Richard Harris

Buro Happold
&
University of Bath

TIMBER- THE KEY TO TOMORROW`S ENVIRONMENT

Arches and Shells in Timber

Tallinn

November 27th 2008

Richard Harris

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Technical Director

Buro Happold

Richard Harris

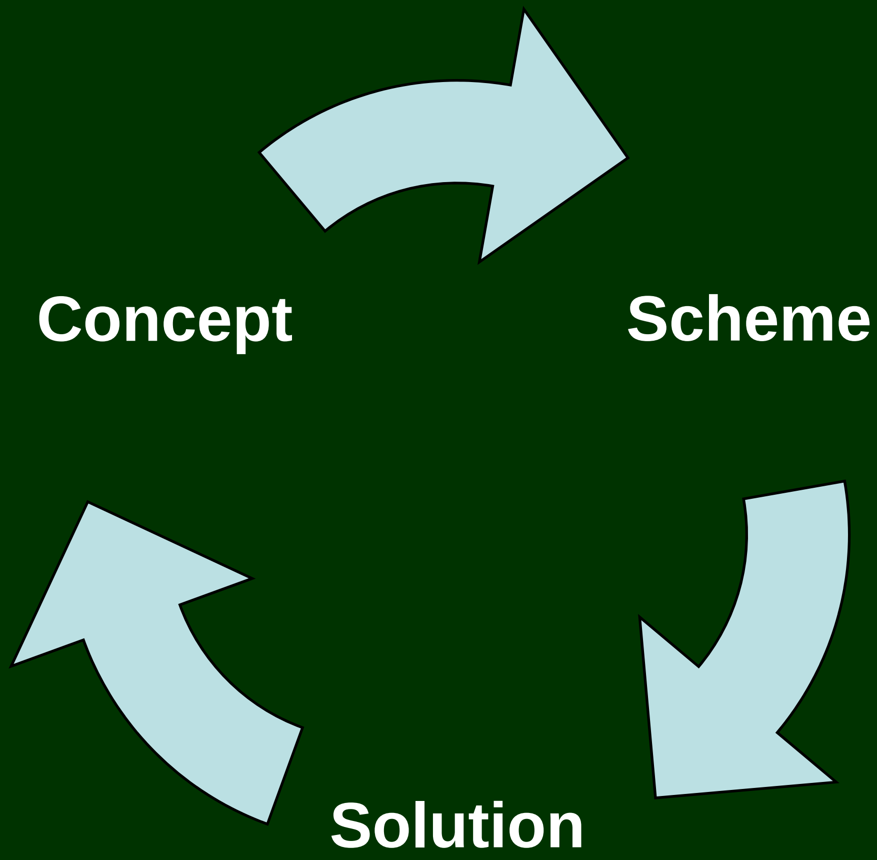
University of Bath

Professor of Timber Engineering

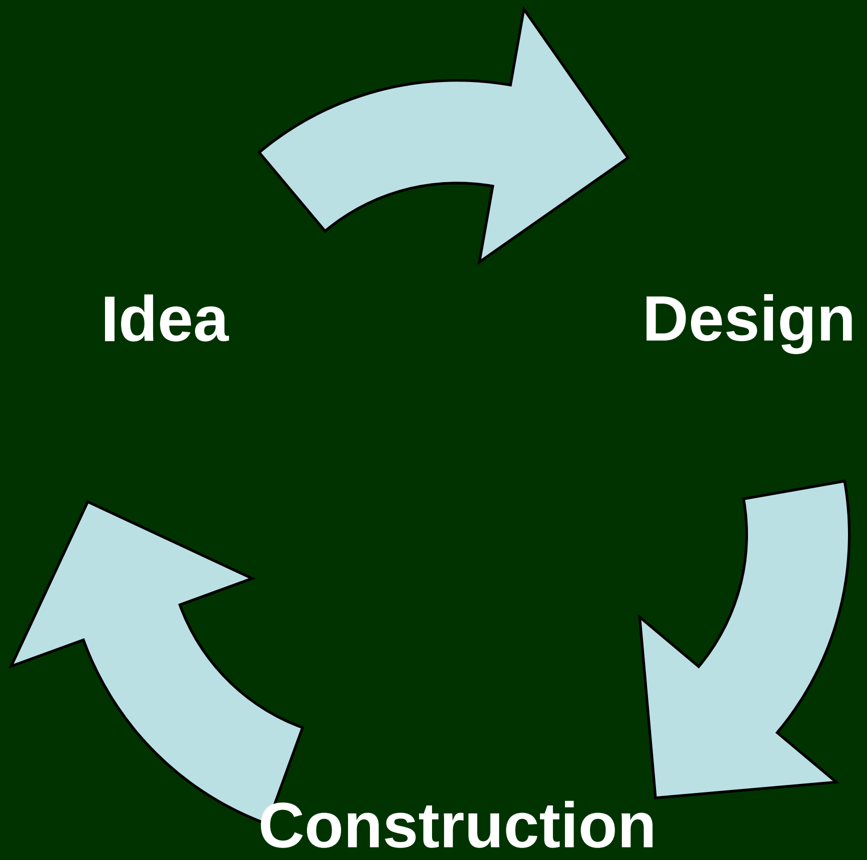
Richard Harris

Timber Engineer

The Design and Construction Process



The Design and Construction Process



The Use of Roundwood

a basic material

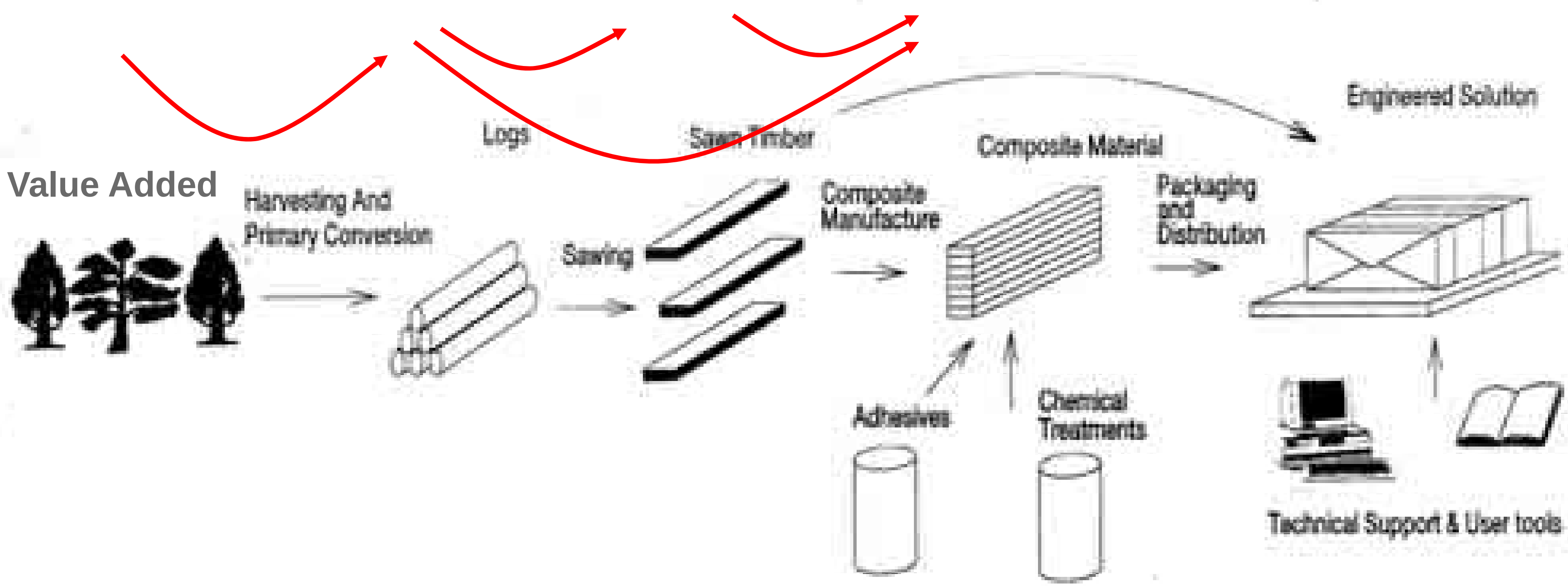
The Use of Roundwood

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 m^2.**

   - This releases value to be used in better management

2. **At 30-35 years**: - Clear fell

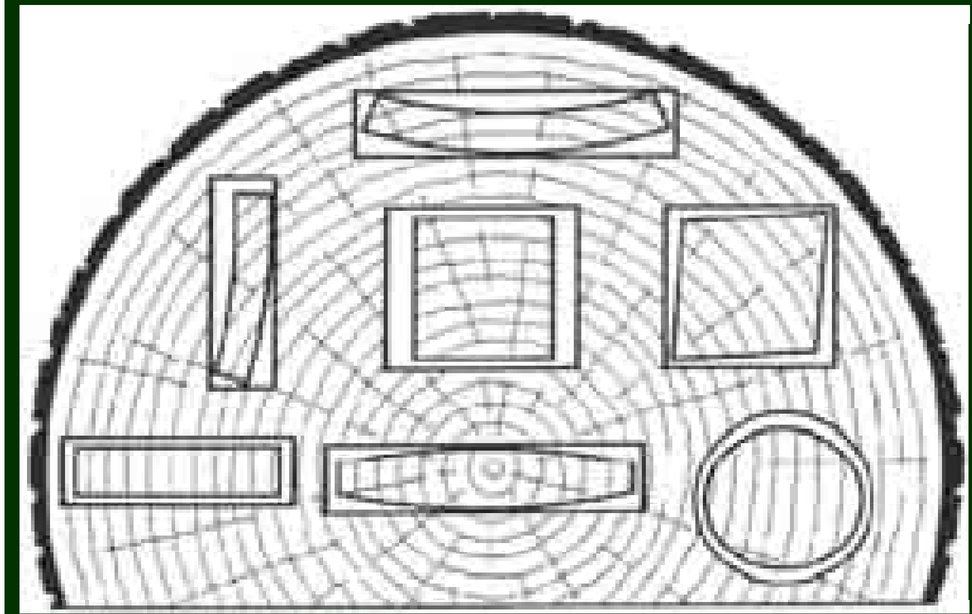
- Use trees not suitable for sawn timber

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



General rules for roundwood properties

- **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


NORTHERN IRELAND
EIRE
Lake District
Leeds
Hull
Manchester
WALES
Birmingham
Norwich
ENGLAND
Cardiff
Bristol
Hooke Park
London
Dover
Calais
Cornwall
Devon
English Channel

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

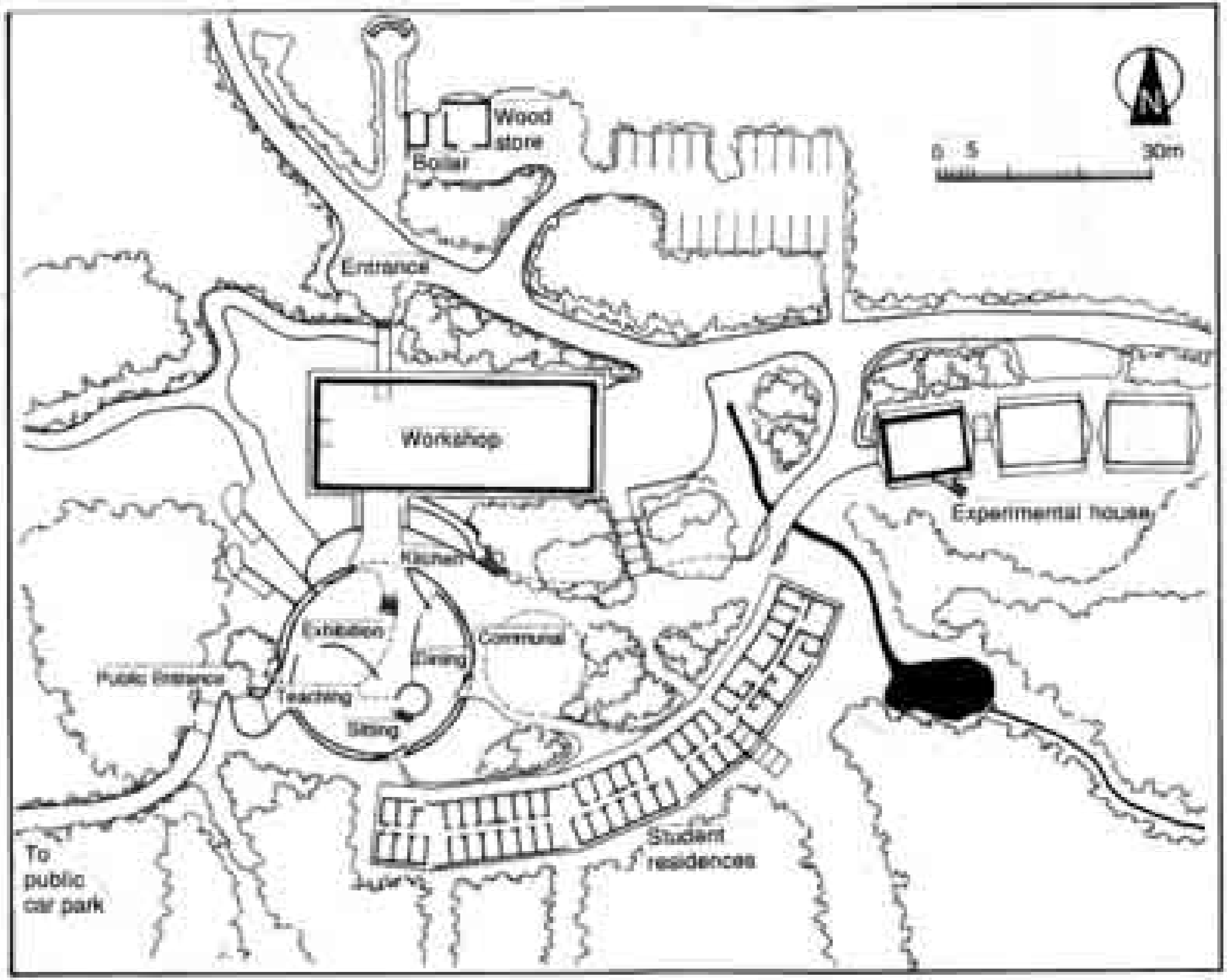
No recognised code or grading

Material with variable dimensions

Hooke Park College, Dorset, England

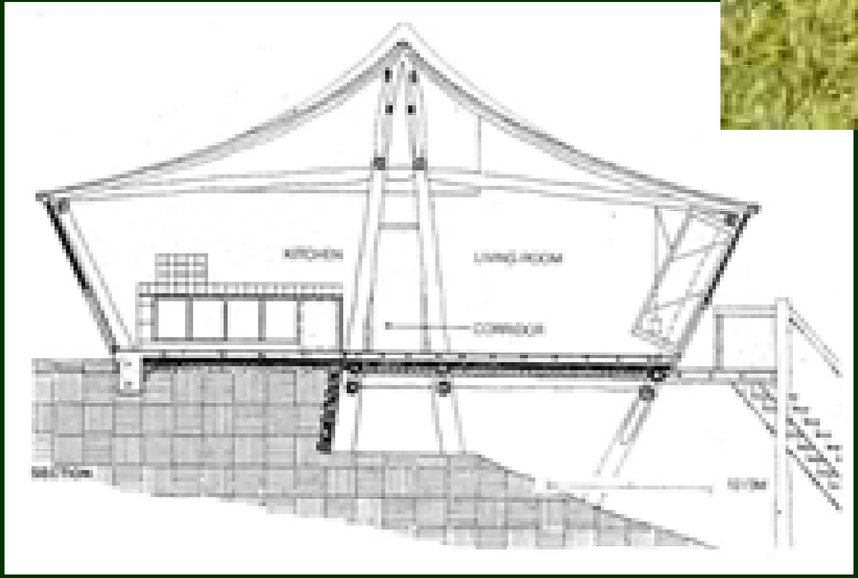
The solution:

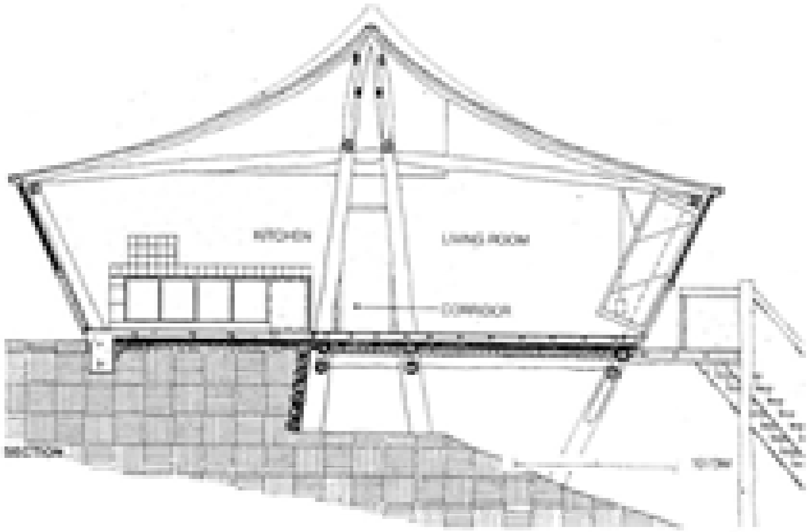
- **Modern architecture**
- **Fundamental understanding of material**
- **Innovative jointing**
- **New construction techniques**


Wood store
Boiler
0 5 30m
Entrance
Workshop
Kitchen
Experimental house
Exhibition
Communal
Dining
Public Entrance
Teaching
Sitting
Student residences
To public car park

