber
- therefore same related standards can be applied to the round timber as sawn timber

Knot angle is optimum

- knot area minimised on surface.
General rules – now

- To design using roundwood
  - choose grading criteria
    - visual or strength related
    - FAIR CT 95-0091. VTT - 1999
  - carry out tests
  - grade the timber
    - using guidelines choose a grade and design with EC5
The solution – 1985 -1995

- To design using roundwood
  - choose grading criteria
    - visual or strength related
  - carry out tests
    - as deemed appropriate
- Grade the timber
  - into appropriate BS5268 Pt 2 classes
Hooke Park College, Dorset, England

The idea

To design modern buildings with a poor quality material

To add value to a low value product
Hooke Park College, Dorset, England

The complication

Material with unknown properties
No recognised code or grading
Material with variable dimensions
The solution:

- Modern architecture
- Fundamental understanding of material
- Innovative jointing
- New construction techniques
Hooke Park College, Dorset - Prototype House

1984
Hooke Park College, Dorset - Workshop

1991
Main arch membrane

75mm Insulation

Noggins of half poles

See detail

15000
Modelling structure
Working with the Material
Full size prototyping
Jointing
Hooke Park College, Dorset
- Westminster Lodge

1996
Model making

Raft foundation

No fines wall on lower side of plate

enable future excavation to the lower plate
 APPROX EIGHT 3M LONG POLES SPLICED TOGETHER FORMING TOP CHORD

THREE 3M LONG POLES SPLICED TO FORM BOTTOM CHORD
Glulam

a historic material
Opened August 1860
Waterloo Entrance to the Festival of Britain - 1951
Glulam – a modern material

Sheffield Winter Gardens
Sheffield Winter Garden

Architect:
Pringle Richards Sharrat

Engineer:
Buro Happold

Timber Engineering contractor
Merk Holzbau GmbH & Co KG
Sheffield Winter Garden

The idea:

To design Gateway Building for Urban Regeneration
Sheffield Winter Garden

The challenge:

To design a building to inspire
To design a building for public enjoyment
Sheffield Winter Garden

The solution:

- A natural environment
- Wood used as a modern material
Sheffield Regeneration
Heart of the City

- Shops
- Peace Gardens
- Town Hall
- Office Development
- Hotel
- Winter Gardens
- Millennium Galleries
- University
- Rail & Bus Stations
Winter Garden: Design Considerations

- **Winter:**
  - Pre-heated air reservoir supplying gallery
  - Winter heat gain from surrounding buildings

- **Summer:**
  - Summertime stack effect ventilation through Winter Garden roof
  - Passive solar and cool air supply to gallery through evaporative cooling

*The Winter Garden - A Lung for Surrounding Buildings*
<table>
<thead>
<tr>
<th>Common Name</th>
<th>Strength Class</th>
<th>Durability Class</th>
<th>Mean Stiffness N/mm²</th>
<th>Density range and Mean</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>European Oak</td>
<td>D30 D40</td>
<td>Durable</td>
<td>10,500 - 13,500</td>
<td>670-710-760</td>
<td>High</td>
</tr>
<tr>
<td>European Larch</td>
<td>C16 C24</td>
<td>Moderately Durable</td>
<td>9,000 - 10,500</td>
<td>470-600-650</td>
<td>Medium</td>
</tr>
<tr>
<td>Douglas Fir <em>N. American</em></td>
<td>C16 C24</td>
<td>Moderately Durable</td>
<td>10,000 - 11,000</td>
<td>510-530-550</td>
<td>Medium</td>
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<tr>
<td>Redwood / Scots Pine</td>
<td>C14 C24</td>
<td>Slightly Durable</td>
<td>9,000 – 10,500</td>
<td>500-520-540</td>
<td>Low</td>
</tr>
<tr>
<td>Douglas Fir <em>UK grown</em></td>
<td>C14 C18</td>
<td>Slightly Durable</td>
<td>9,500 – 11,000</td>
<td>470-510-520</td>
<td>Medium</td>
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<tr>
<td>European Whitewood (Silver Fir/ Norway Spruce)</td>
<td>C16 C24</td>
<td>Slightly Durable</td>
<td>8,800 – 10,800</td>
<td>440-460-470</td>
<td>Low</td>
</tr>
<tr>
<td>Sitka Spruce (UK Sitka)</td>
<td>C14 C18</td>
<td>Not durable</td>
<td>6,500 – 8,000</td>
<td>400-440-450</td>
<td>Low</td>
</tr>
</tbody>
</table>
The Structure

75m long; 20m high; 22m span

The principal structural element sizes are:

- Arches - 210mm wide x 910mm deep
- Purlins - 150mm wide x 225mm deep
- Raking Struts – 245 mm diameter

All timber is Polish Larch to grade GL28. Glulam manufactured by Derix and fabricated by Merk, in Germany. The steelwork is mild steel, galvanised to avoid staining the wood.
Arch Geometry – arches at 3.75 metre spacing

Galleries

Hotel & Restaurant
Structure

Access from Hotel & Galleries
Superstructure
Superstructure
Superstructure
Details: Arch Apex
Details: Base
Timber Gridshell

sophisticated structures
Timber Gridshell Construction

The idea: ..................
Timber Gridshell Construction – the principle
## Gridshell precedents

<table>
<thead>
<tr>
<th>Gridshell</th>
<th>Span</th>
<th>No of Layers</th>
<th>Lath size</th>
<th>Material</th>
<th>Bracing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mannheim</td>
<td>60m x 60m</td>
<td>4</td>
<td>50mm x 50mm at 0.5 m</td>
<td>Hemlock</td>
<td>Twin 6mm cables</td>
</tr>
<tr>
<td>Japan Pavilion</td>
<td>72m x 35m</td>
<td>2</td>
<td>120mm rad at 1.0m</td>
<td>Cardboard tube</td>
<td>Glulam ladders</td>
</tr>
<tr>
<td>Earth Centre</td>
<td>6 x 6m</td>
<td>2</td>
<td>32mm x 15mm at 0.4m</td>
<td>Oak</td>
<td>Twin 2mm cables</td>
</tr>
<tr>
<td>Downland Gridshell</td>
<td>48m x 15m</td>
<td>4</td>
<td>50mm x 35 mm at 1.0m</td>
<td>Oak</td>
<td>Timber cladding rails</td>
</tr>
<tr>
<td>Savill Garden</td>
<td>90m x 25m</td>
<td>4</td>
<td>80mm x 50mm at 1.0m</td>
<td>Larch</td>
<td>12mm birch plywood</td>
</tr>
<tr>
<td>Chiddingstone Castle</td>
<td>12m x 5m</td>
<td>4</td>
<td>40mm x 30mm at 1.0m</td>
<td>Sweet Chestnut</td>
<td>Twin 4mm cables</td>
</tr>
</tbody>
</table>
Gridshell Precedents
Mannheim Bundesgartenschau

50m span
4 Layers
50 x 50 hemlock

Design Team: Frei Otto / Ove Arup
Mannheim – a funicular structure
Mannheim Gridshell
Mannheim
Earth Centre Doncaster

6m span
2 Layers
32 x 15 oak

Design Team: Grant Associates / Buro Happold
Earth Centre Gridshells
Earth Centre Gridshells

32mm x 15mm at 0.4m.  
Bracing: twin 2 mm cables
Earth Centre Gridshells
The Japan Pavilion Hanover EXPO 2000

30m span
2 Layers
Cardboard Tubes

Design Team: Shigeru Ban/ Buro Happold
The Japan Pavilion Hanover Expo 2000

120mm radius Cardboard tube at 1.0m
Bracing: Glulam ladder beams
Japan Pavilion
The Japan Pavilion
Hanover EXPO 2000
Downland Gridshell

48m x 15 m
4 Layers
50mm x 35mm oak

Design Team: Edward Cullinan Architects/ Buro Happold
Downland Gridshell

The Client Brief:

To design modern building in a sensitive environment

To use an innovative design
Downland Gridshell

The complication:

- Re-discover the techniques used in 1975 at Mannheim
- Devise design methods
- Develop construction technique and teach others
- Maintain confidence of the Client and design team
Downland Gridshell

The solution:

Innovative design and method
Prototyping – model and full scale
Good communication
Structural principle

Not a funicular Structure!
Construction Method
Mannheim
layers B and D run parallel to one another

shear block to enable horizontal shear transfer between layers B and D

layers A and C run parallel to one another

eys shear blocks between each layer

Section

Plan
M8 Bolt

Slots in outermost layers ranging in length from 50mm to 150mm
105mm x 105mm (approx) steel plates with rounded corners

6mm thick plates top and bottom

Packaging (all bolts) at 'high shear' nodes

4mm thick plates between laths dia x 20 long. Locating stud fitted into pre drilled holes, welded to 4mm plate

M8 bolt
105mm x 105mm (approx) steel plates with rounded corners

Rear lath

M8 bolt

4mm thick plates between laths d3 x 20 long. Locating stud fitted into pre-drilled holes, welded to 4mm plates