Hooke Park College, Dorset - Prototype House

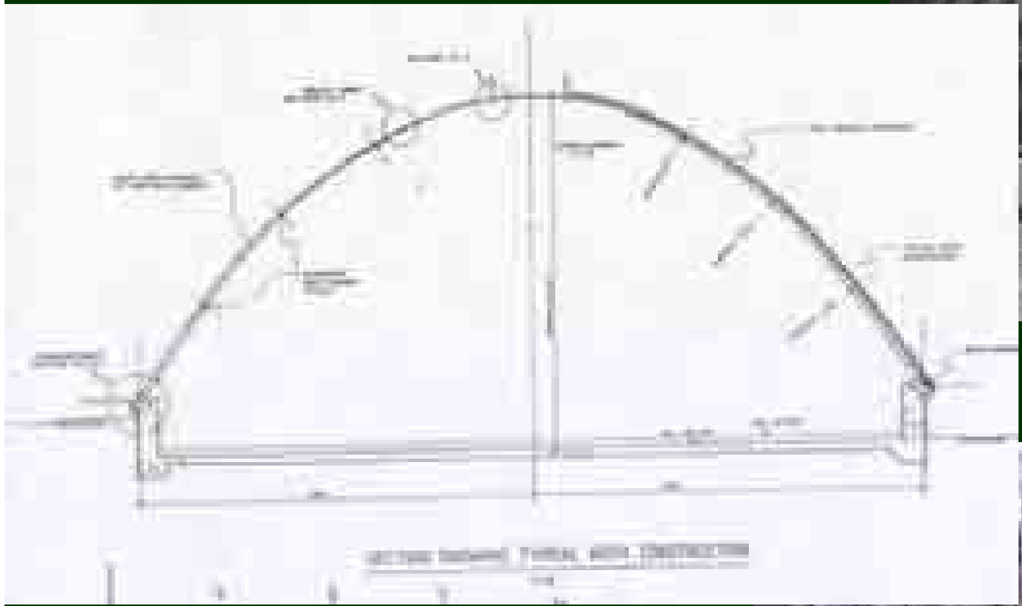
1984

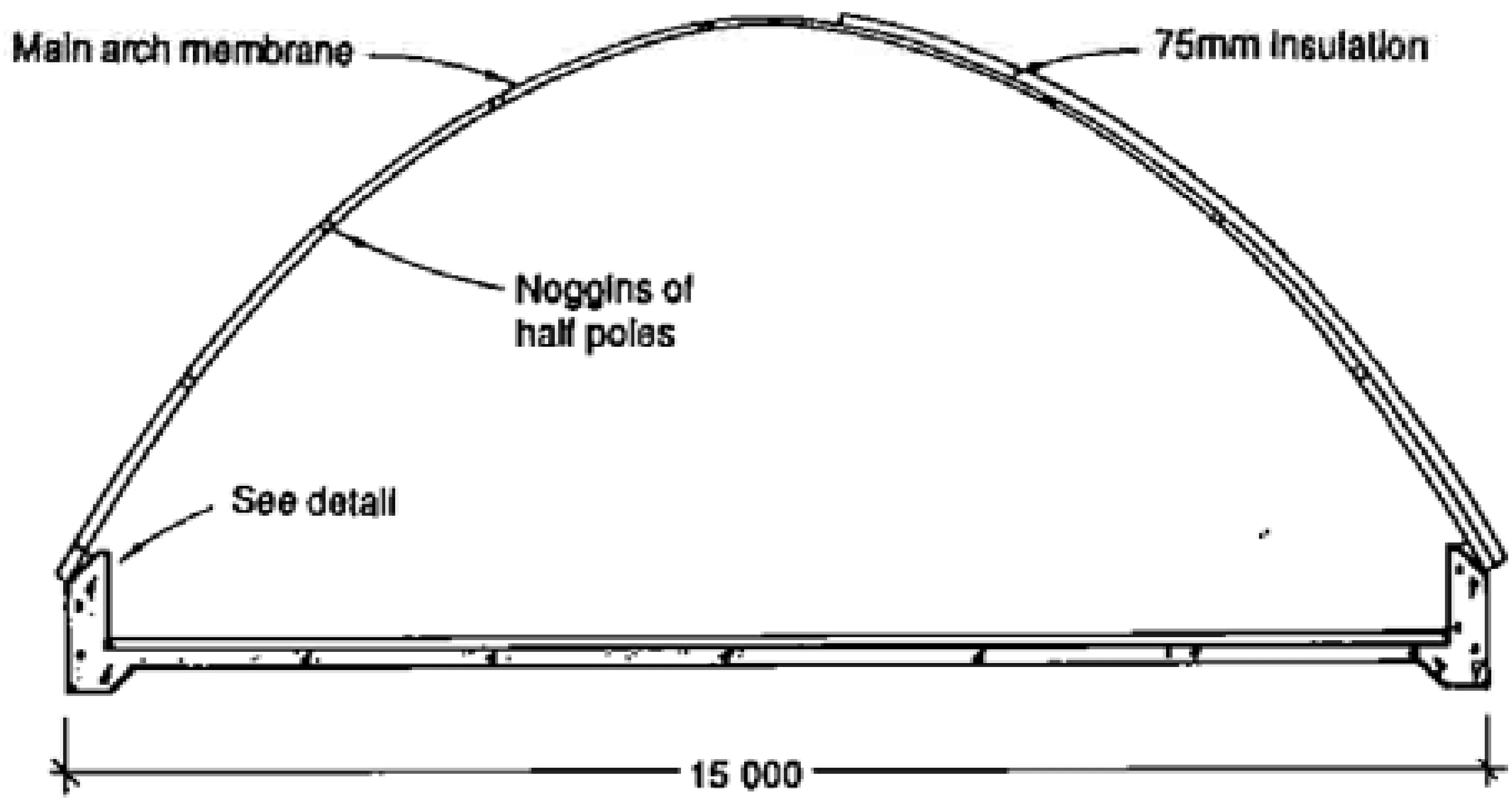



KITCHEN
LIVING ROOM
CORRIDOR
SECTION

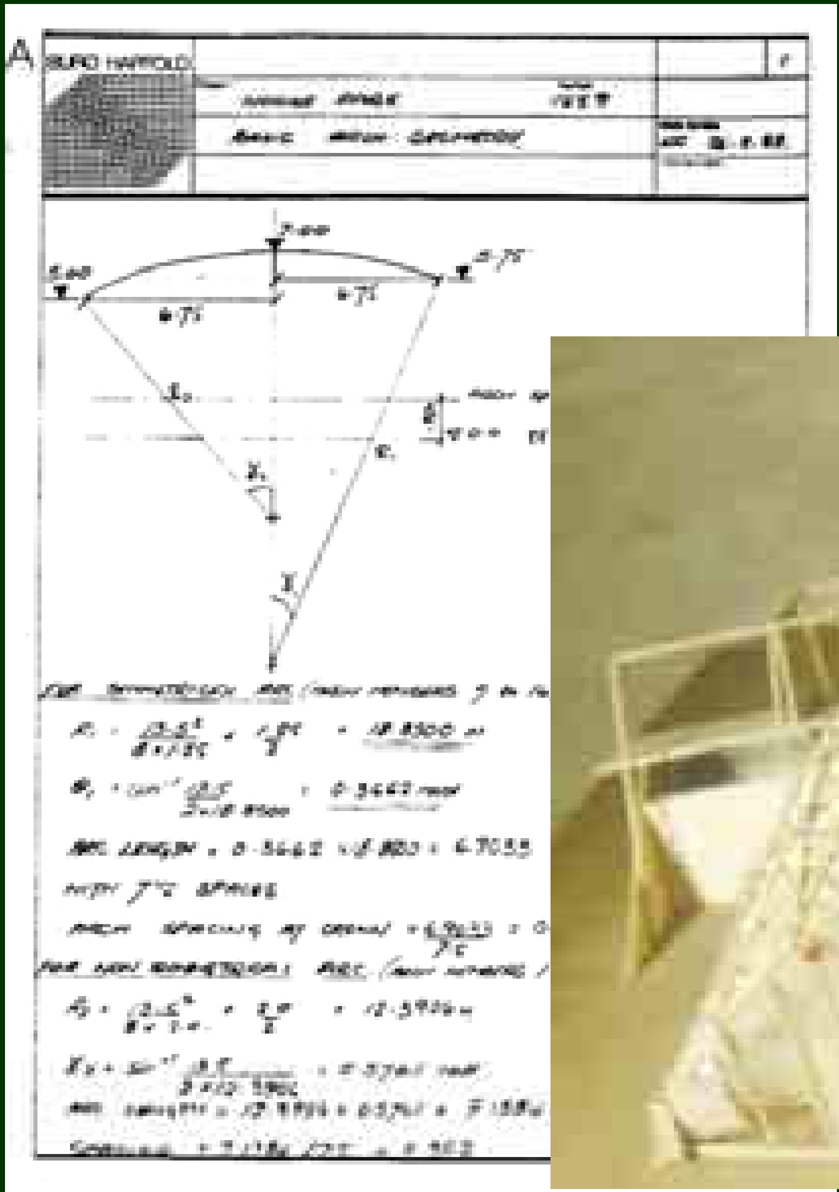
Hooke Park College, Dorset - Workshop

1991




Main arch membrane
75mm insulation
Noggins of
half poles
See detail
15 000

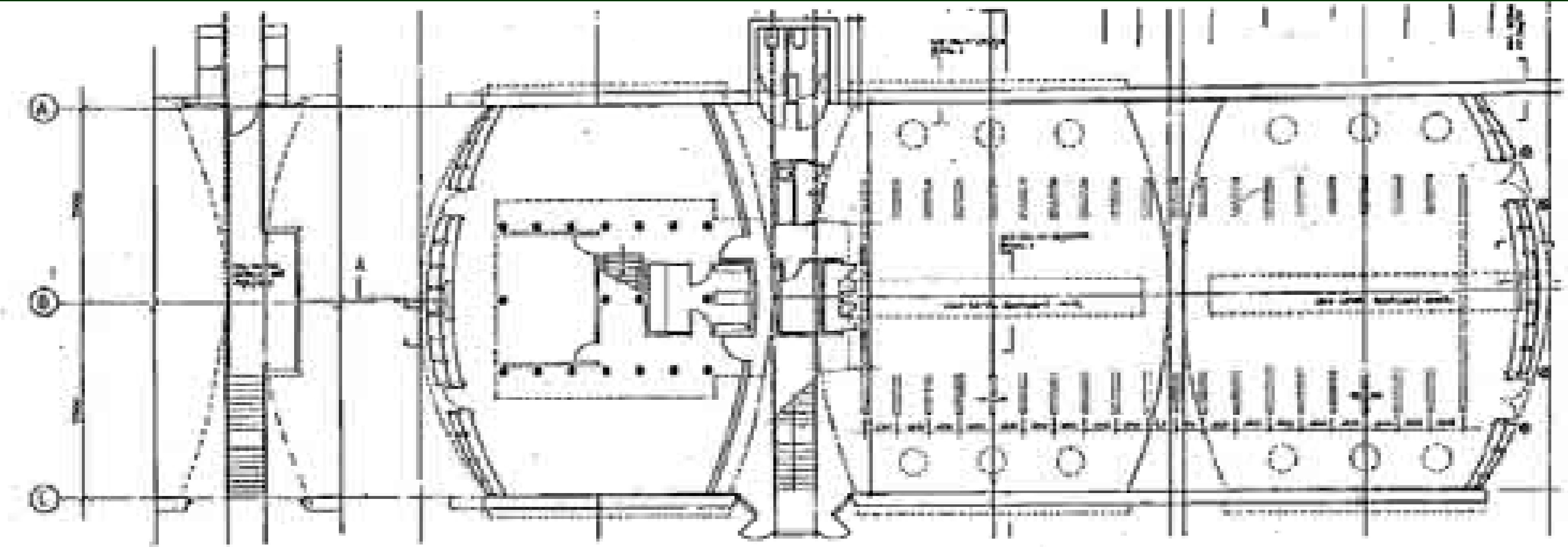
Modelling structure



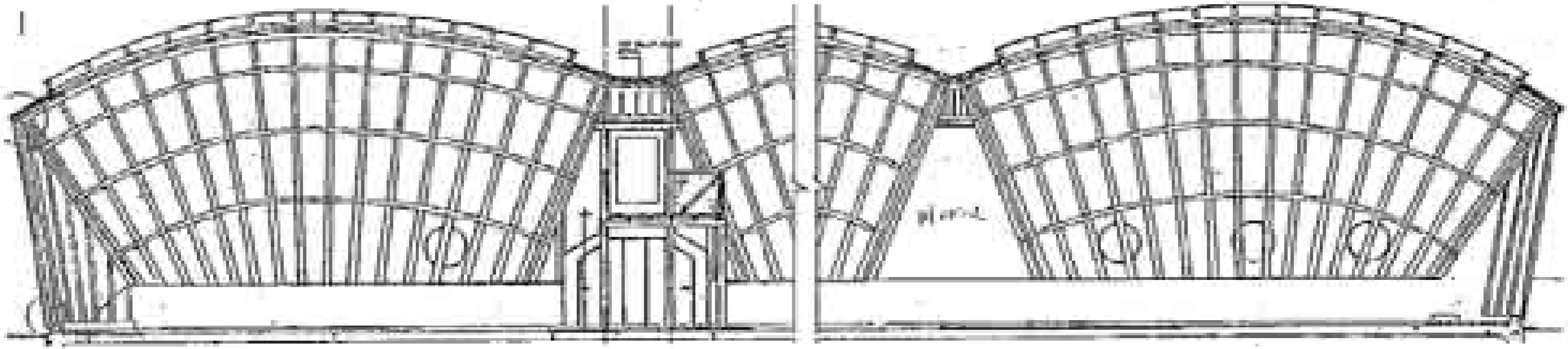
Working with the Material

Full size prototyping

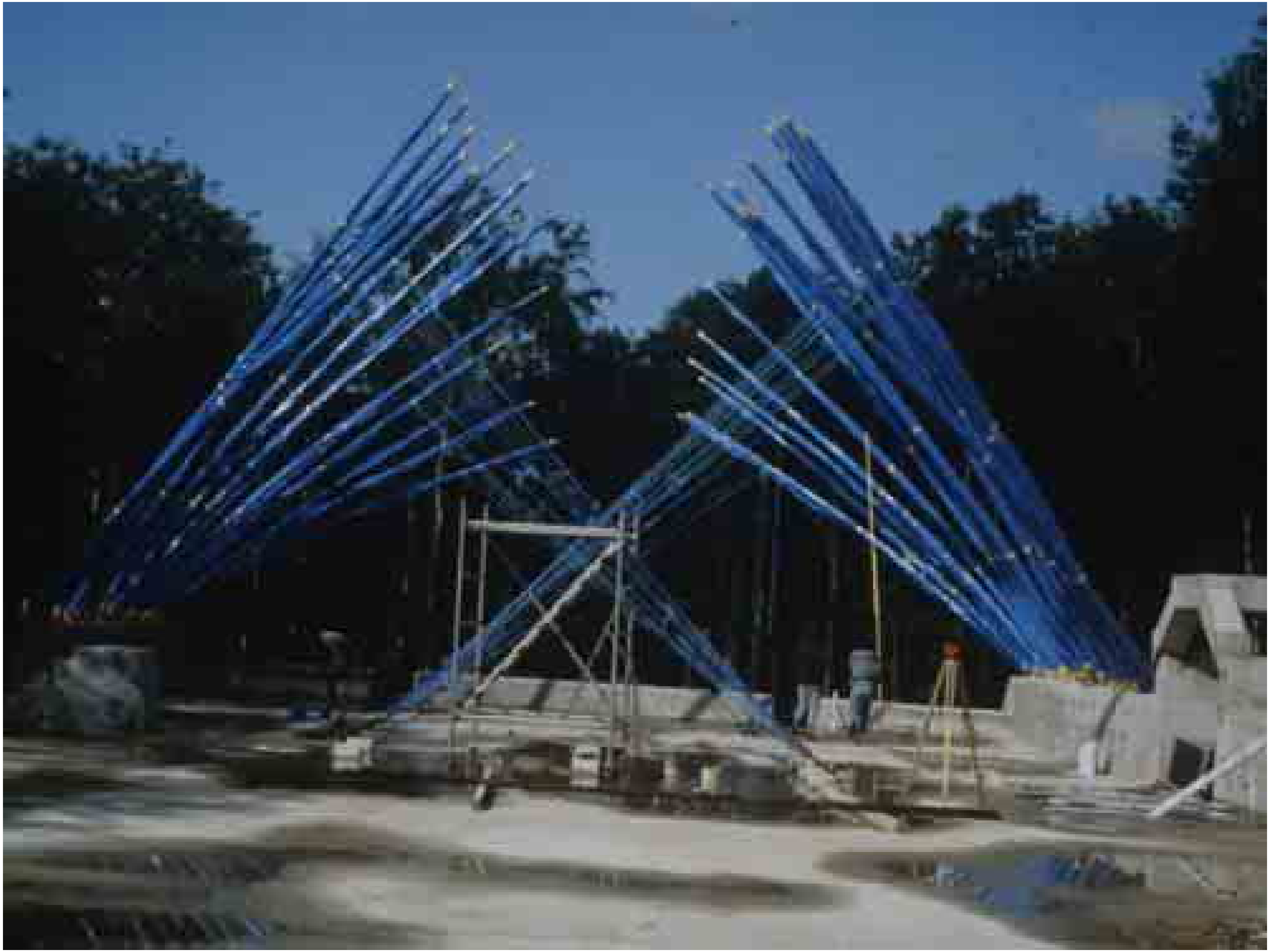
Jointing



workshop long section



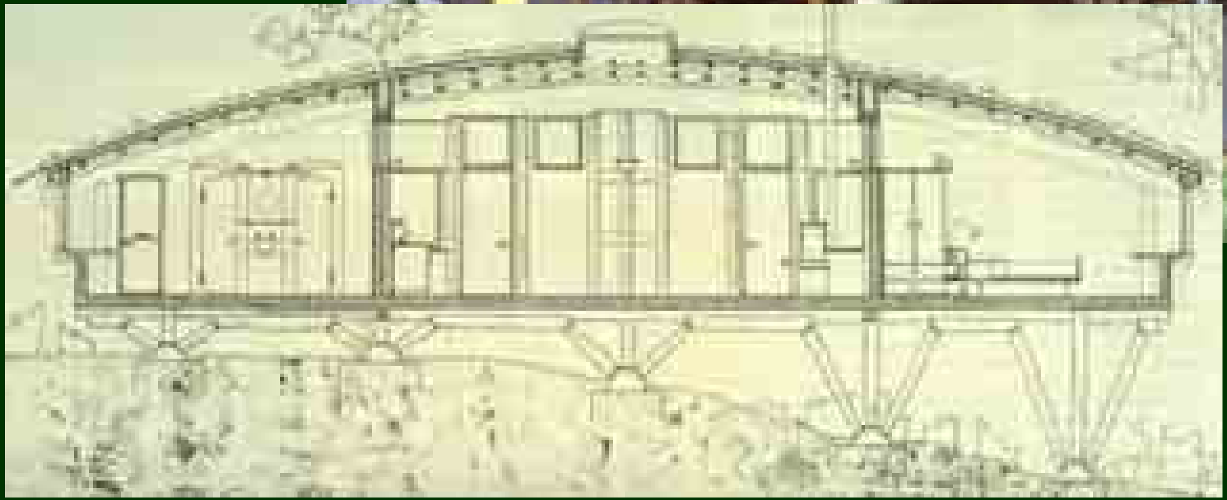
46|P

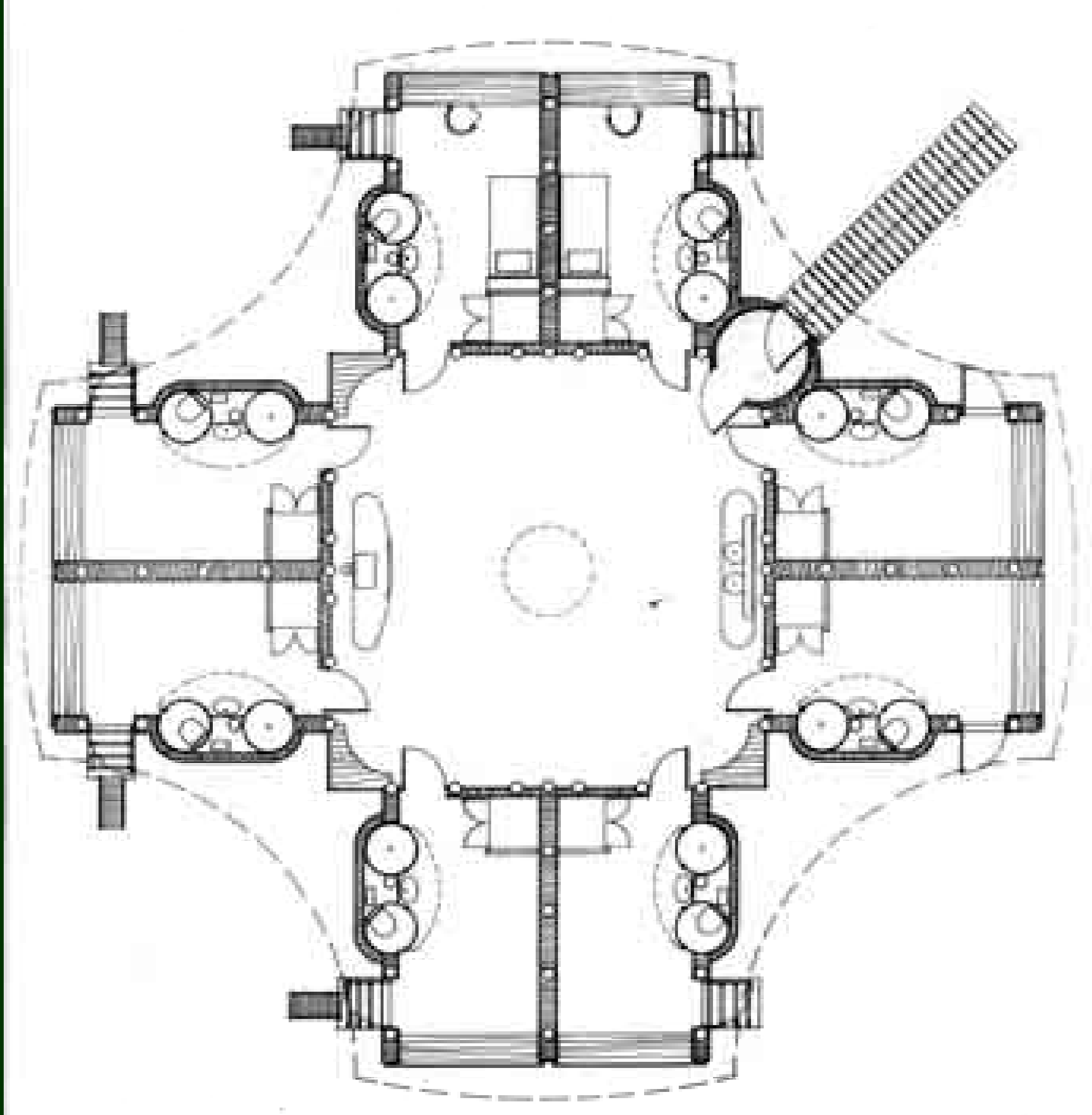


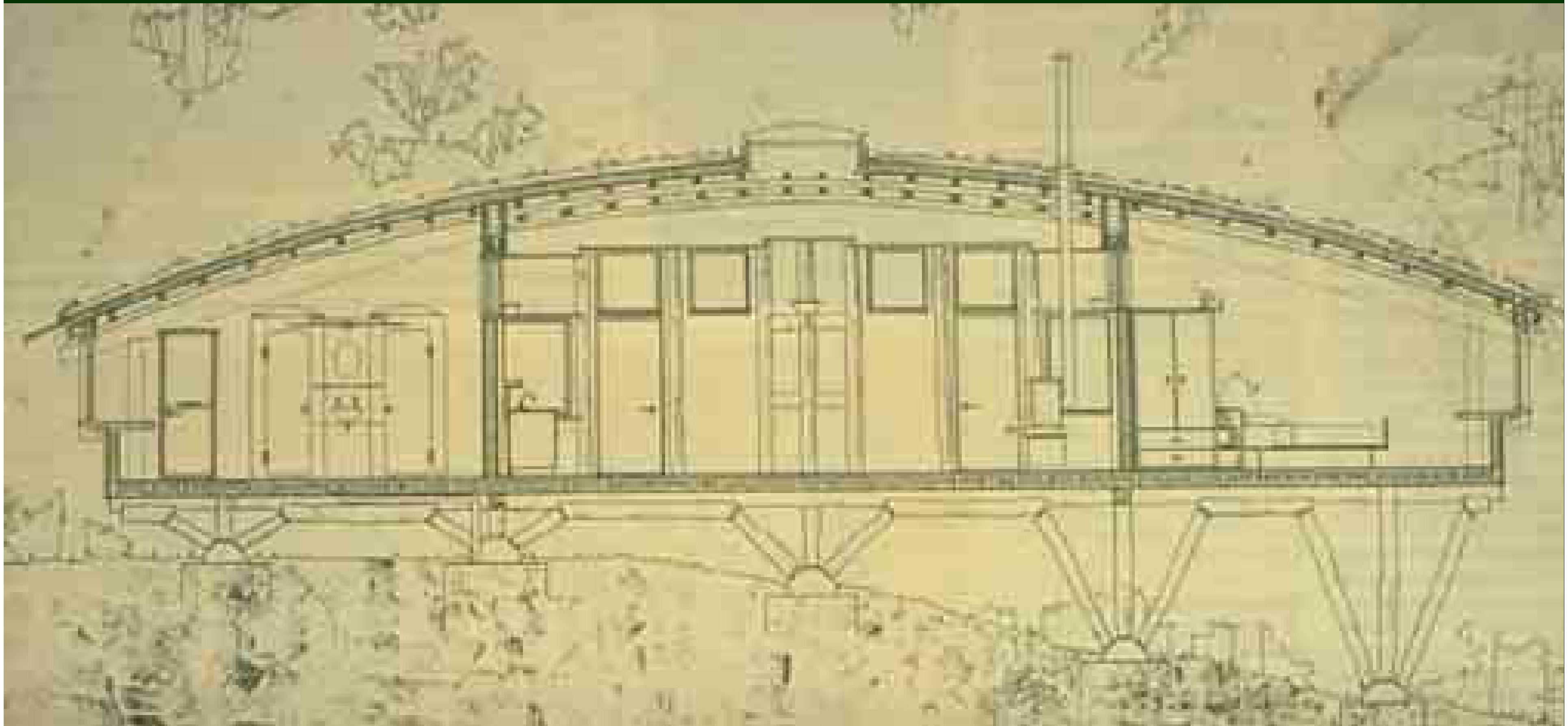
Hooke Park College, Dorset

- Westminster Lodge

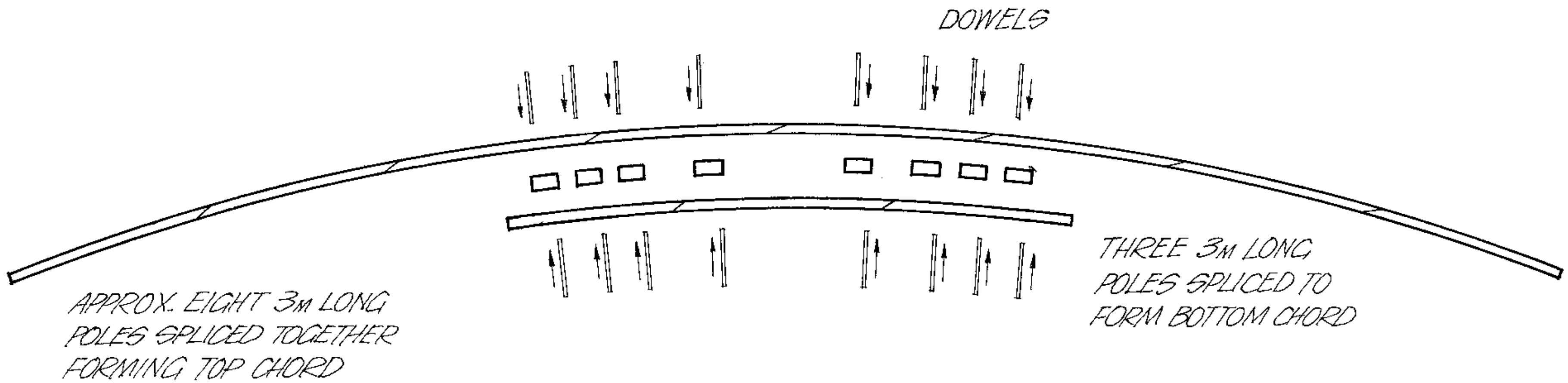
1996

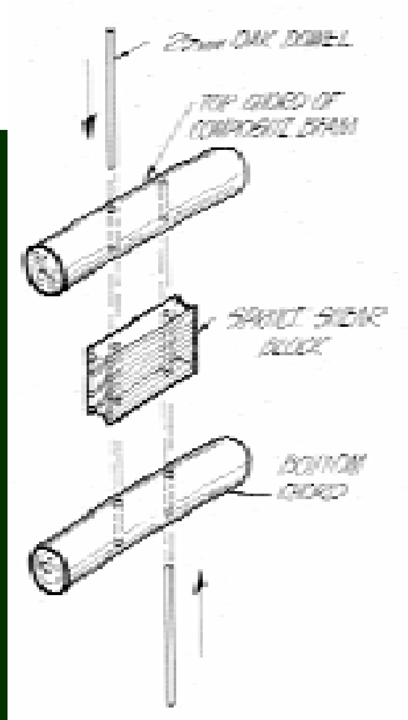






Model making


DOWELS
APPROX. EIGHT 3M LONG
POLES SPLICED TOGETHER
FORMING TOP CHORD
THREE 3M LONG
POLES SPLICED TO
FORM BOTTOM CHORD



Glulam

a historic material

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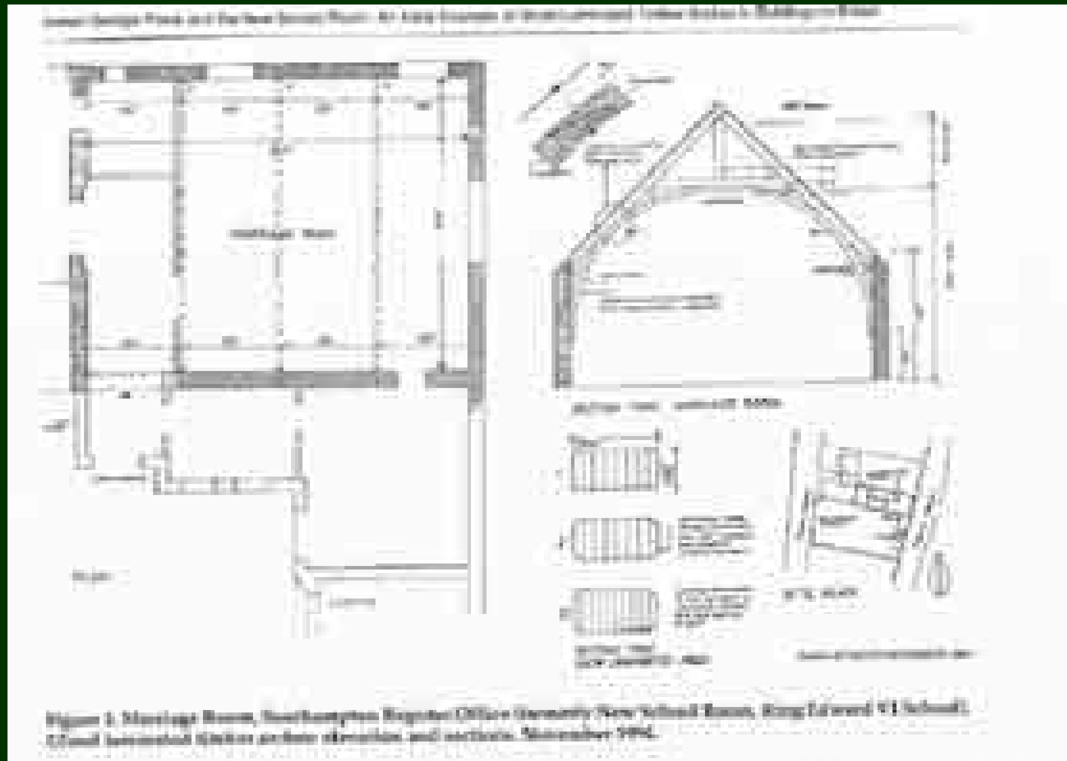
Calais
Cornwall
Devon
English Channel
Southampton



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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Dover
Calais
Cornwall
Devon
English Channel

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:

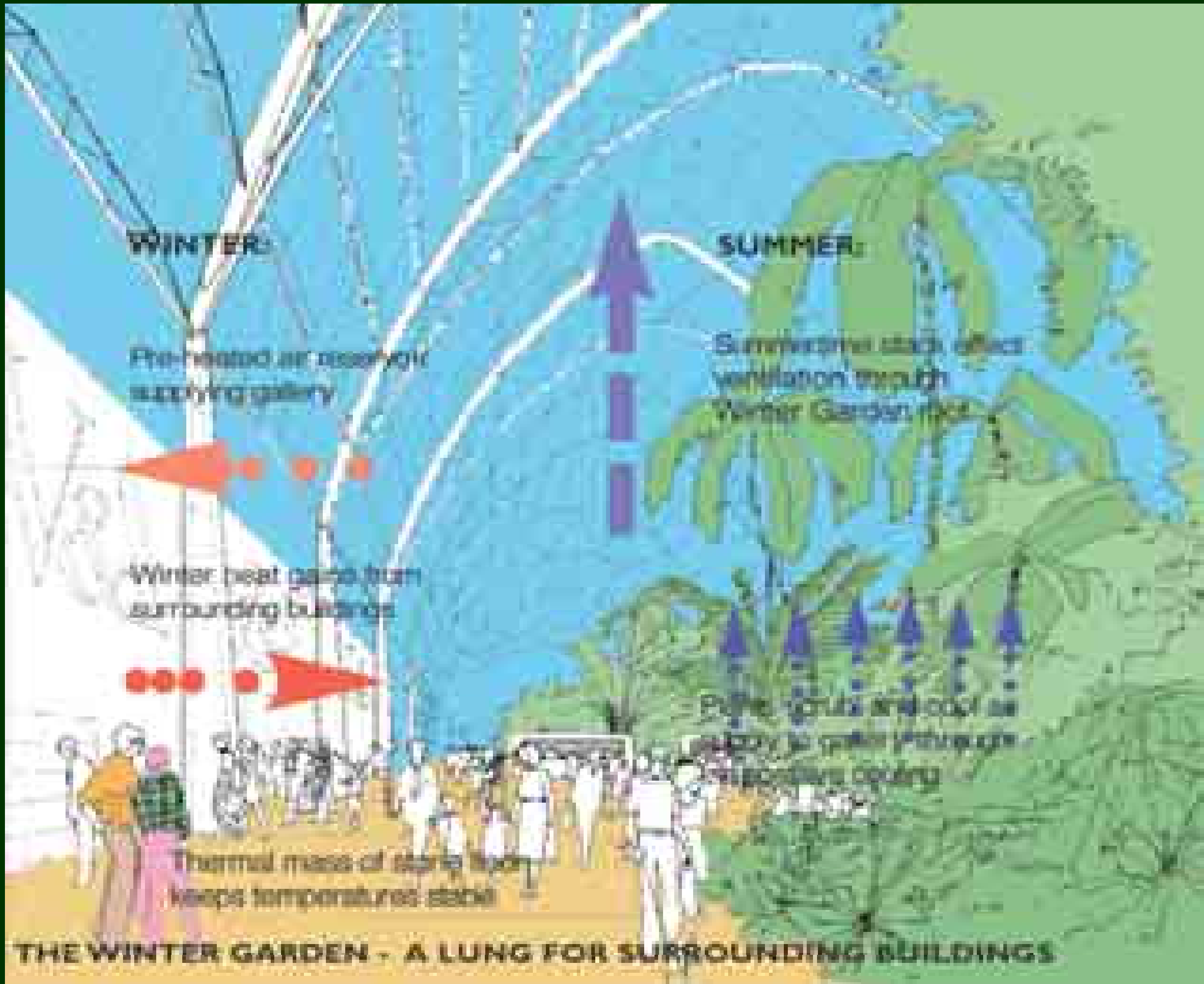
A natural environment

Wood used as a modern material

Sheffield Regeneration

Heart of the City

Winter Garden: Design Considerations



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

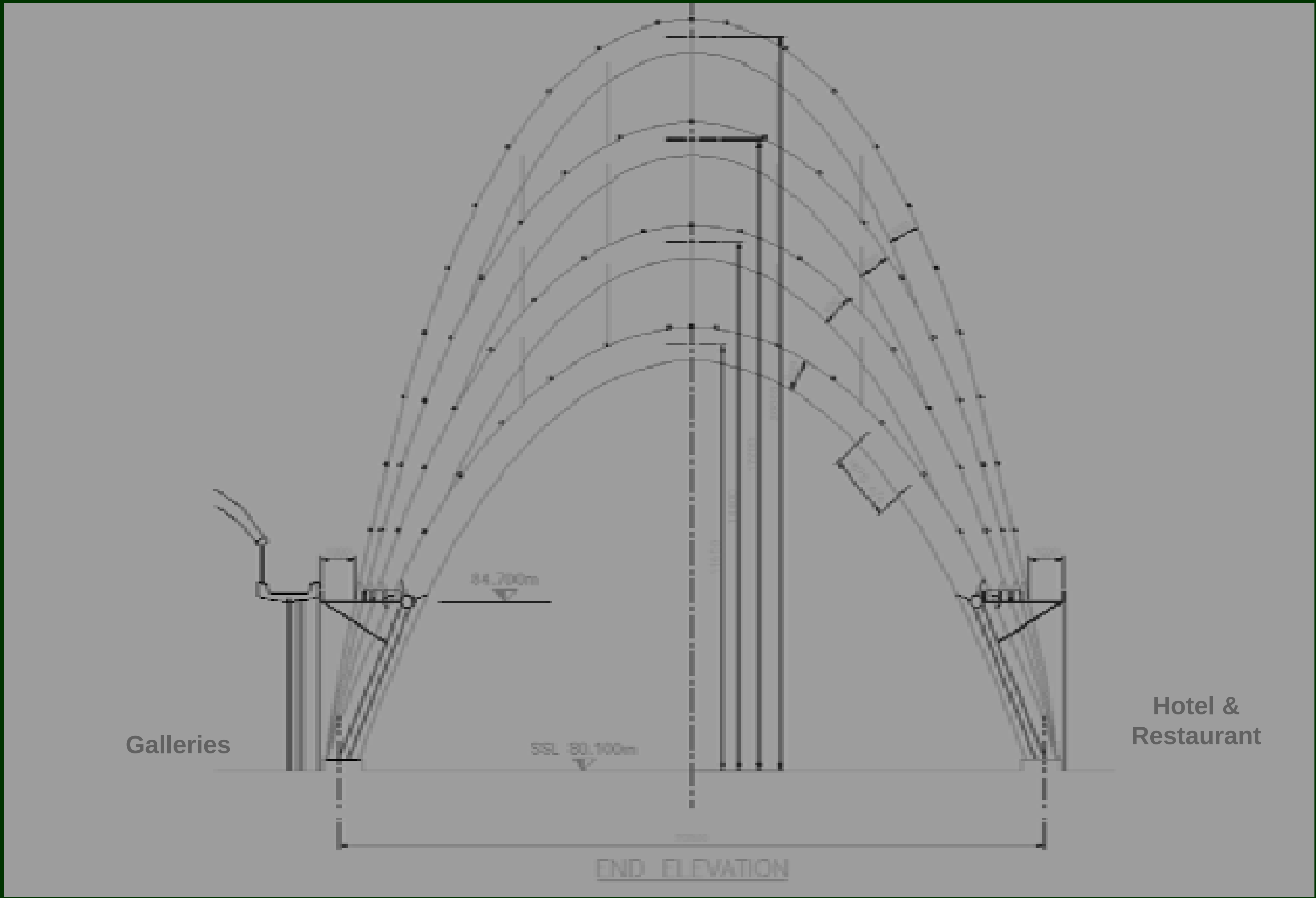
The Structure
75m long; 20m high; 22m span

The principal structural element sizes are:

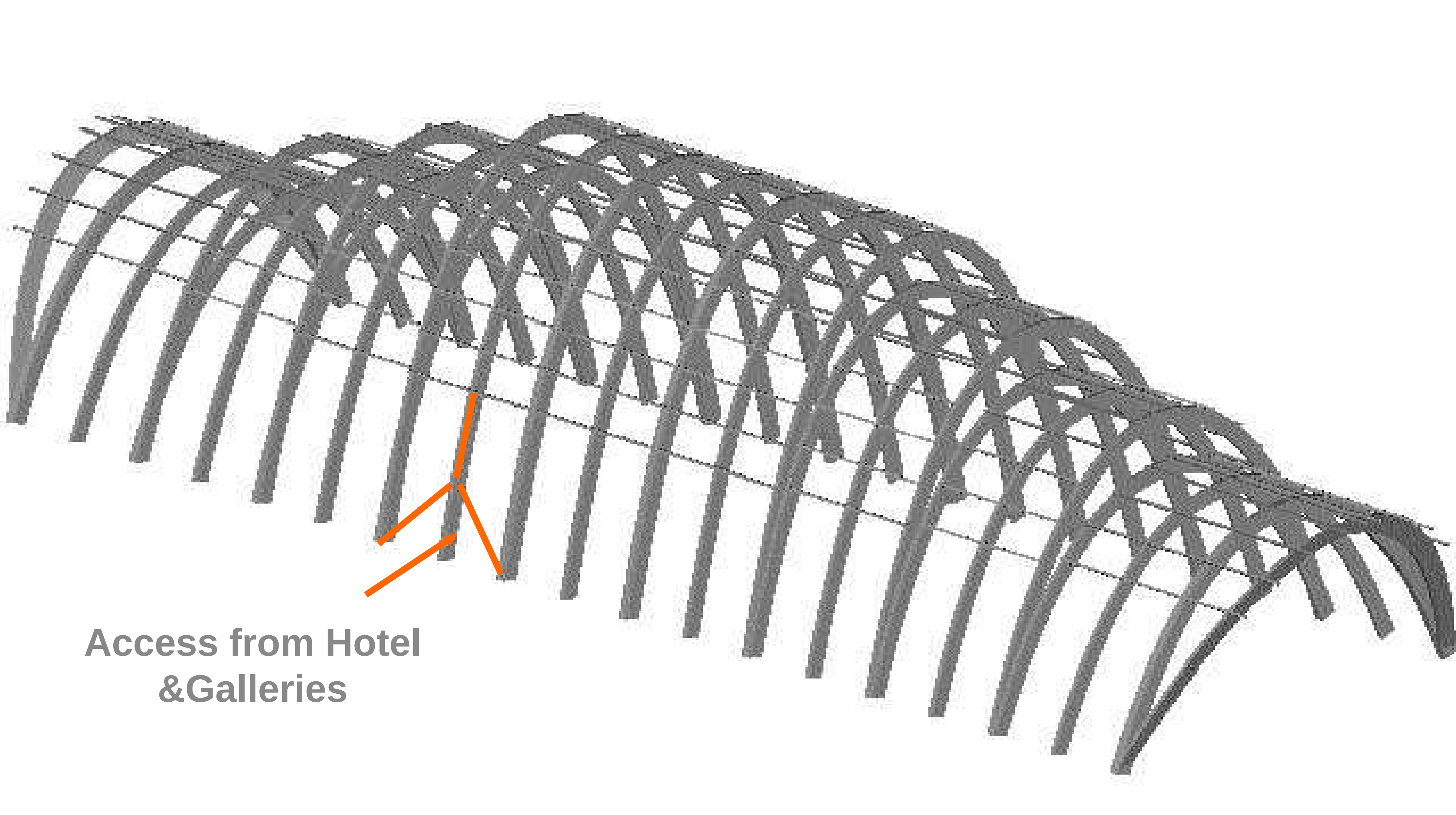
- Arches - 210mm wide x 910mm deep
- Purlins - 150mm wide x 225mm deep
- Raking Struts – 245 mm diameter

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



Structure

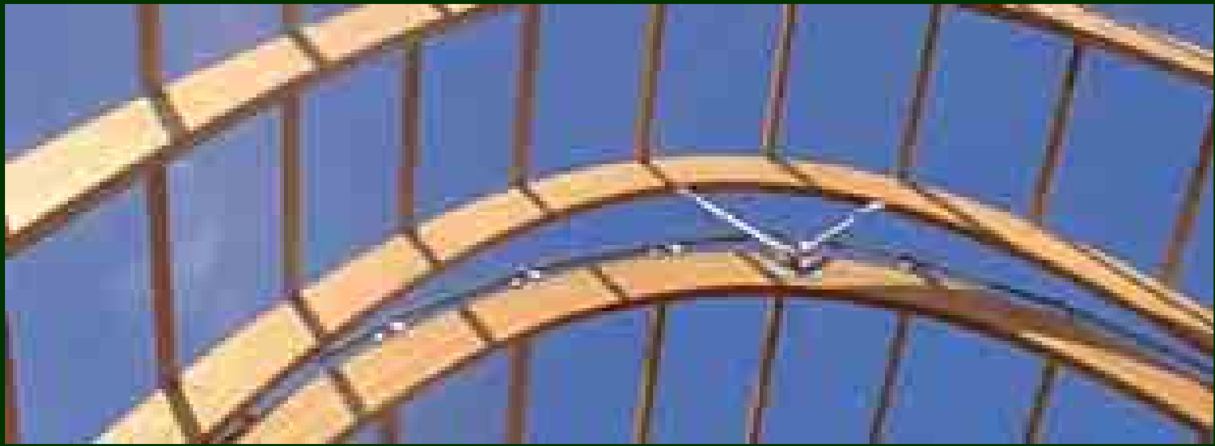


Superstructure

Superstructure

Superstructure

Details: Arch Apex



Finished Building

Details: Base

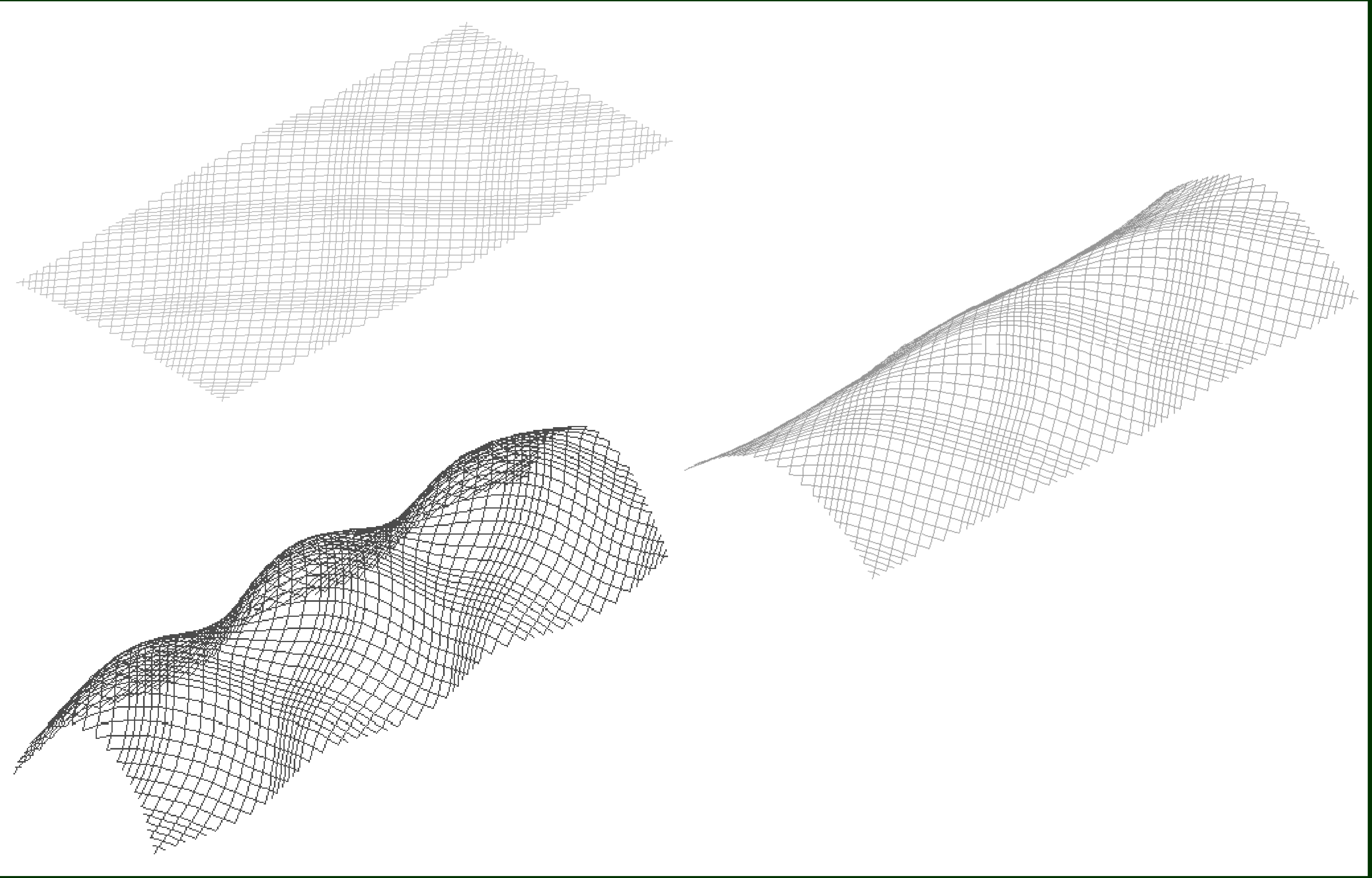
Timber Gridshell

sophisticated structures

Timber Gridshell Construction

The idea: ………………..

Timber Gridshell Construction – the principle



Gridshell precedents

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

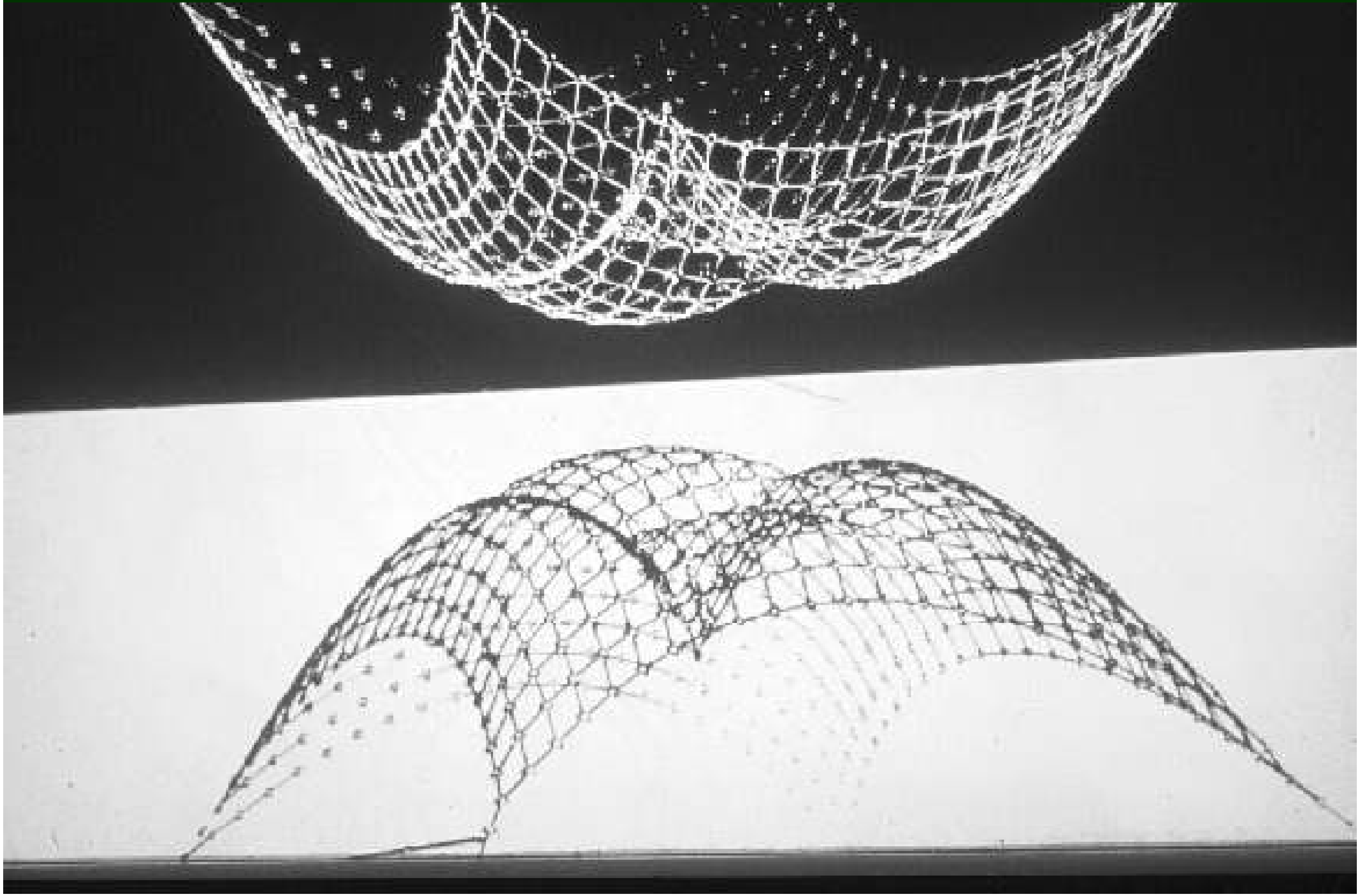
Gridshell Precedents

Mannheim Bundesgartenschau

50m span
4 Layers
50 x 50 hemlock

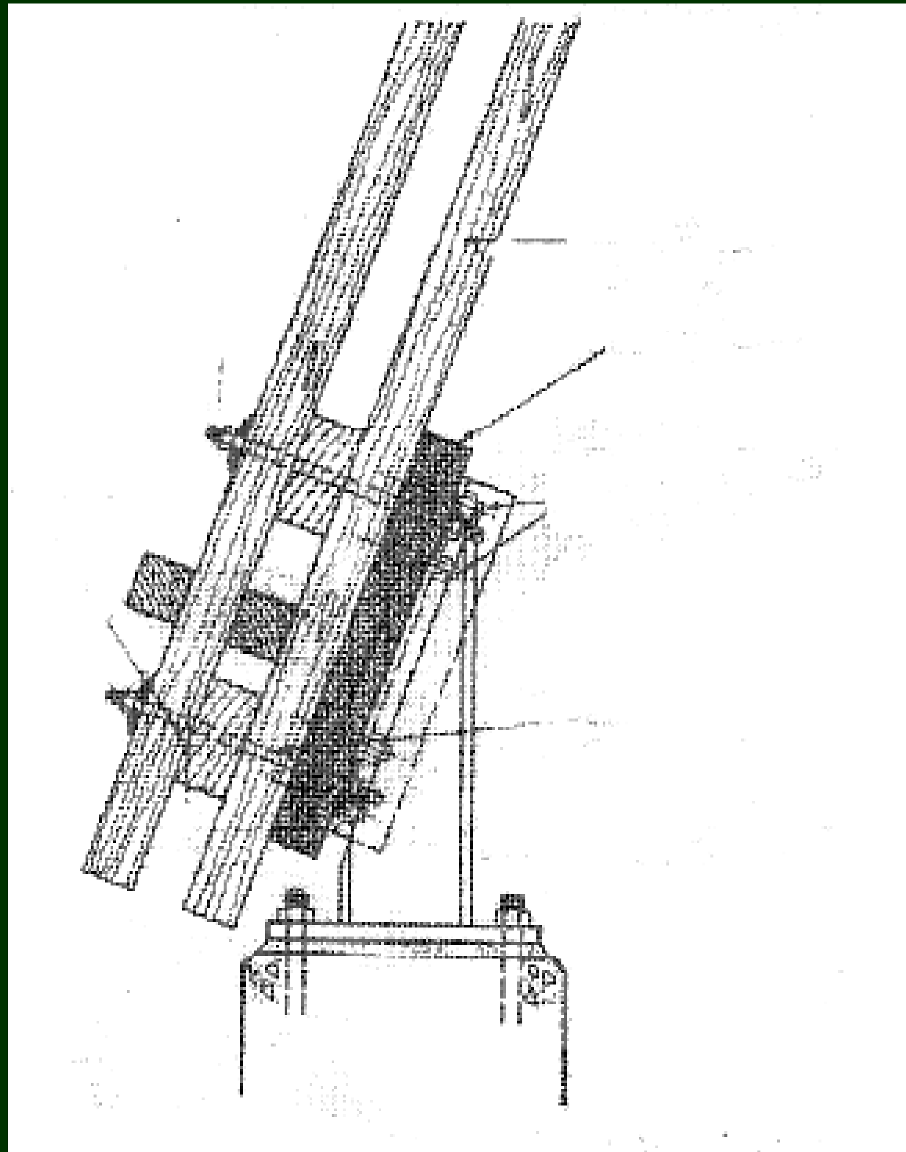
Design Team: Frei Otto / Ove Arup

Mannheim – a funicular structure



Mannheim Gridshell

Mannheim

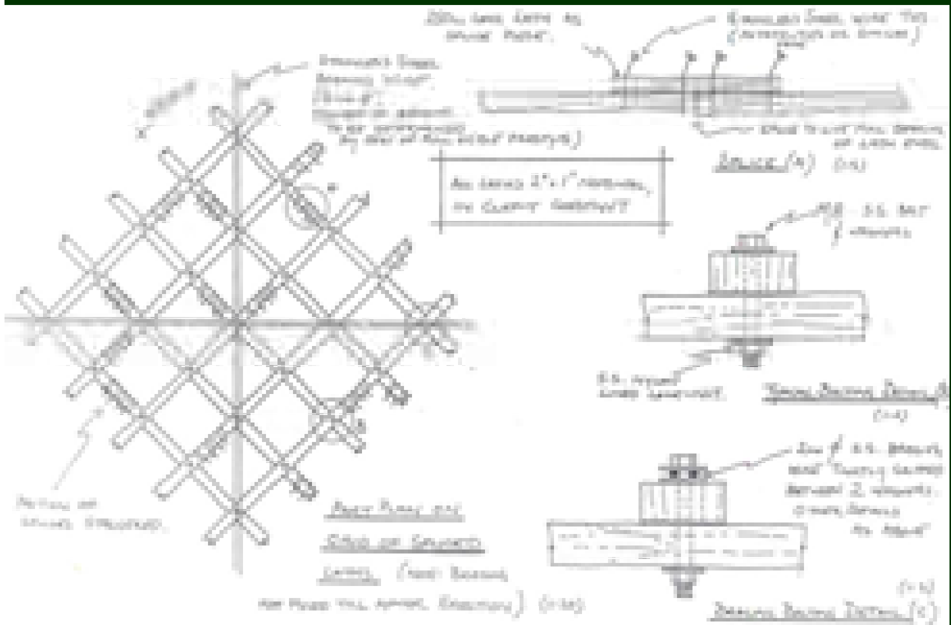


Earth Centre Doncaster

6m span
2 Layers
32 x 15 oak

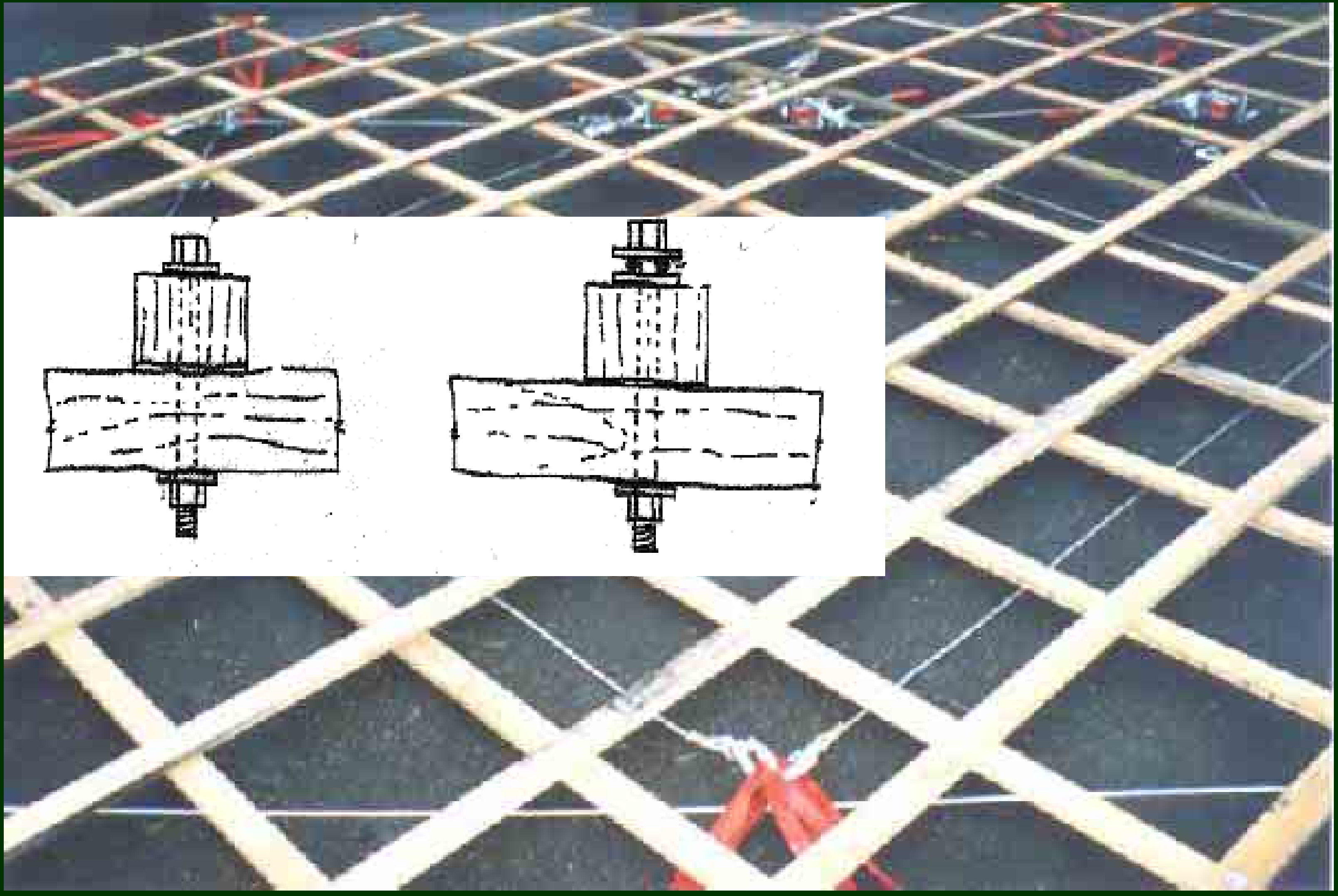
Design Team: Grant Associates / Buro Happold