6mm thick plates top and bottom

Packing (all bolts) at 'high shear' nodes
Forming the laths
The Savill Building

90m x 25m
4 Layers 80 x 50 mm Larch

Glenn Howells Architects

Engineers HRW

Buro Happold – Roof Engineers
The challenge:

To design a large modern building for a very sensitive site

To use local timber
The Savill Building

The complication:

Fixed budget and client / design team with little experience of innovative design and construction

Material with unknown properties
The Savill Building

The solution:

Good communication
Use of EC5 for reliable design outcome
Material testing
Competition sketch
Glenn Howells Architects
Defining the Form – Mathematical

Form-finding with University of Bath

Perimeter slab is set out using arcs of two intersecting circles
- Curved centreline on plan, midline between the circles.
- Centre line of the roof, in section, generated by cosine curve, of varying amplitude (peaks and troughs at the tops of domes and bottoms of valleys).
- Cross-section is set out, across the sinusoidal centre line, as series of parabolic curves of varying shape.
• $z = f(x, y)$ with a damped cosine wave in the $x$ direction and upside down parabolas in the $y$ direction
• clear geometric basis to the surface shape
• architects and engineers could work together to adjust and agree shape to meet aesthetic practical constraints
• Perimeter of shell set out by cutting the surface with planes – thus structural element trimming the edge is bent in only two dimensions
Defining the Form

grid of equal length elements by constructing a Tchebyshev net

Establishing the Structure
Analysis, Design and Detailing
Edge Detail: Carpentry advice
Timber Testing

BS EN 384: 1995: Structural timber - Determination of characteristic values of mechanical properties and density

BS EN 408: 1995: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties
Timber testing and properties
Determination of properties

<table>
<thead>
<tr>
<th>Property</th>
<th>BS4, BS5, BS6, BS8, BS10, BS12, BS14, BS16, BS18, BS20, BS22, BS24, BS26, BS28, BS30, BS32, BS34, BS36, BS38, BS40, BS42, BS44, BS46, BS48, BS50, BS52, BS54, BS56, BS58, BS60, BS62, BS64, BS66, BS68, BS70, BS72, BS74, BS76, BS78, BS80, BS82, BS84, BS86, BS88, BS90, BS92, BS94, BS96, BS98, BS100</th>
<th>BS30, BS32, BS34, BS36, BS38, BS40, BS42, BS44, BS46, BS48, BS50, BS52, BS54, BS56, BS58, BS60, BS62, BS64, BS66, BS68, BS70, BS72, BS74, BS76, BS78, BS80, BS82, BS84, BS86, BS88, BS90, BS92, BS94, BS96, BS98, BS100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending</td>
<td></td>
<td></td>
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<tr>
<td>Tension-parallel</td>
<td></td>
<td></td>
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<tr>
<td>Tension perpendicular</td>
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<td></td>
</tr>
<tr>
<td>Compression-parallel</td>
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<tr>
<td>Compression perpendicular</td>
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<tr>
<td>Shear</td>
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<tr>
<td>Ultimate properties</td>
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<tr>
<td>Mean modulus of elasticity parallel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% modulus of elasticity parallel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean modulus of elasticity perpendicular</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean shear modulus</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BS EN 338 Structural timber – Strength classes
Savill Building Grade I and Grade II

Sapwood excluded - protective treatment of roof timbers against house longhorn beetle
Design Development - prototyping
Full Size Section of shell
Full Size Section of shell
Roof Construction
Finger jointing
Grade and check m.c.

Grade 1 Larch

Grade 2 Larch
Lay out bottom mat of two layers
Lower into position
Bolt edge plates into position
Bring edge of mat onto plates
Fix Shear Blocks
Bracing of shell

Local larch for structure, local oak for rain screen

Bracing: 2 layers 12mm birch ply
Plywood skin – structural bracing
Strike the scaffold
Glazing and Rainscreen
Oak Cladding
Oak cladding
Edge detail
Finished Building
The Garden Context
another gridshell
Chiddingstone Castle Orangery
Another Challenge

Andrew Wright Associates with S&P Architects Architects
The Scheme
The Competition
The Scheme
Precedent – Timber Geodesics
The Scheme
The Scheme – Exploded
Defining the Roof Surface
Formfinding – Tenyssl ‘Hanging Chain model’
Defining the Roof Surface
Defining the Roof Grid

take surface

define a grid

map grid onto surface
Defining the Roof Grid

1. Define a grid
2. Take the surface
3. Map the grid onto the surface
4. Relax the grid using dynamic relaxation
Defining the Roof Grid
The Structural Solution - Roof
The Structural Solution - Roof
The Structural Solution
The Structural Solution - Cladding