Earth Centre Gridshells



Earth Centre Gridshells

Earth Centre Gridshells



32mm x 15mm at 0.4m. **Bracing: twin 2 mm cables**

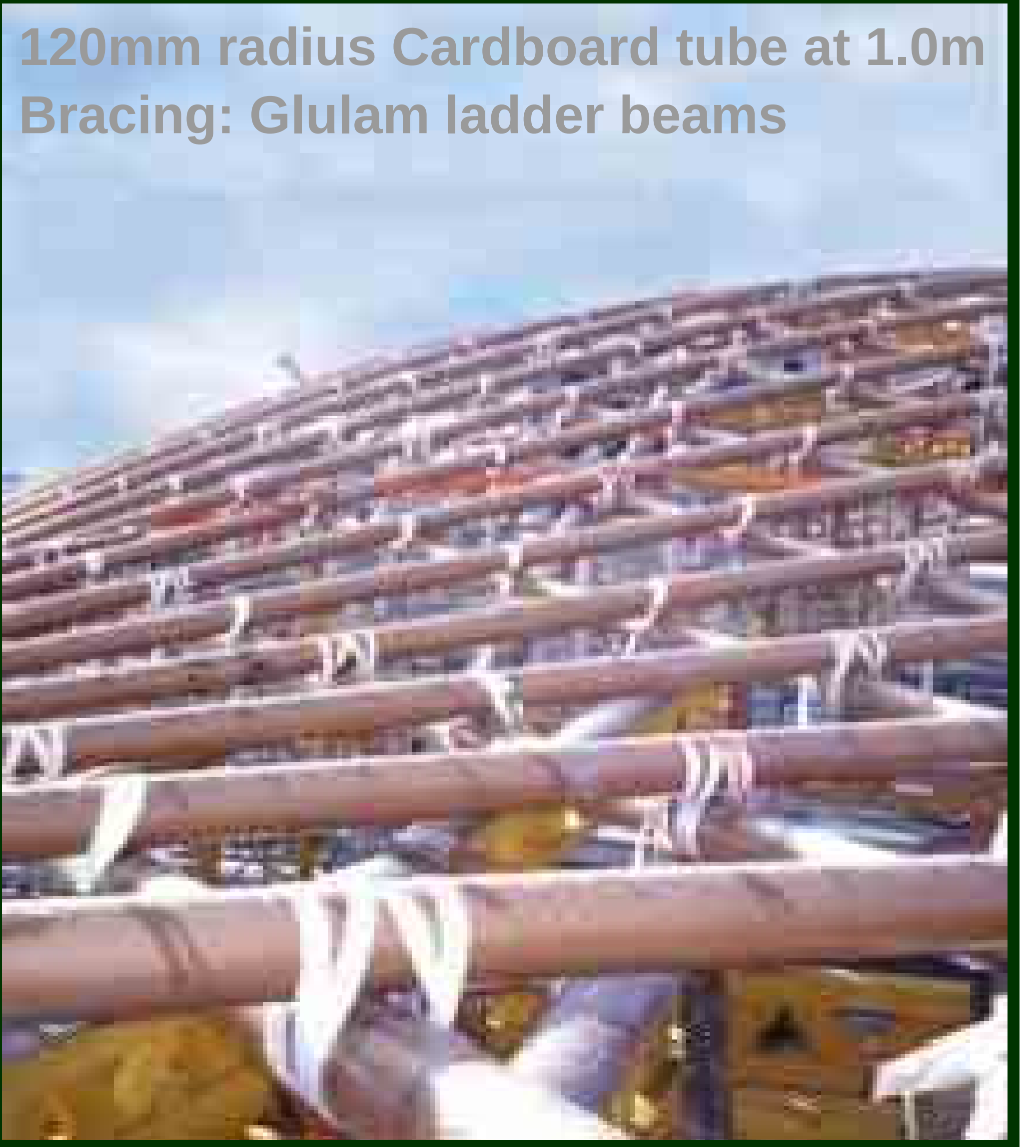
Earth Centre Gridshells

The Japan Pavilion Hanover EXPO 2000

30m span
2 Layers
Cardboard Tubes

Design Team: Shigeru Ban/ Buro Happold

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


NORTHERN
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Manchester
WALES
Birmingham
Norwich
ENGLAND
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Calais
Cornwall
Devon
Singleton
English Channel

Downland Gridshell

The Client Brief:

To design modern building in a sensitive environment

To use an innovative design

Downland Gridshell

The complication:

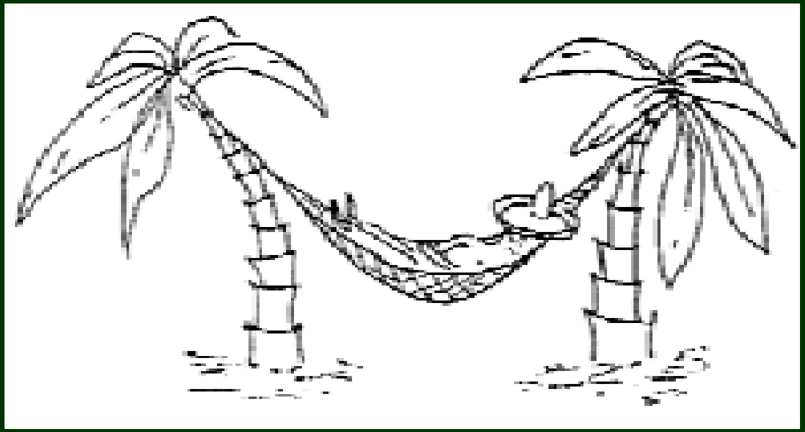
- Re-discover the techniques used in 1975 at Mannheim
- Devise design methods
- Develop construction technique and teach others
- Maintain confidence of the Client and design team

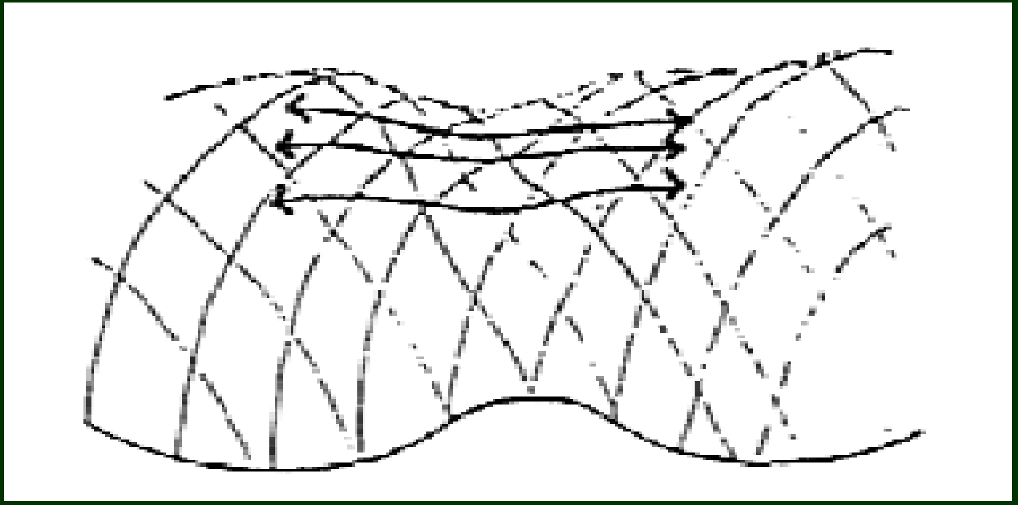
Downland Gridshell

The solution:

- Innovative design and method
- Prototyping – model and full scale
- Good communication

Structural principle





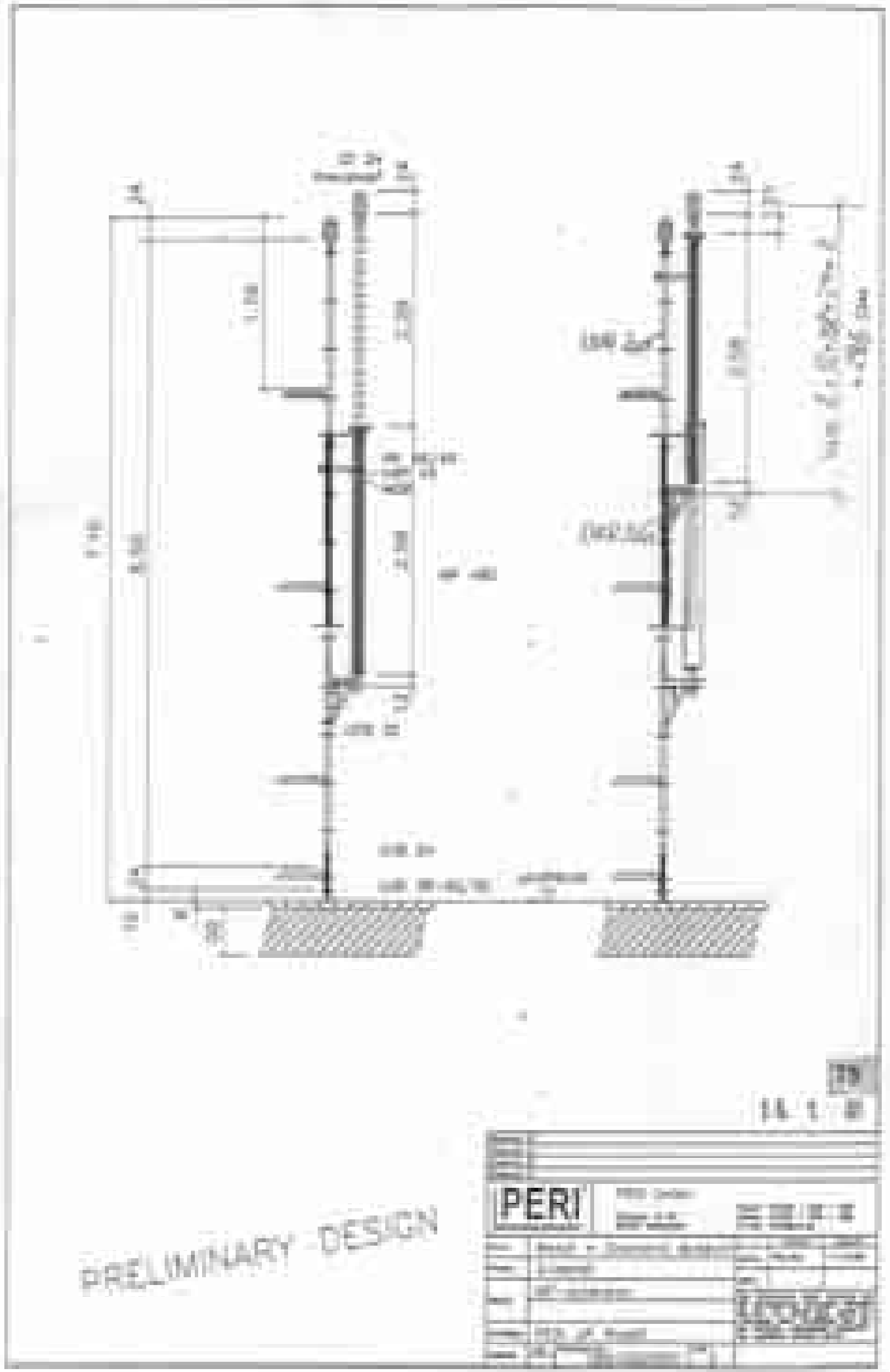
Not a funicular Structure!

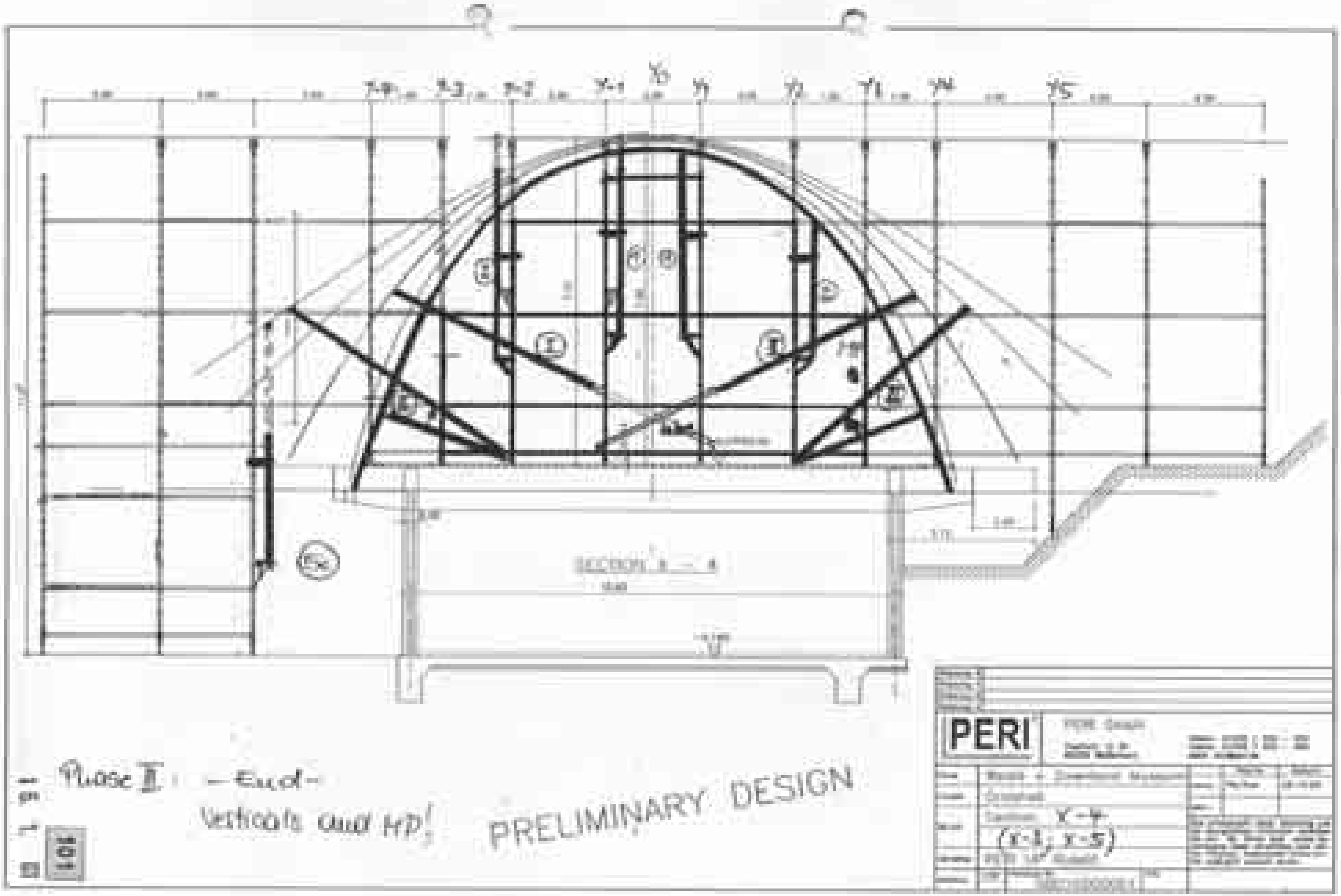
Construction Method

Mannheim

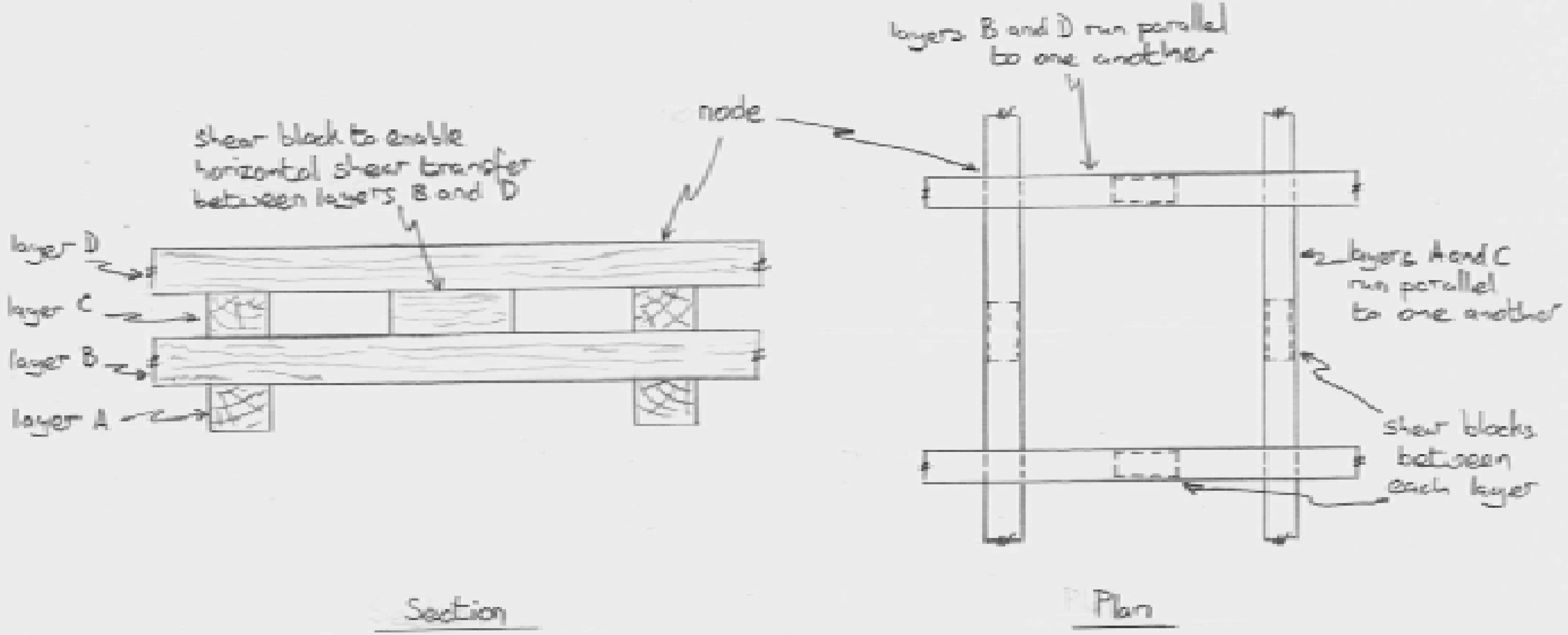

20

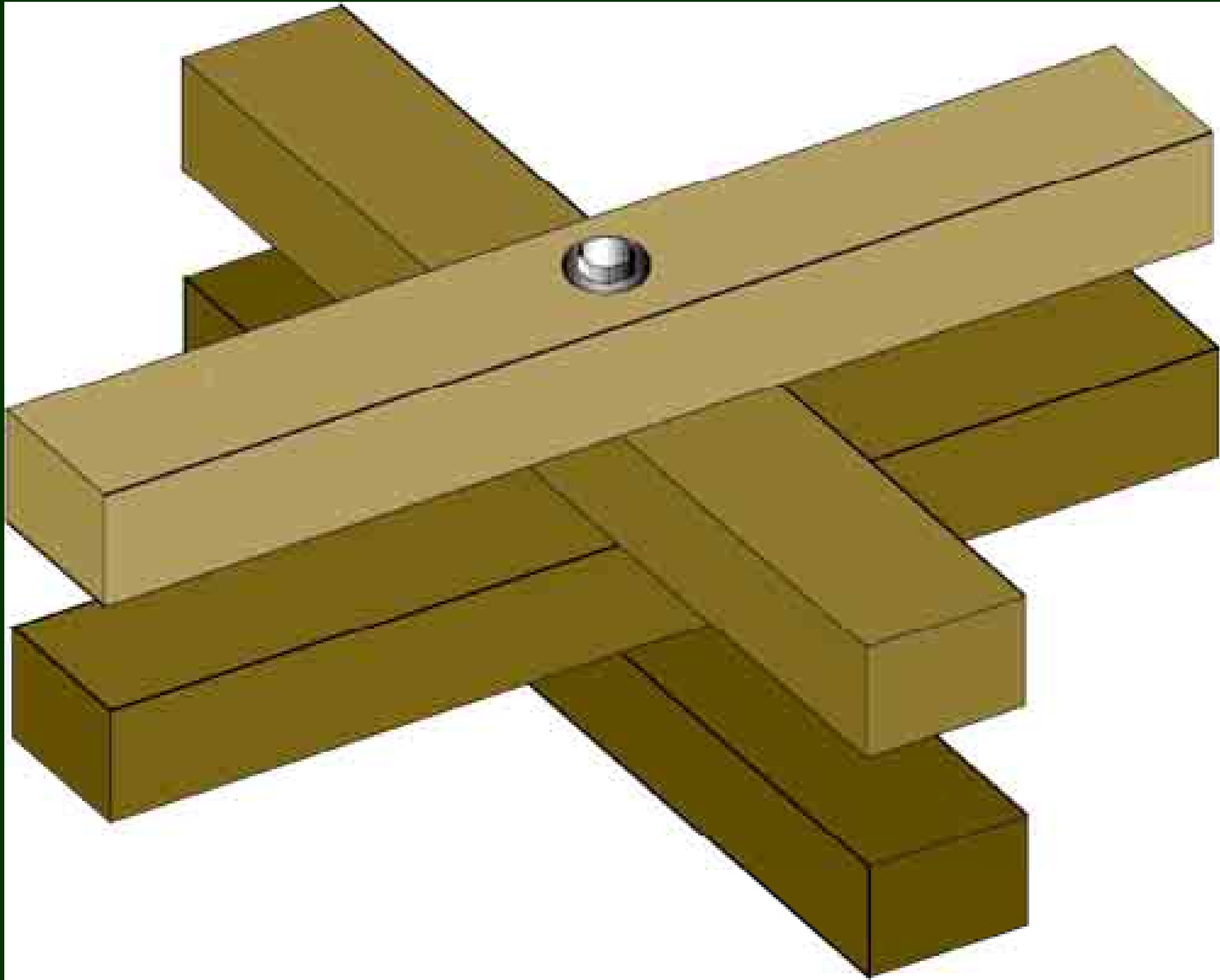
Japan Pavilion

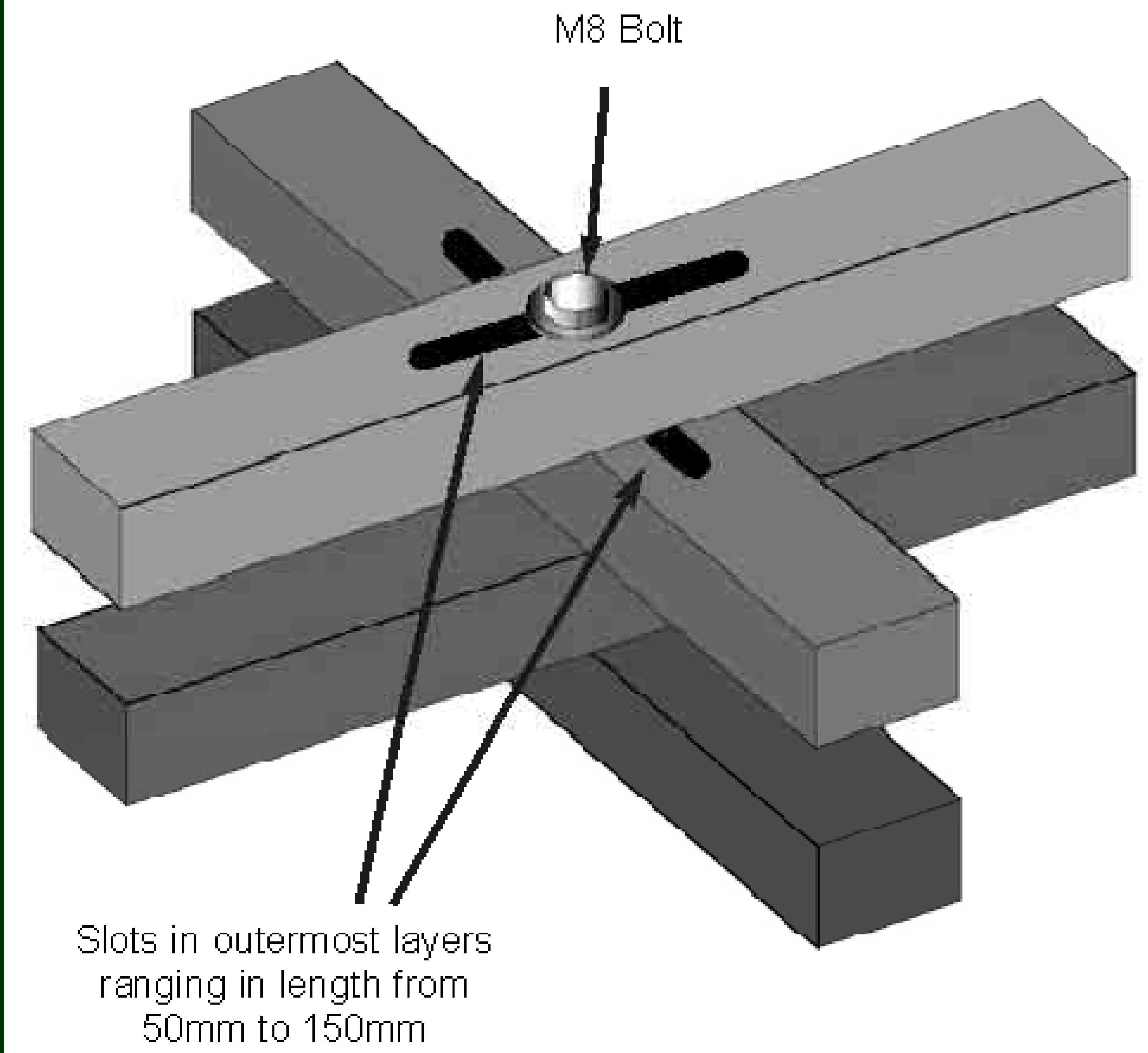

PRELIMINARY DESIGN
PERI

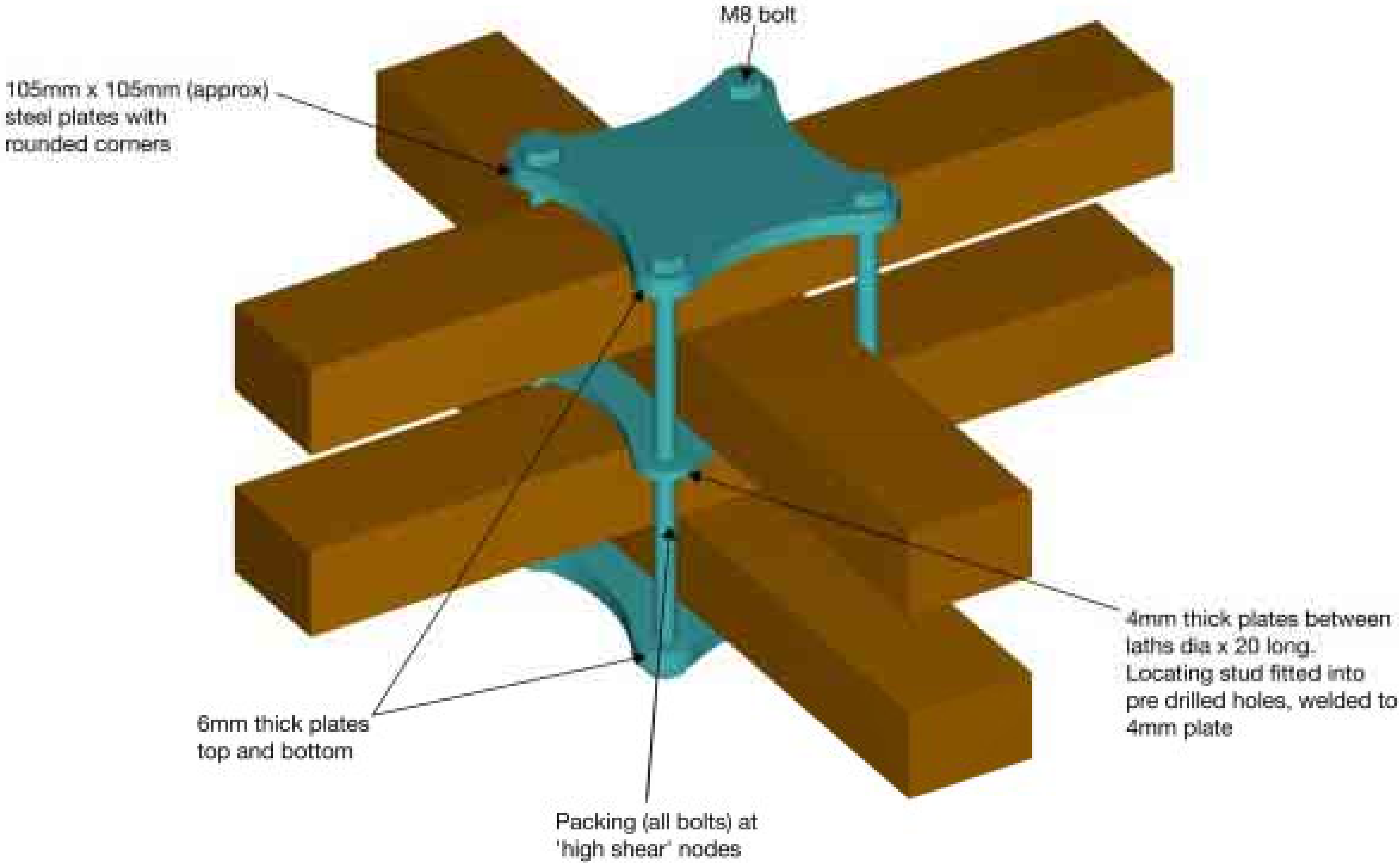


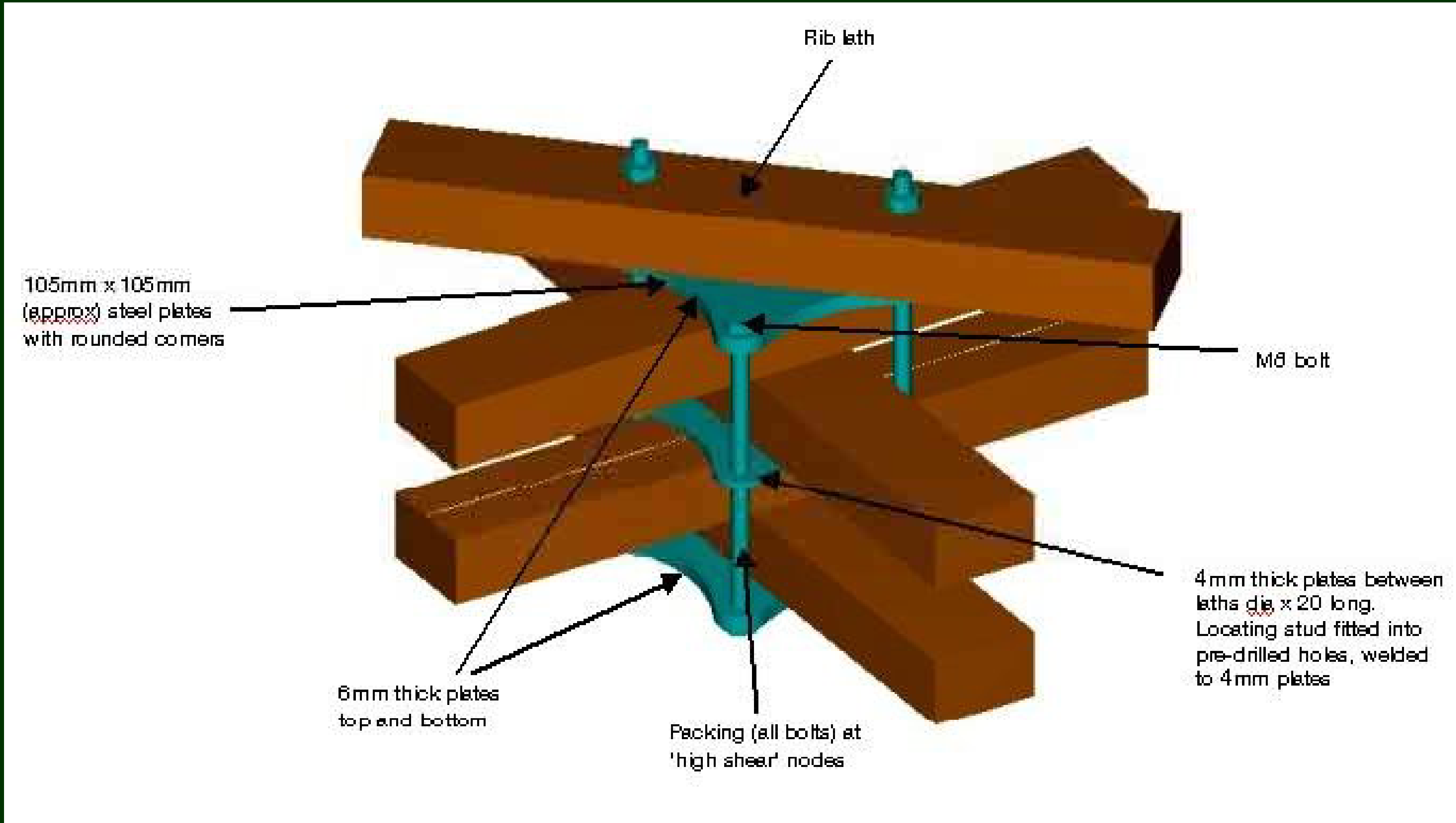
PERI
SECTION A - A
Phase II : - End -
Verticals and HD!
PRELIMINARY DESIGN

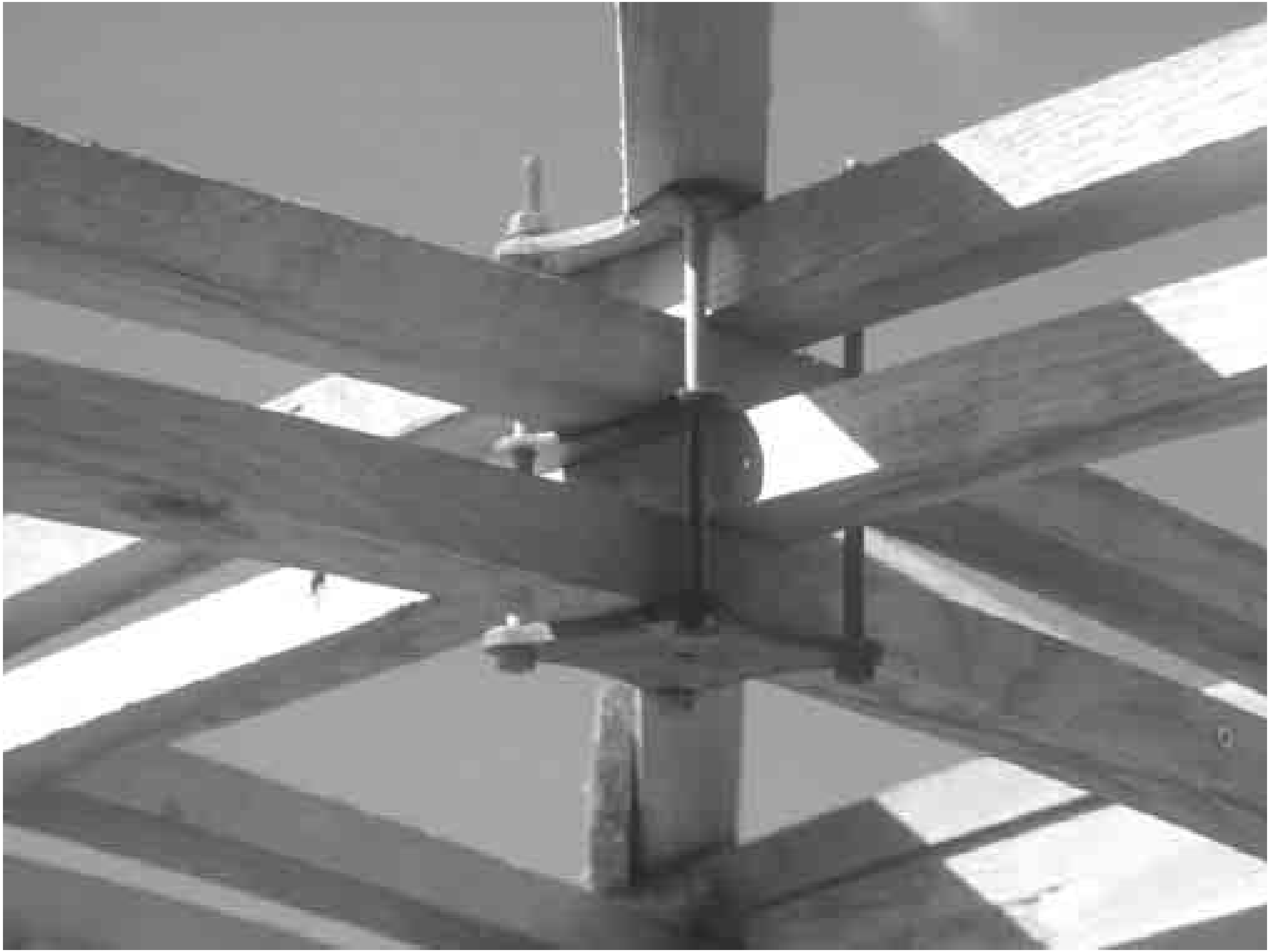

shear block to enable horizontal shear transfer between layers B and D
node
layer D
layer C
layer B
layer A
layers B and D run parallel to one another
layers A and C run parallel to one another
shear blocks between each layer
Section
Plan

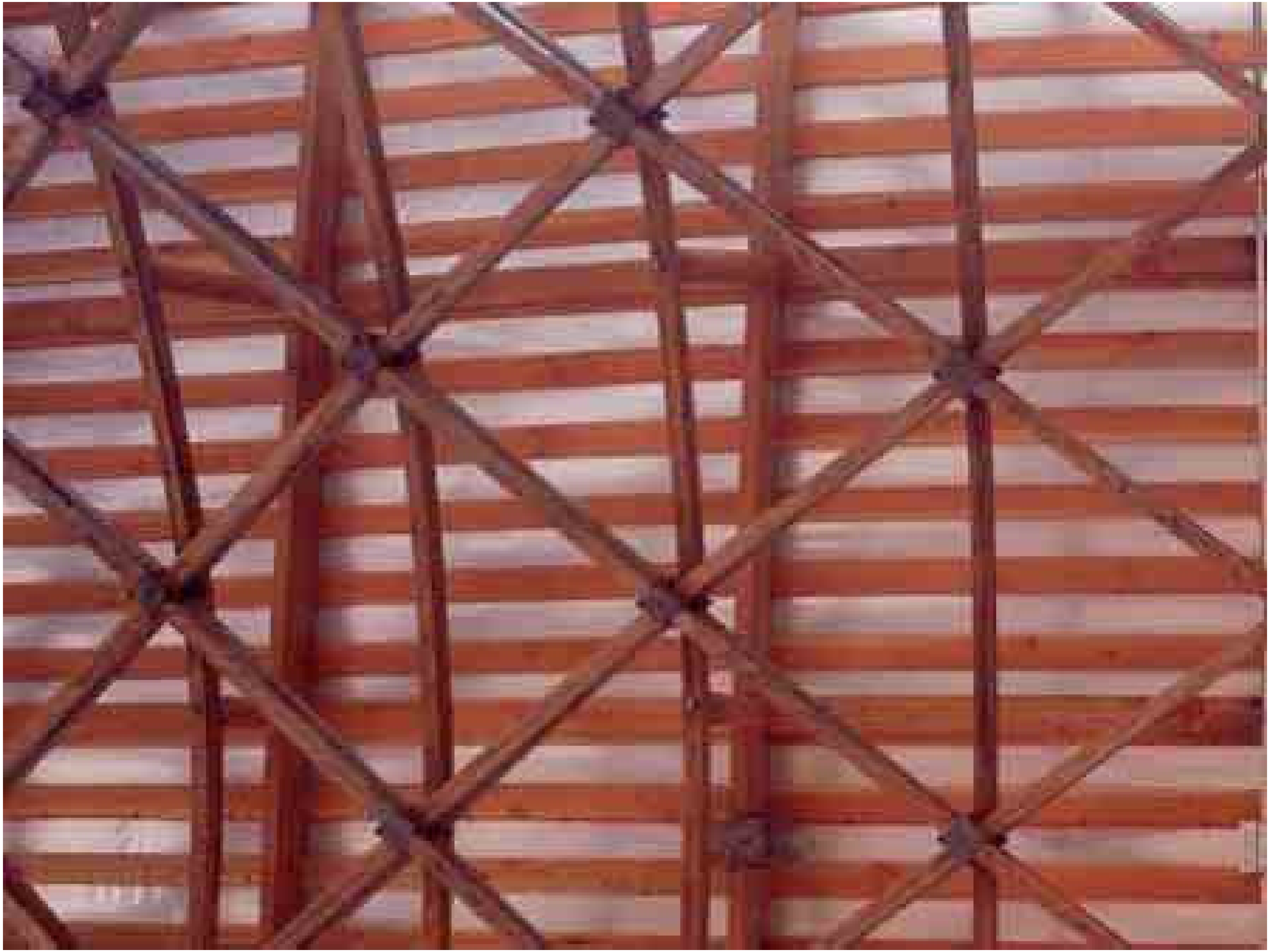



M8 Bolt
Slots in outermost layers ranging in length from 50mm to 150mm


M8 bolt
105mm x 105mm (approx) steel plates with rounded corners
4mm thick plates between laths dia x 20 long. Locating stud fitted into pre drilled holes, welded to 4mm plate
6mm thick plates top and bottom
Packing (all bolts) at 'high shear' nodes


Rib lath
105mm x 105mm
(approx) steel plates
with rounded corners
M8 bolt
4mm thick plates between
laths dia 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

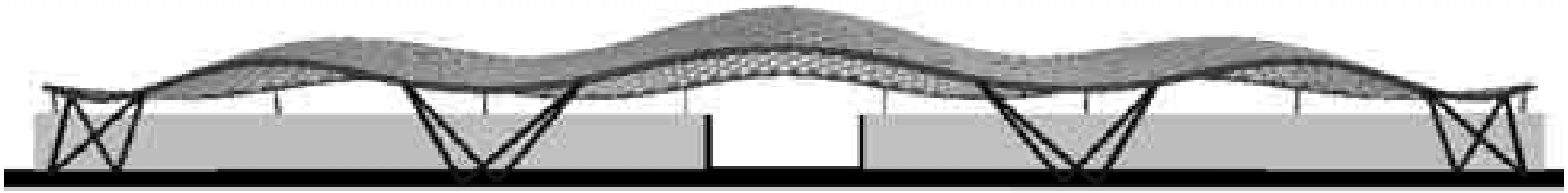




Forming the laths


PERI

The Savill Building



90m x 25m

4 Layers 80 x 50 mm Larch

Glenn Howells Architects

Engineers HRW

Buro Happold – Roof Engineers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Windsor
Cornwall
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English Channel

The Savill Building

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

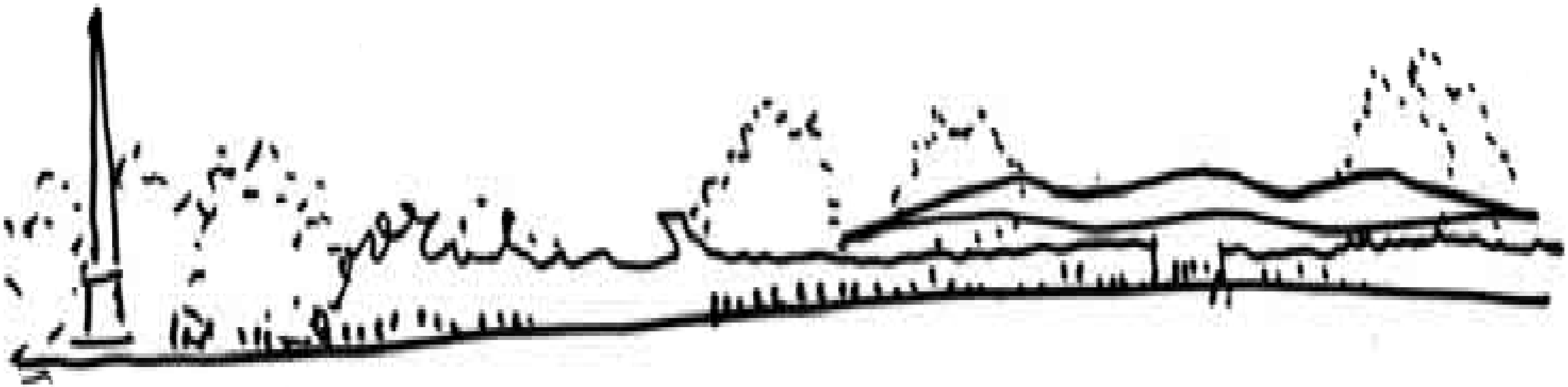
Material with unknown properties

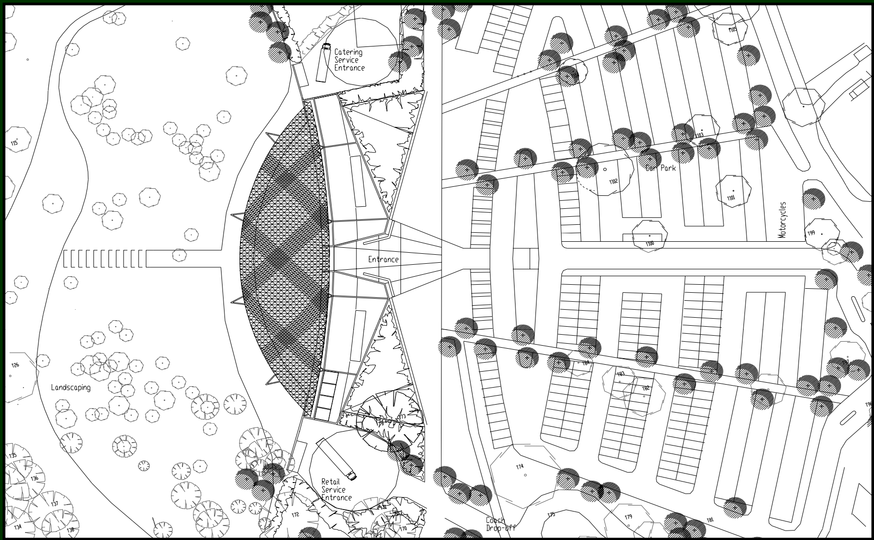
The Savill Building

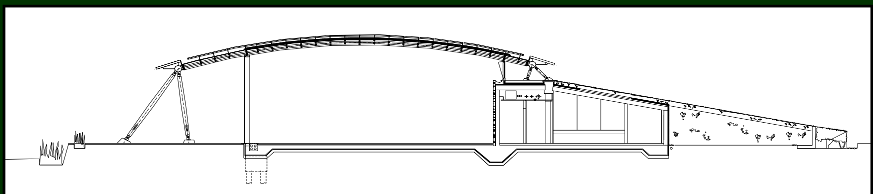
The solution:

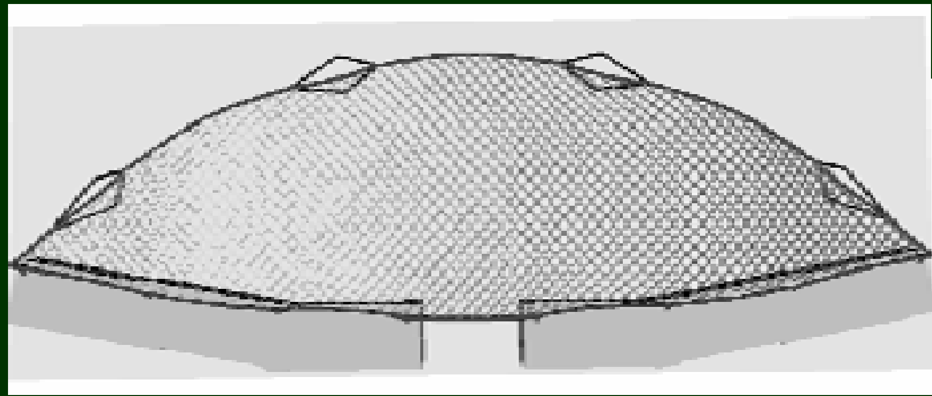
- Good communication
- Use of EC5 for reliable design outcome
- Material testing

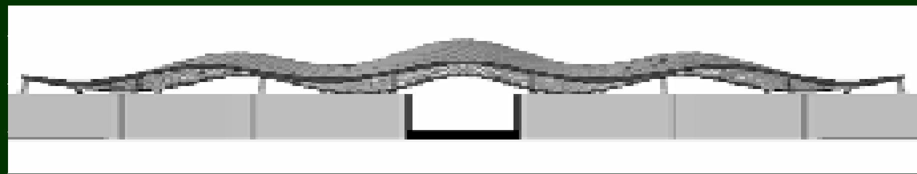
Competition sketch

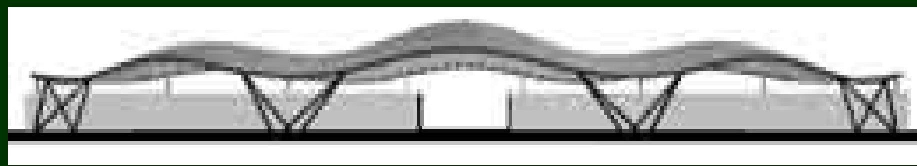


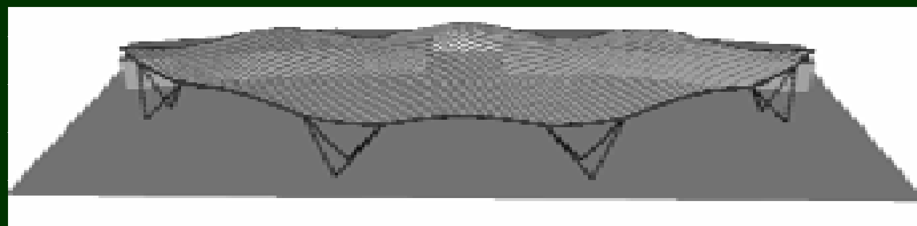






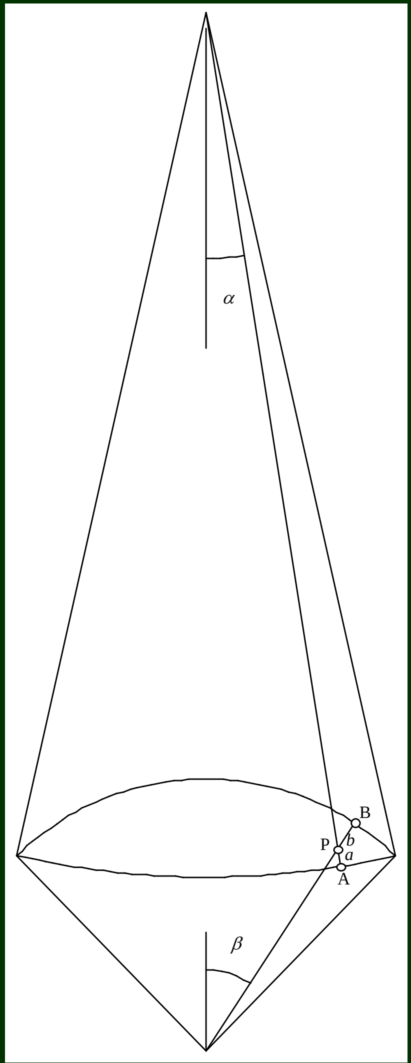






Glenn Howells Architects

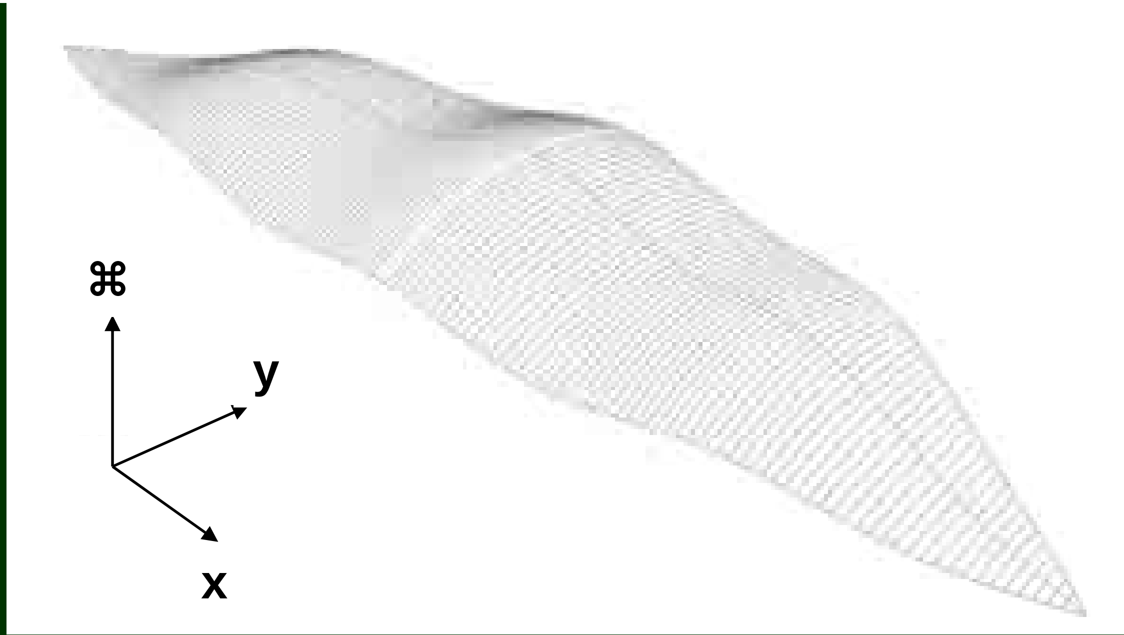
Defining the Form – Mathematical



UNIVERSITY OF BATH

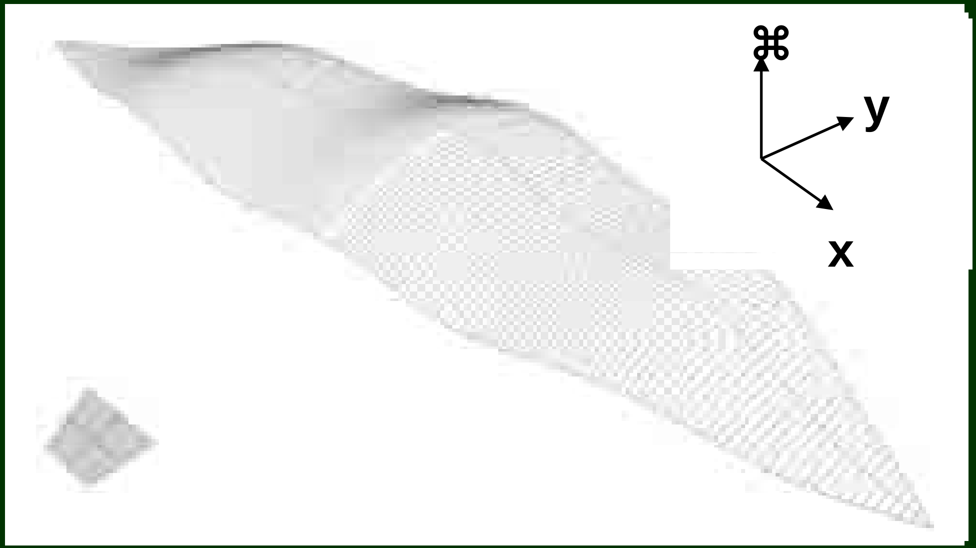
Form-finding with University of Bath

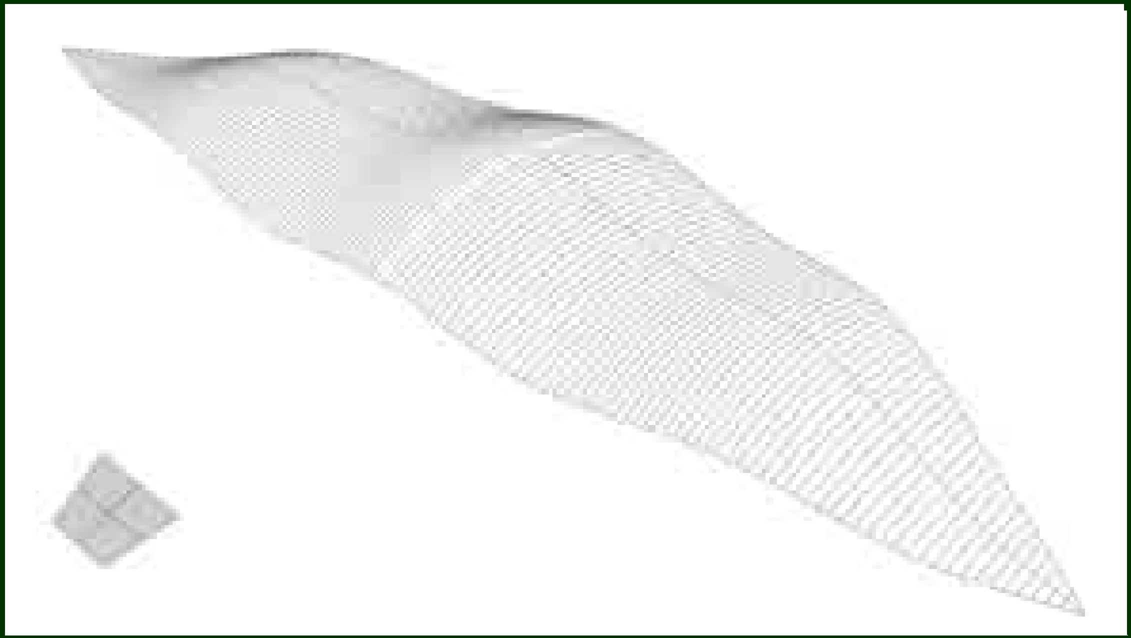
Perimeter slab is set out using arcs of two intersecting circles



- 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.

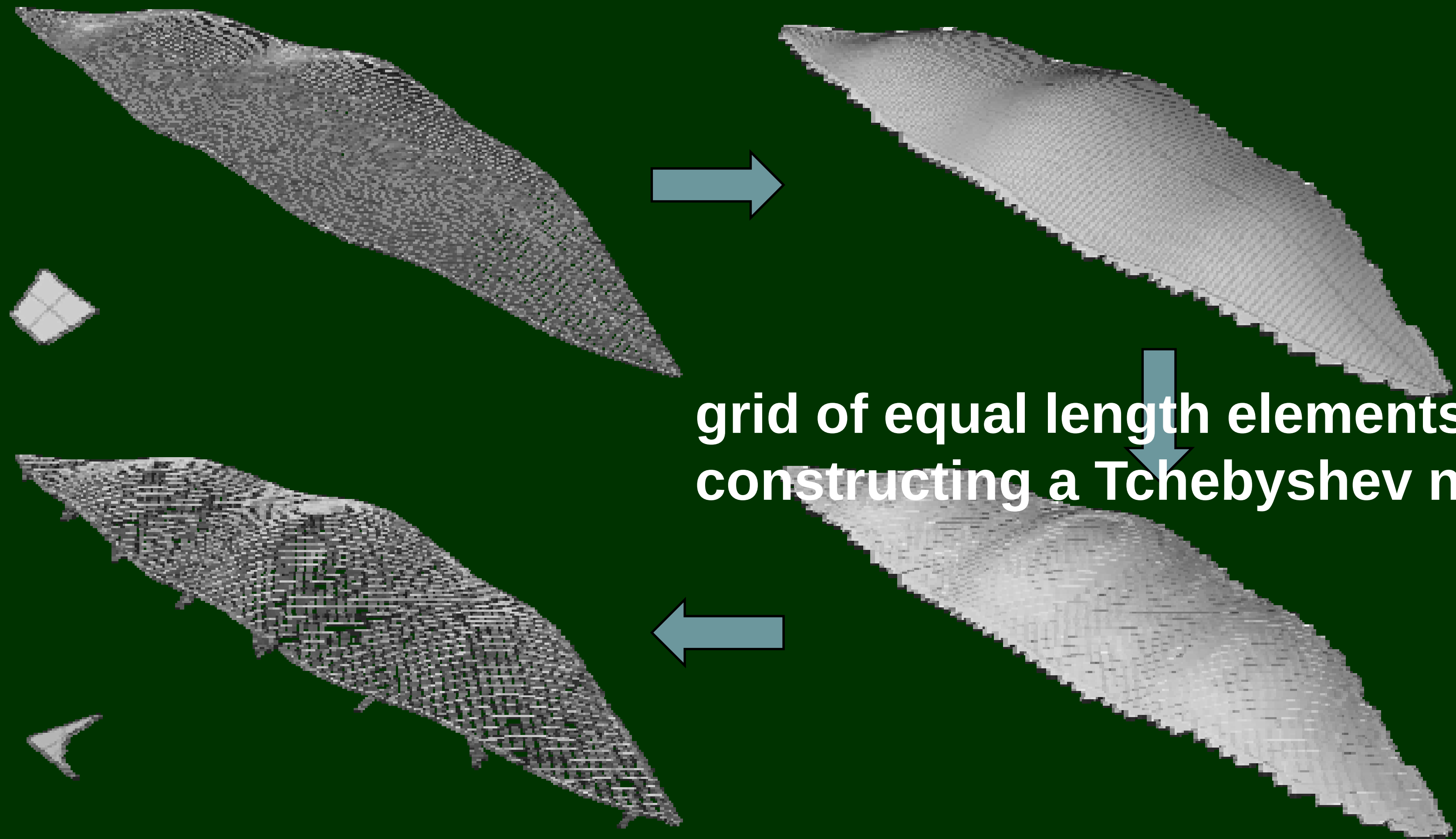
- z = f(x, y) with a damped cosine wave in the x direction and upside down parabolas in the y direction
- clear geometric basis to the surface shape
- architects and engineers could work together to adjust and agree shape to meet aesthetic practical constraints





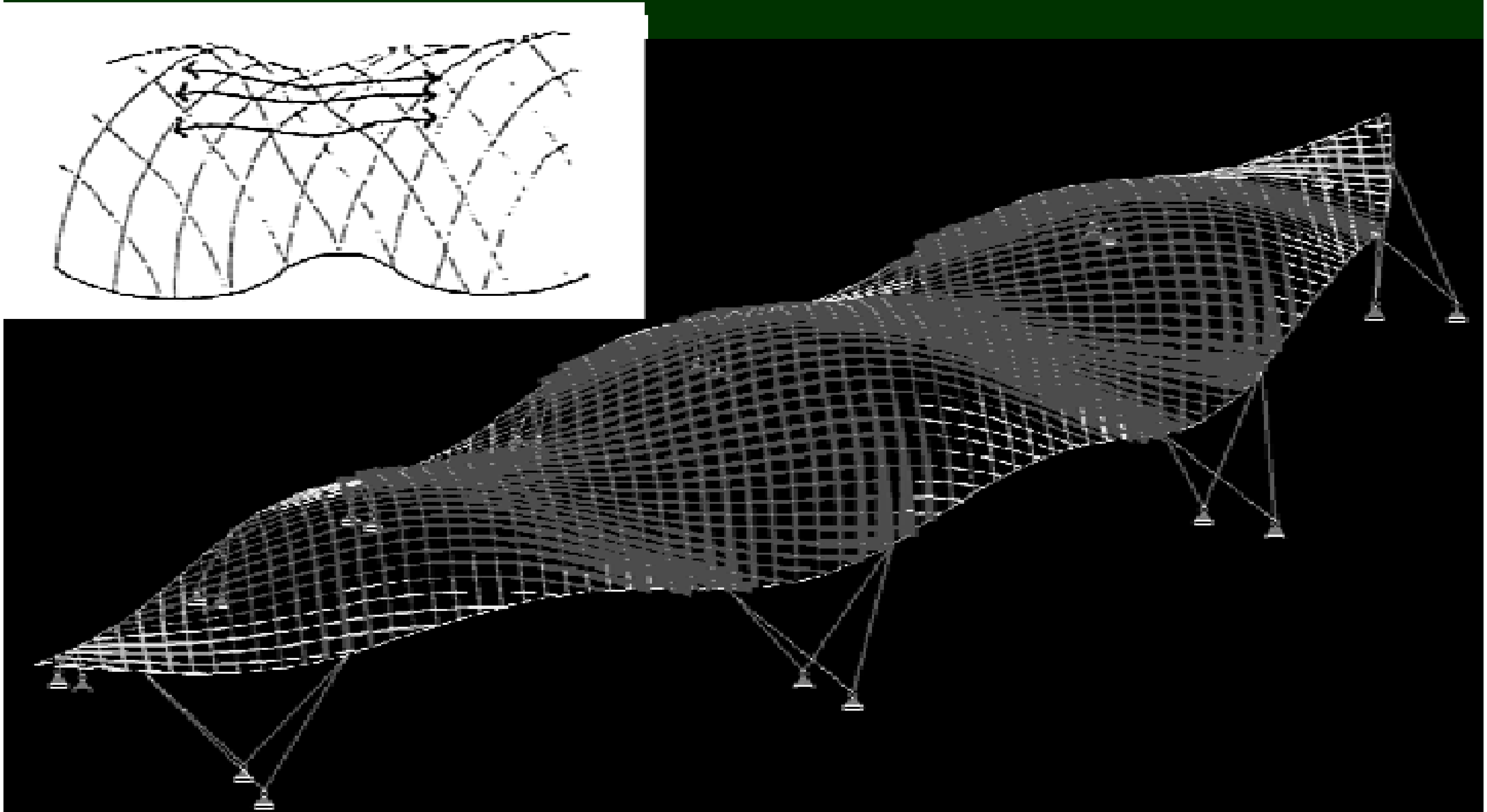
- Perimeter of shell set out by cutting the surface with planes – thus structural element trimming the edge is bent in only two dimensions

Defining the Form

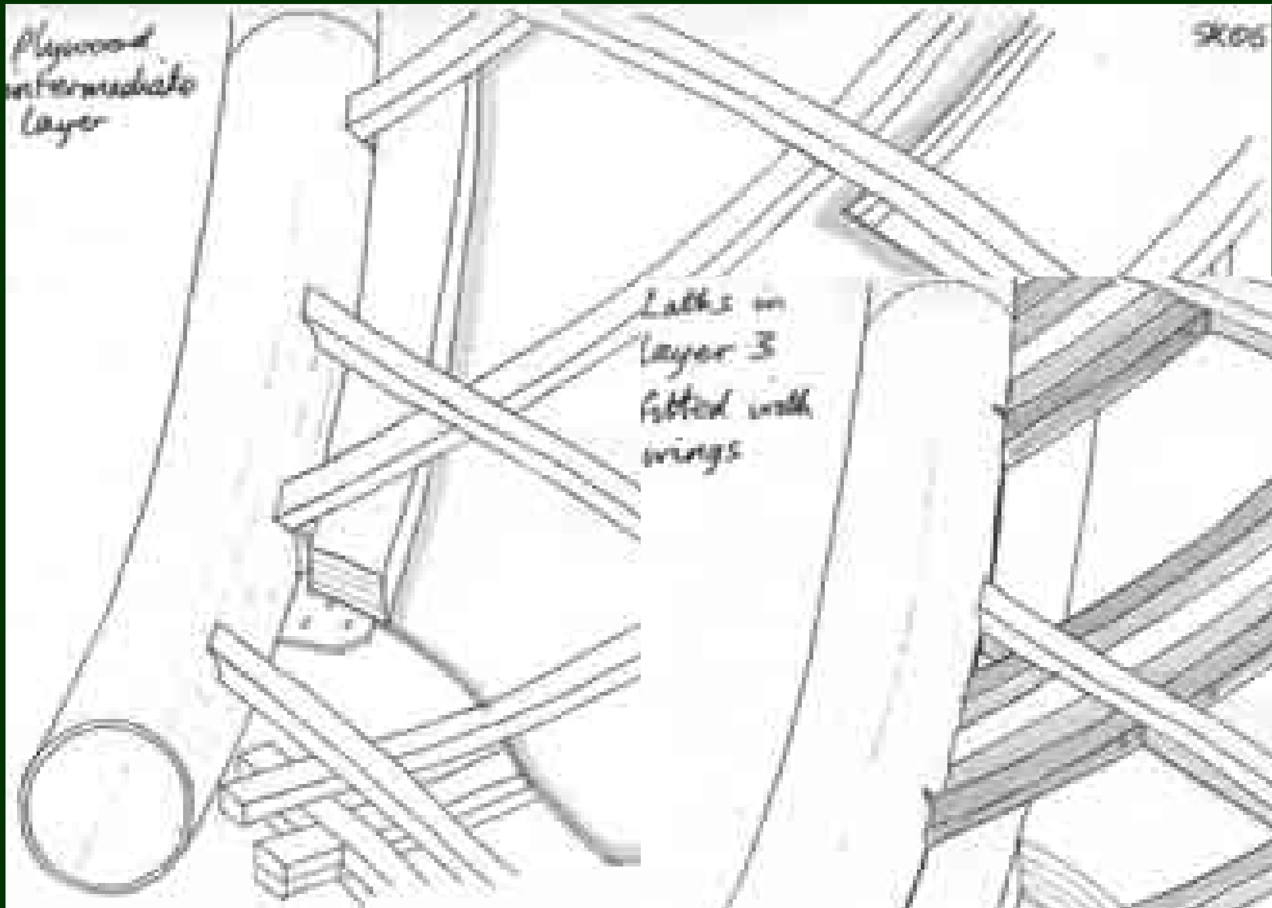


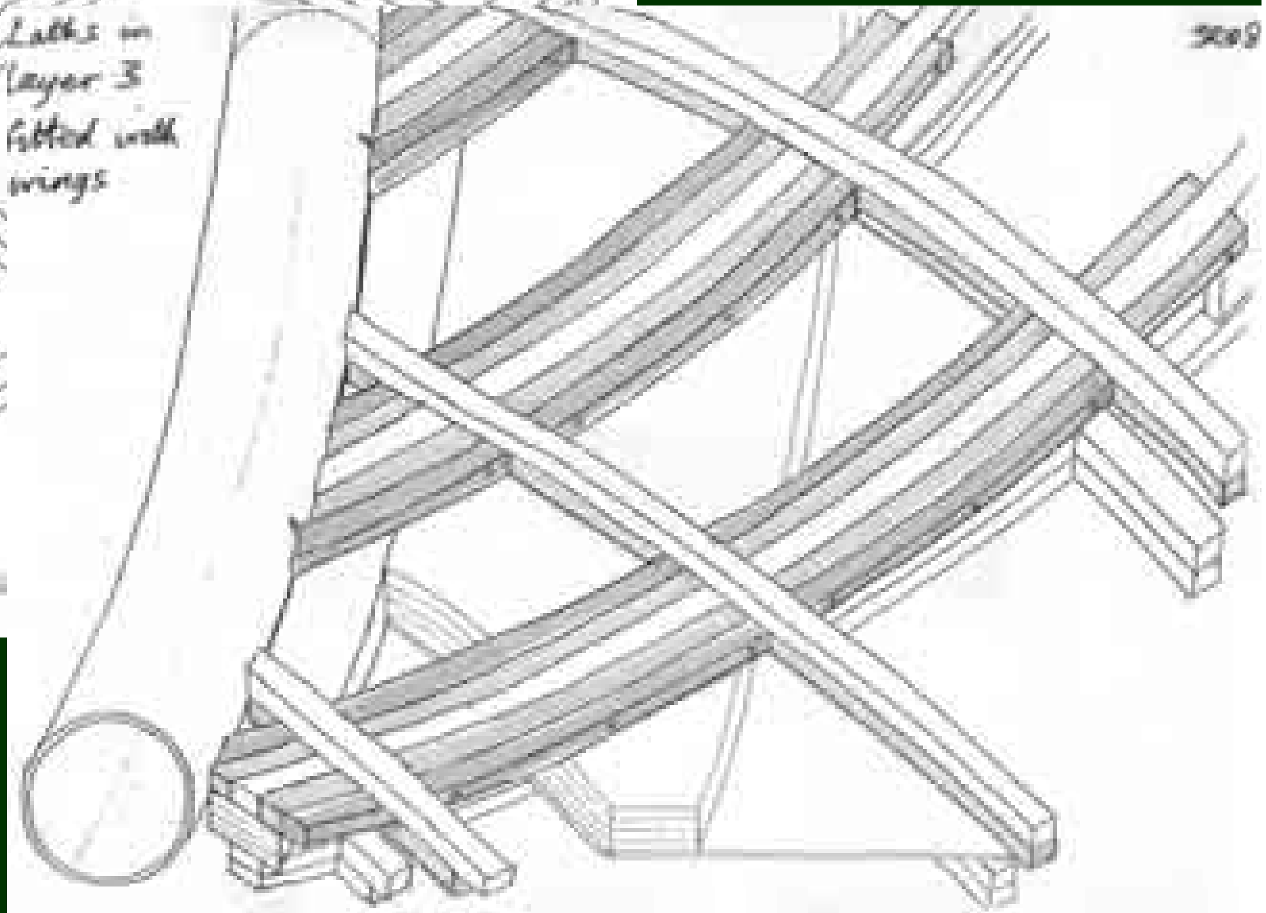
Establishing the Structure

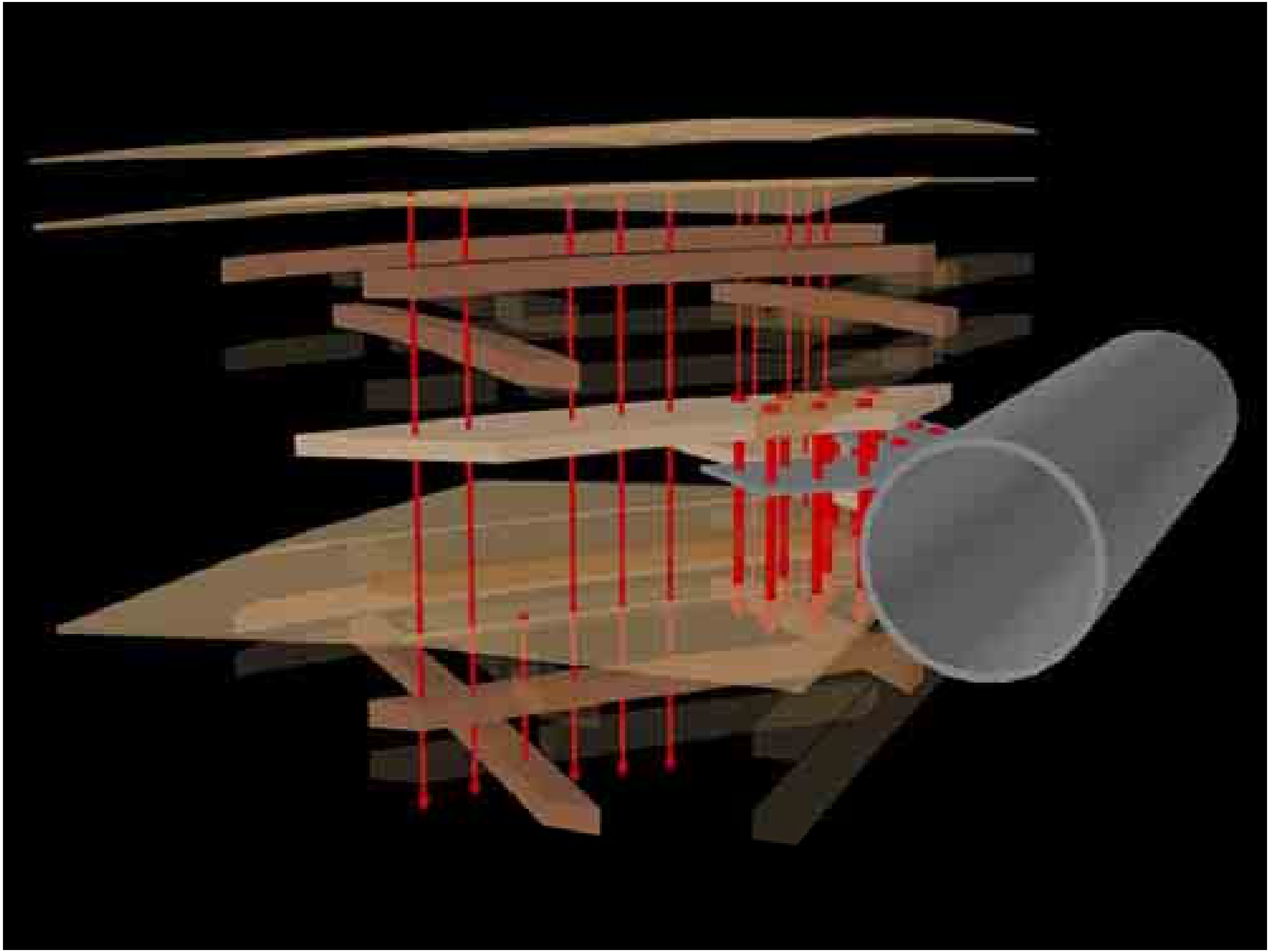
Analysis, Design and Detailing

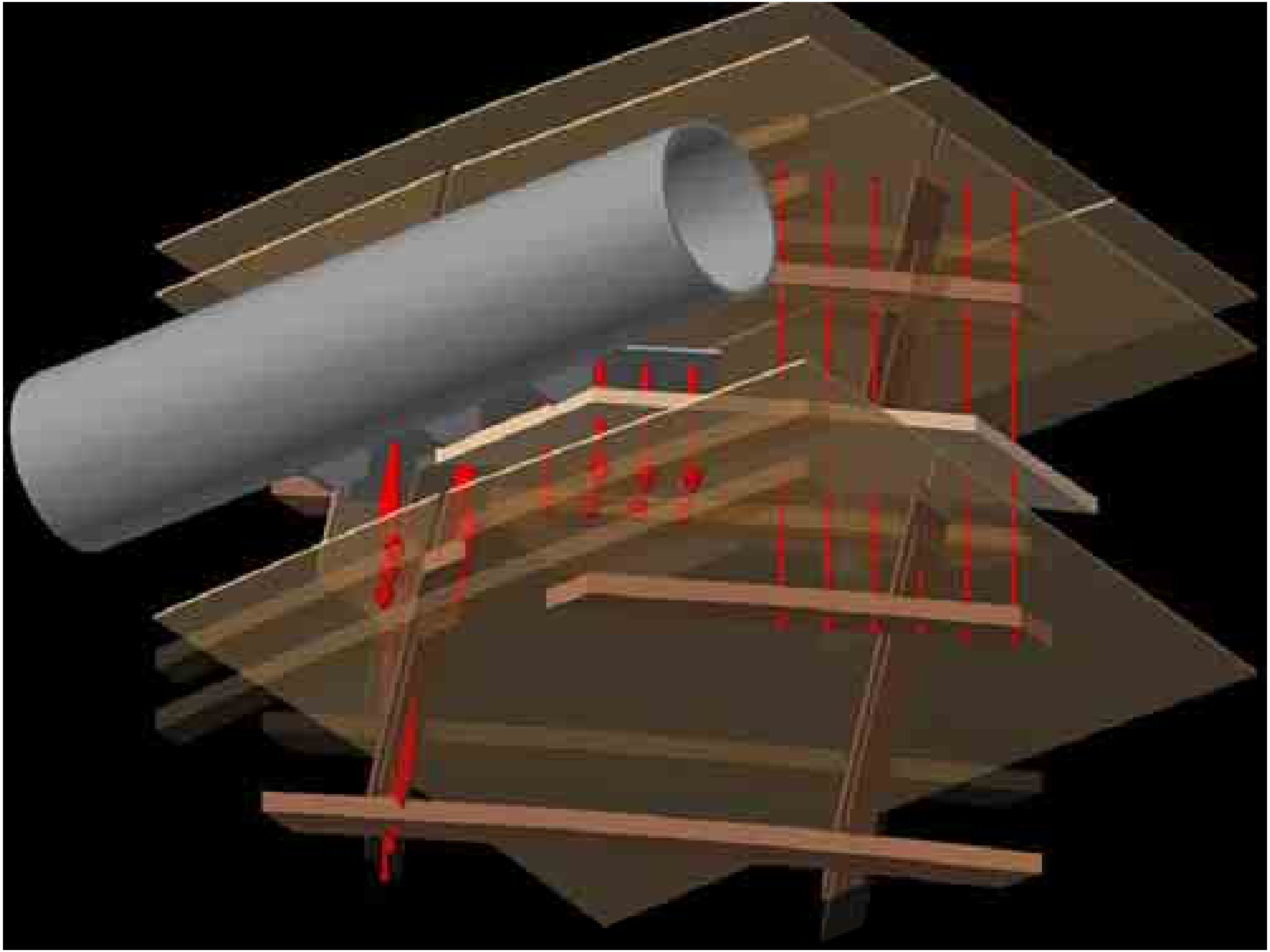


Edge Detail: Carpentry advice









Timber Testing

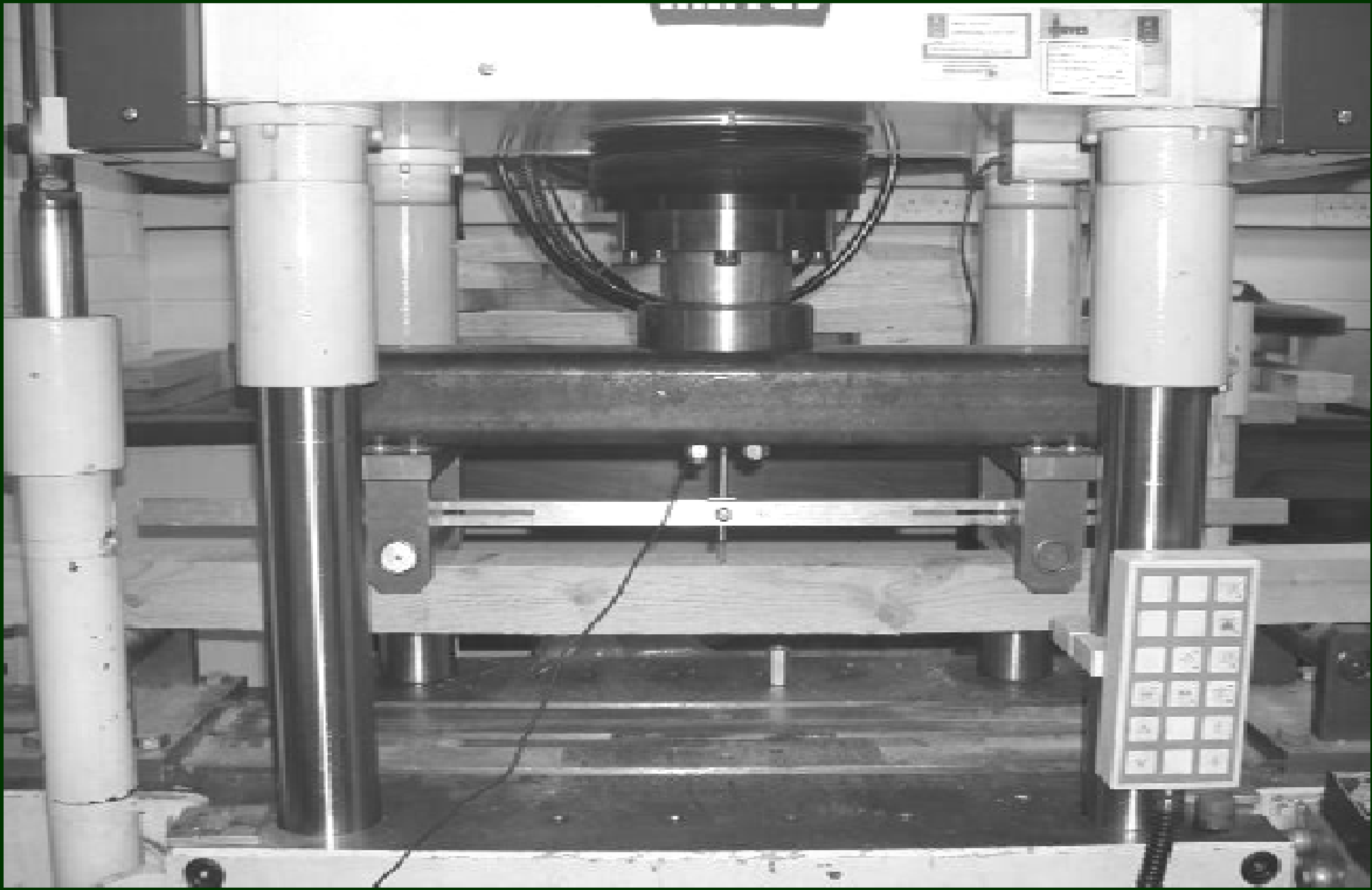
BS EN 384: 1995: Structural timber - Determination of characteristic values of mechanical properties and density

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

Testing by

University of Bath

Timber testing and properties



Determination of properties

Table 1 — Strength classes - Characteristic values

		Poplar and softwood species												Hardwood species					
		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50	D30	D35	D40	D50	D60	D70
Strength properties (in N/mm²)																			
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50	30	35	40	50	60	70
Tension parallel	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30	18	21	24	30	36	42
Tension perpendicular	$f_{t,90,k}$	0,4	0,5	0,5	0,5	0,5	0,5	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
Compression parallel	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29	23	25	26	29	32	34
Compression perpendicular	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2	8,0	8,4	8,8	9,7	10,5	13,5
Shear	$f_{v,k}$	1,7	1,8	2,0	2,2	2,4	2,5	2,8	3,0	3,4	3,8	3,8	3,8	3,0	3,4	3,8	4,6	5,3	6,0
Stiffness properties (in kN/mm²)																			
Mean modulus of elasticity parallel	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16	10	10	11	14	17	20
5% modulus of elasticity parallel	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7	8,0	8,7	9,4	11,8	14,3	16,8
Mean modulus of elasticity perpendicular	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53	0,64	0,69	0,75	0,93	1,13	1,33
Mean shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00	0,60	0,65	0,70	0,88	1,06	1,25
Density (in kg/m³)																			
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460	530	560	590	650	700	900
Mean density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550	640	670	700	780	840	1080

NOTE [illegible]

[illegible]

[illegible]

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

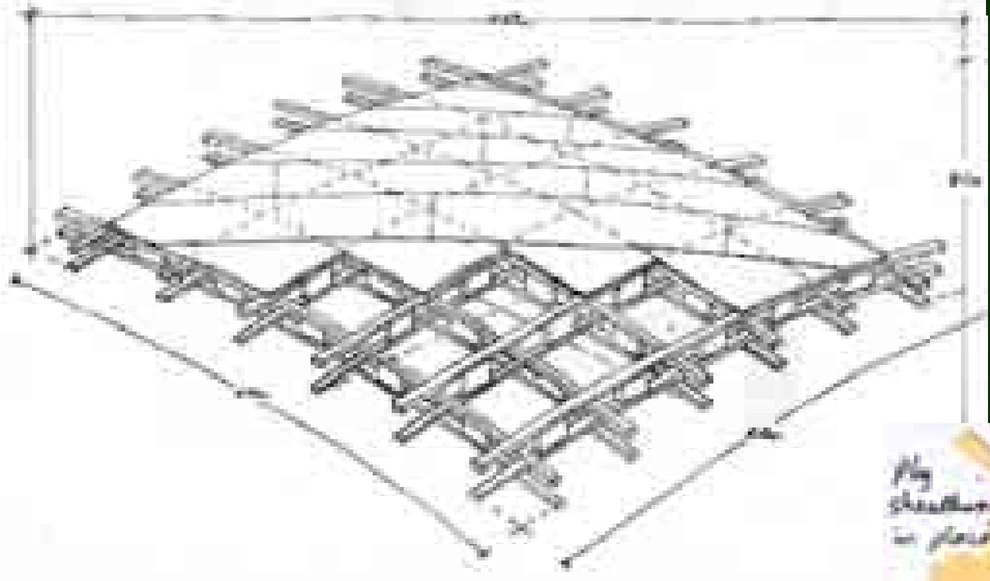
Bolt edge plates into position

Bring edge of mat onto plates

Fix Shear Blocks

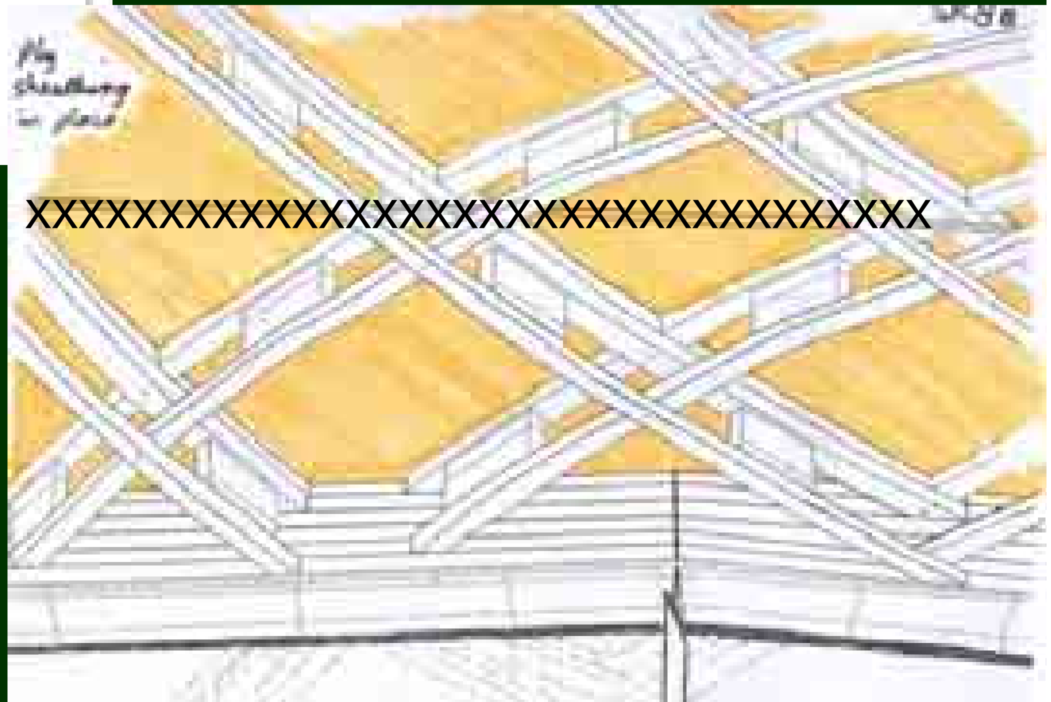
Fix Shear Blocks

Bracing of shell



Local larch for structure, local oak for rain screen

Bracing: 2 layers 12mm birch ply



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Plywood skin – structural bracing

Strike the scaffold

Glazing and Rainscreen

Oak Cladding

Oak cladding

Edge detail

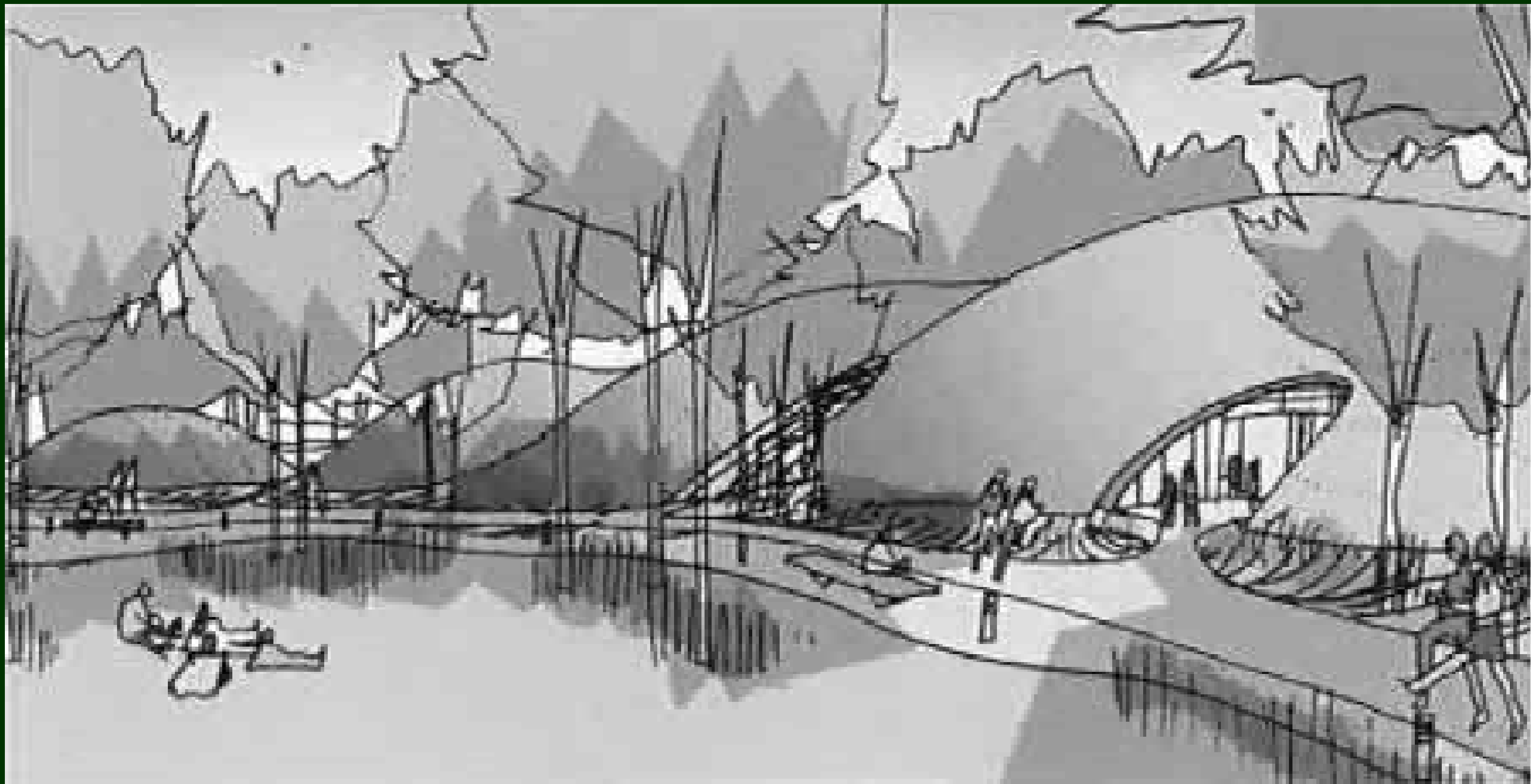
Finished Building

The Garden Context

another gridshell

Chiddingstone Castle Orangery

Another Challenge

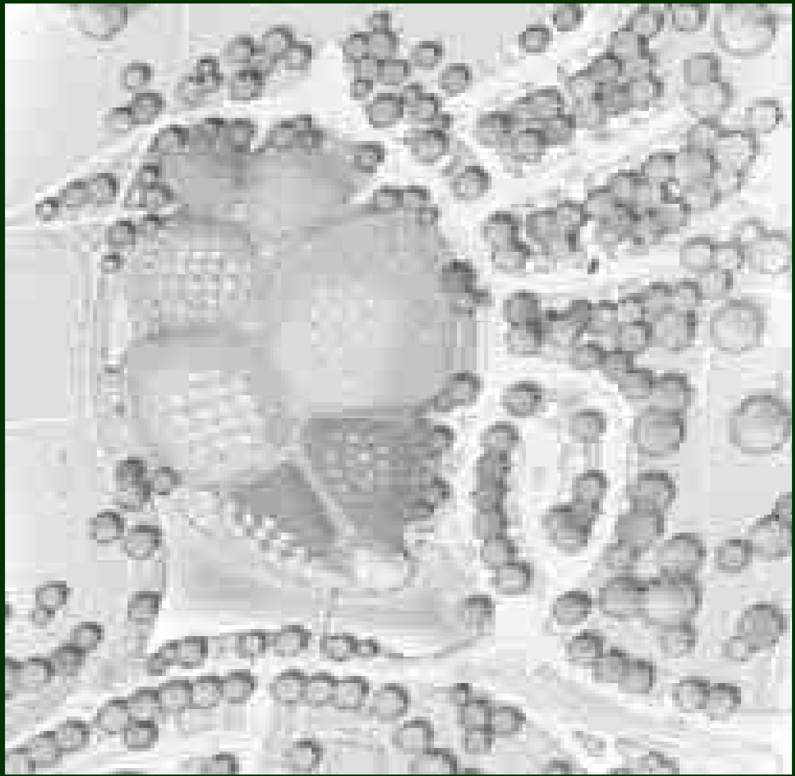


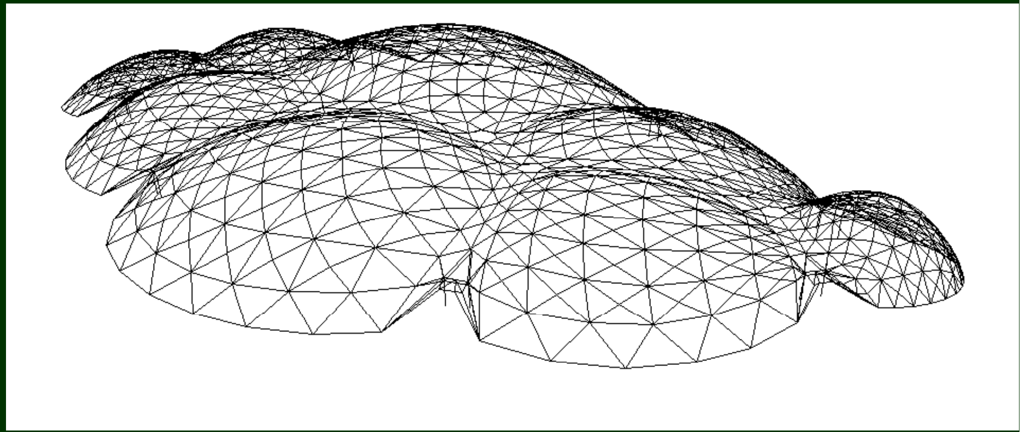
Andrew Wright Associates with S&P Architects Architects

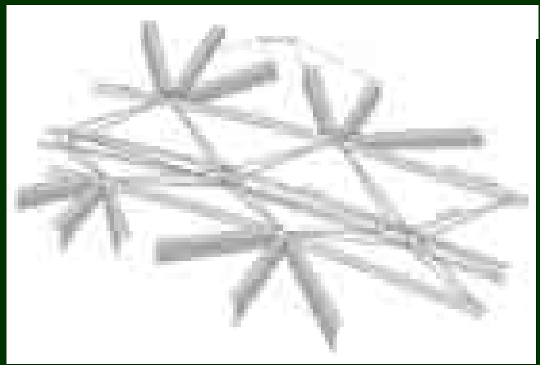
NORTHERN IRELAND
EIRE
Lake District
Leeds
Hull
Scunthorpe
Manchester
WALES
Birmingham
Norwich
ENGLAND
Cardiff
Bristol
London
Dover
Calais
Cornwall
Devon
English Channel

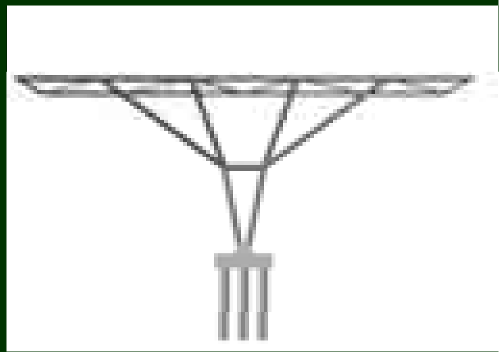
The Scheme

The Competition

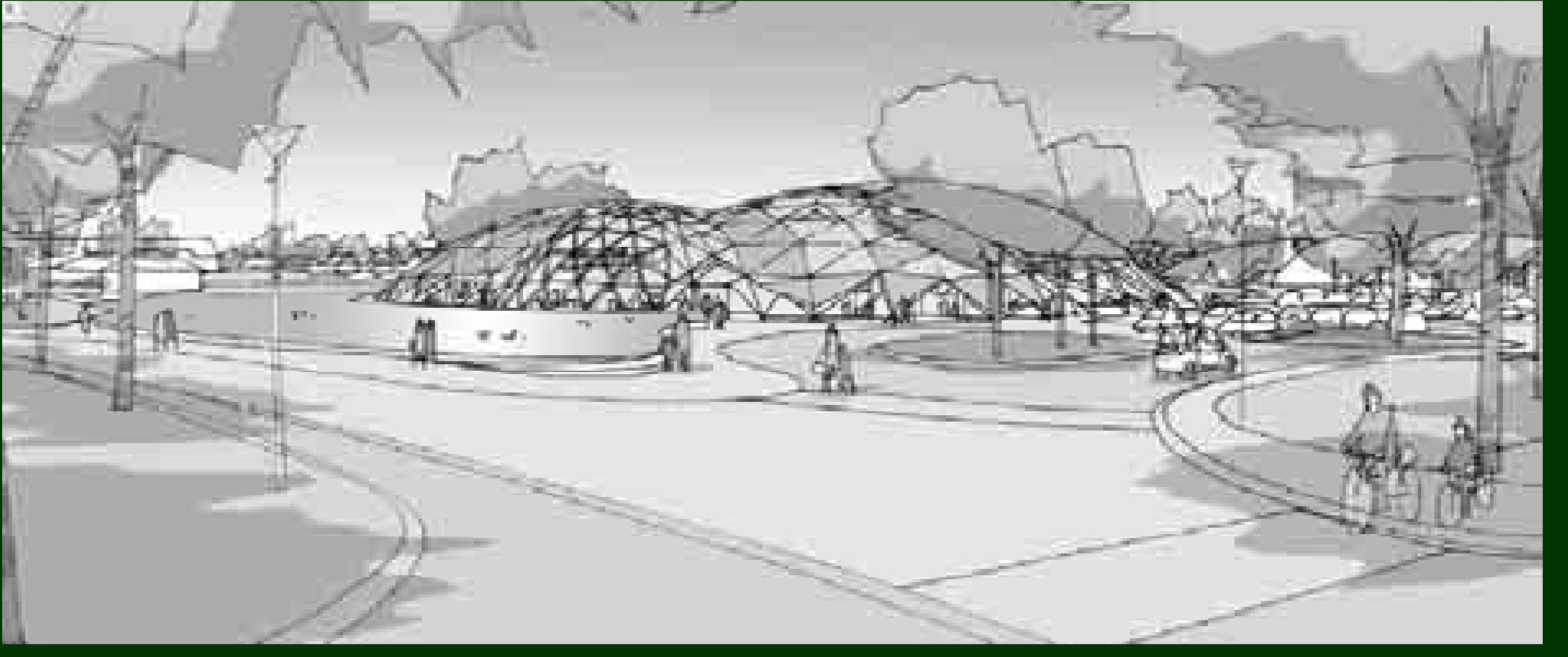






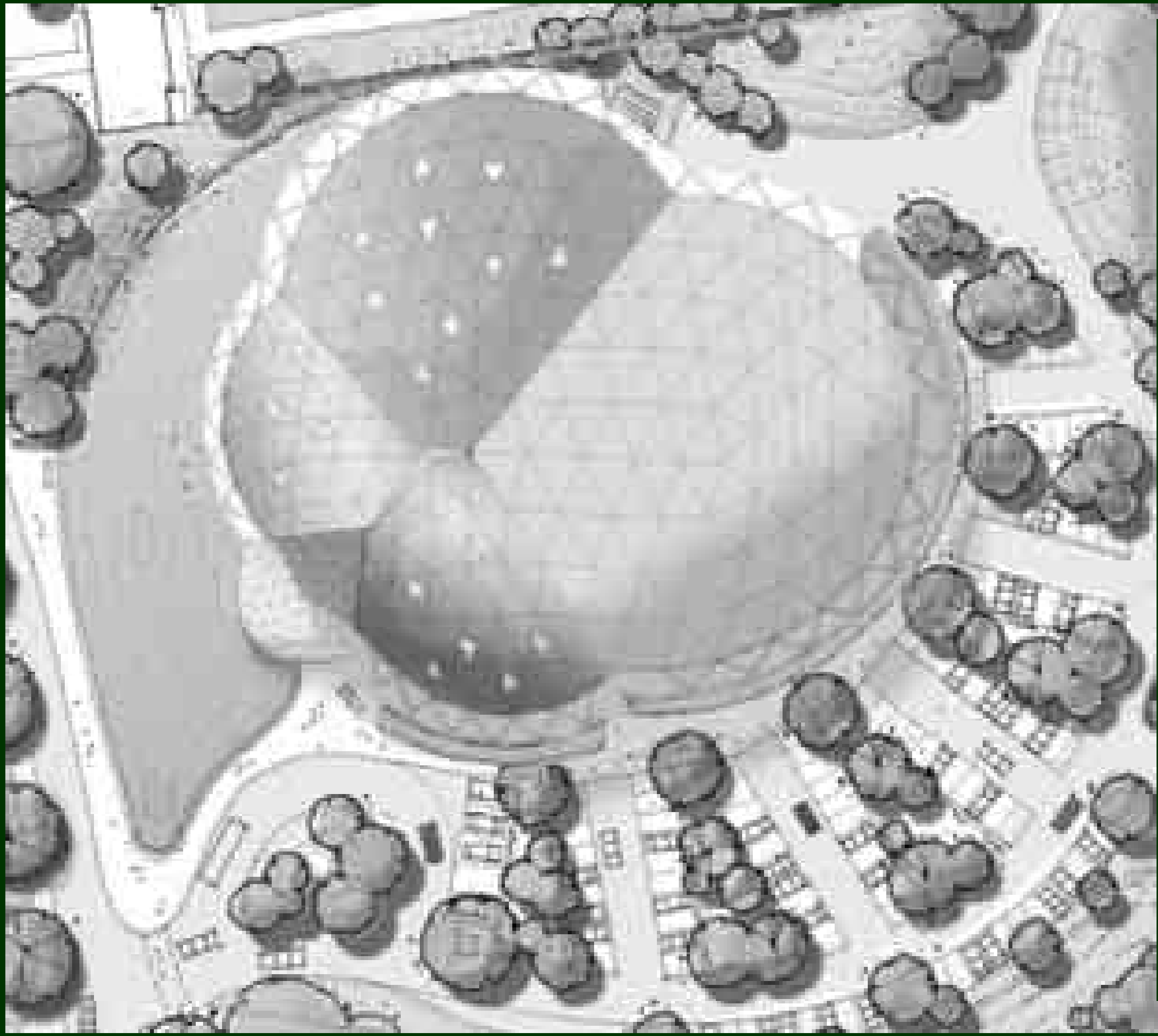


The Scheme

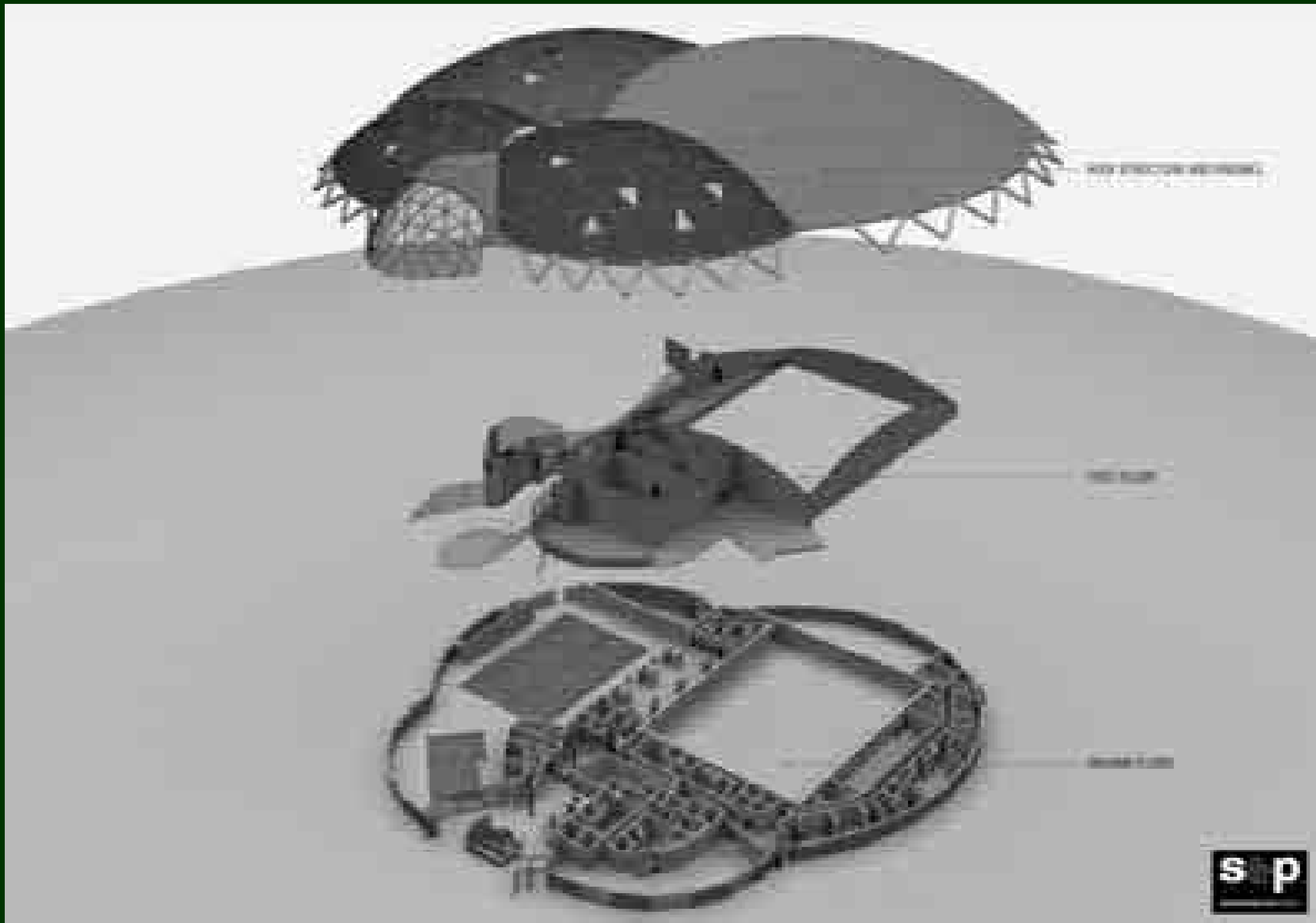


Precedent – Timber Geodesics

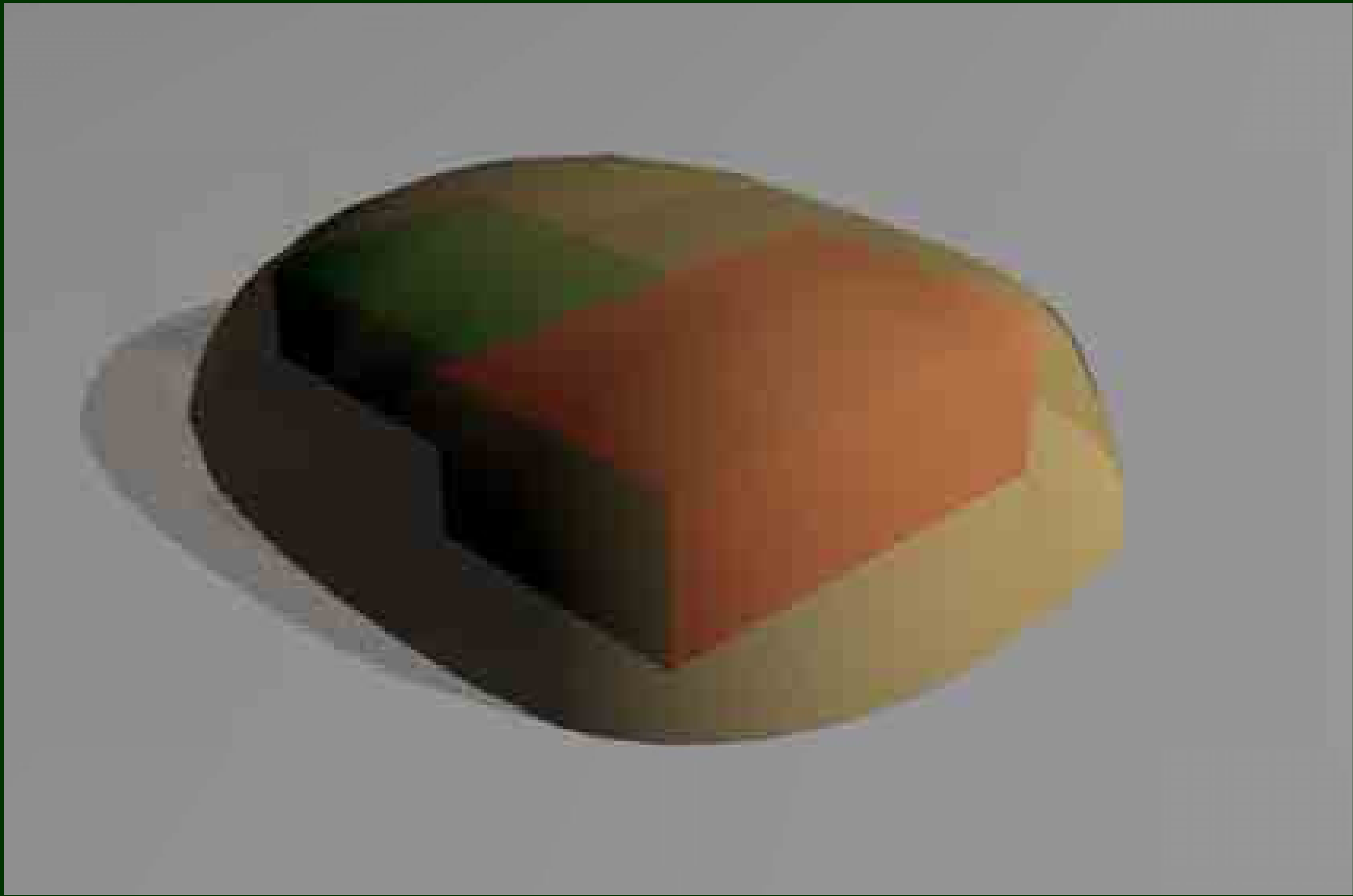
The Scheme



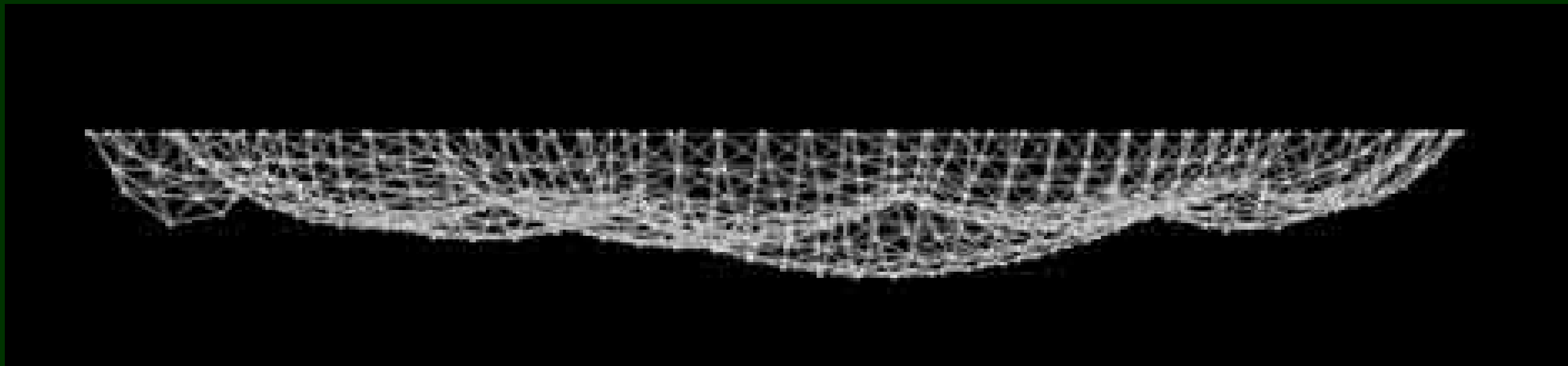
The Scheme – Exploded



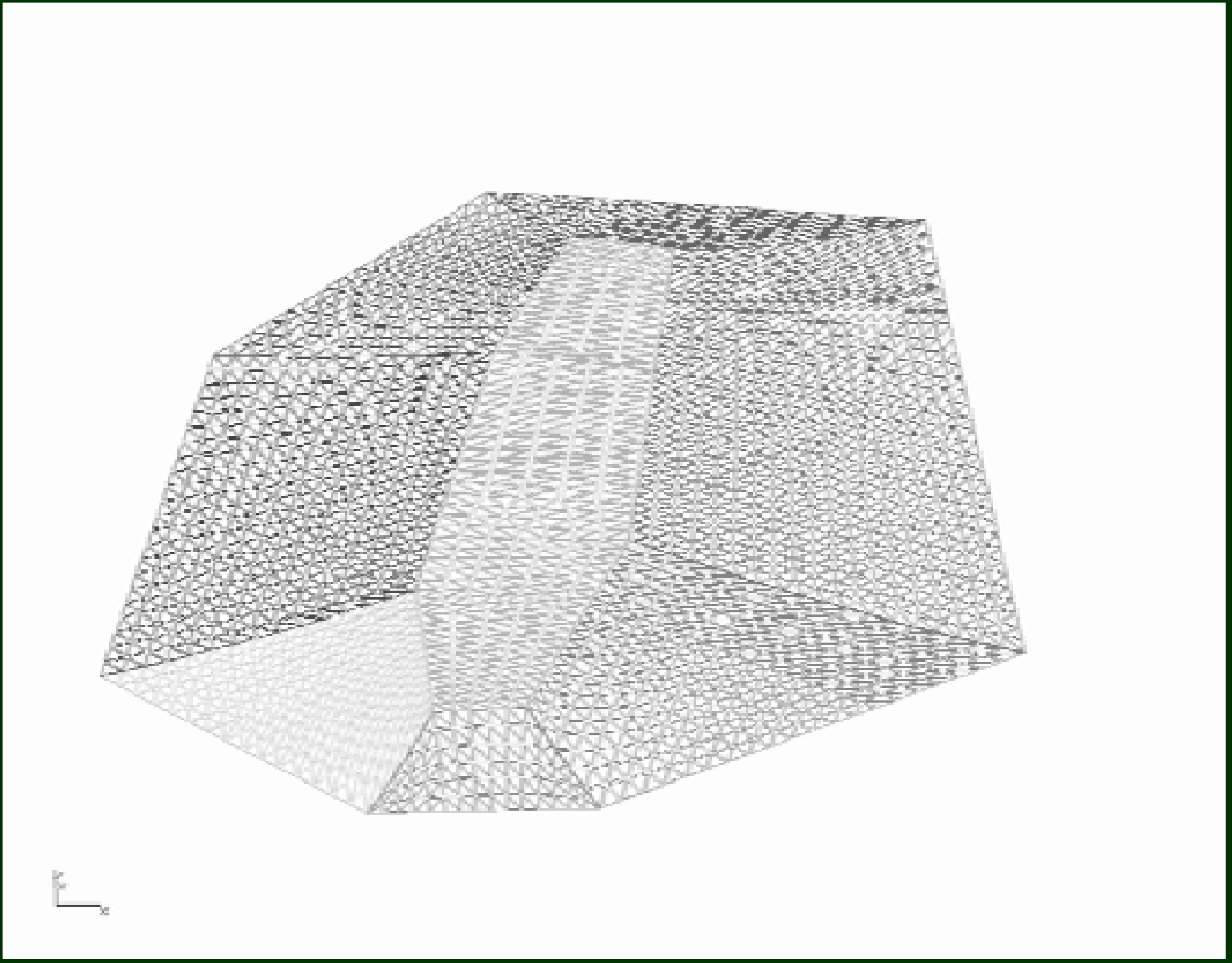
Defining the Roof Surface



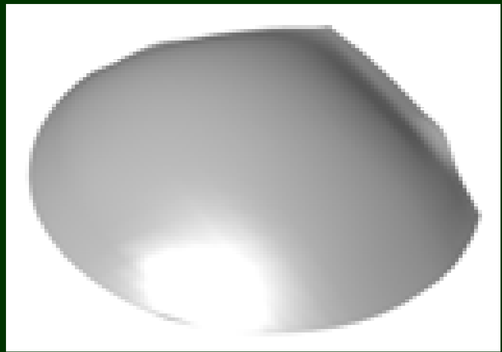
Formfinding – Tenysl 'Hanging Chain model'



Defining the Roof Surface

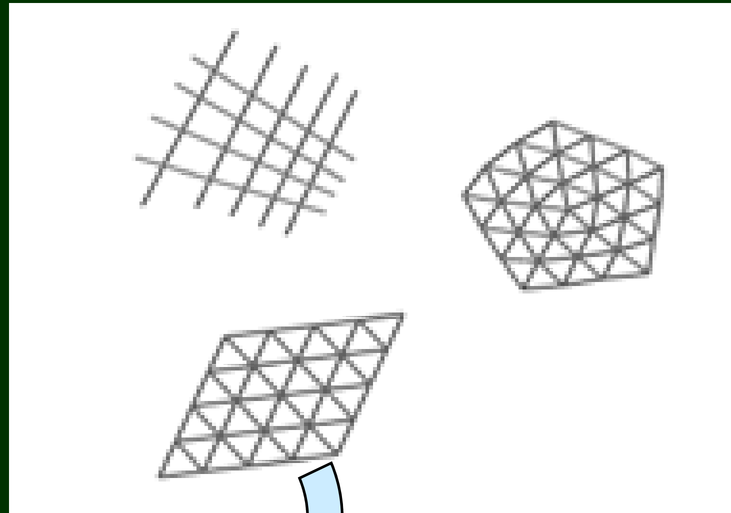


Defining the Roof Grid

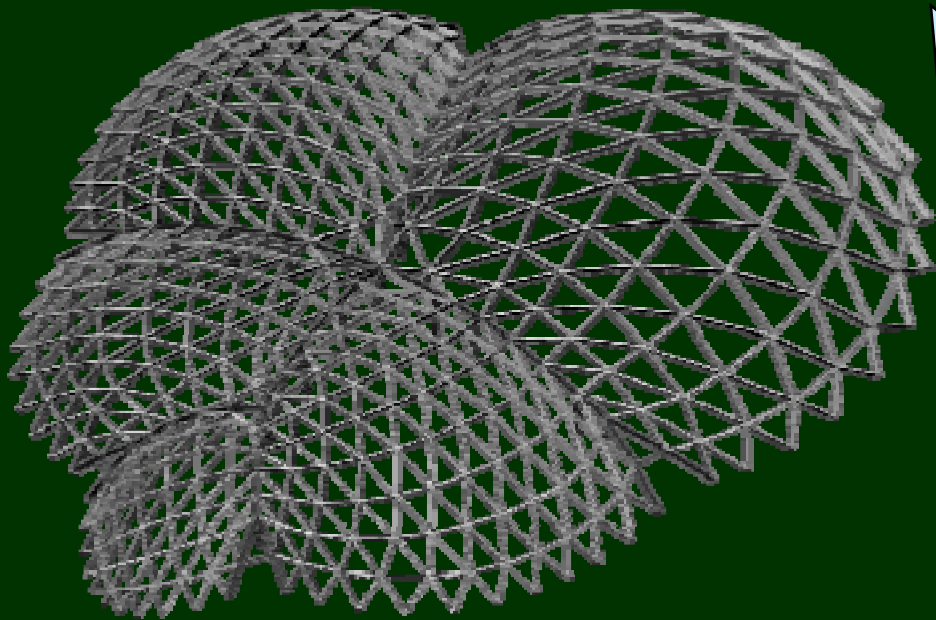


take surface

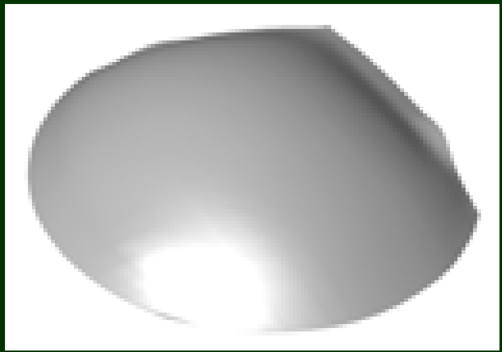
define a
grid



map grid
onto surface

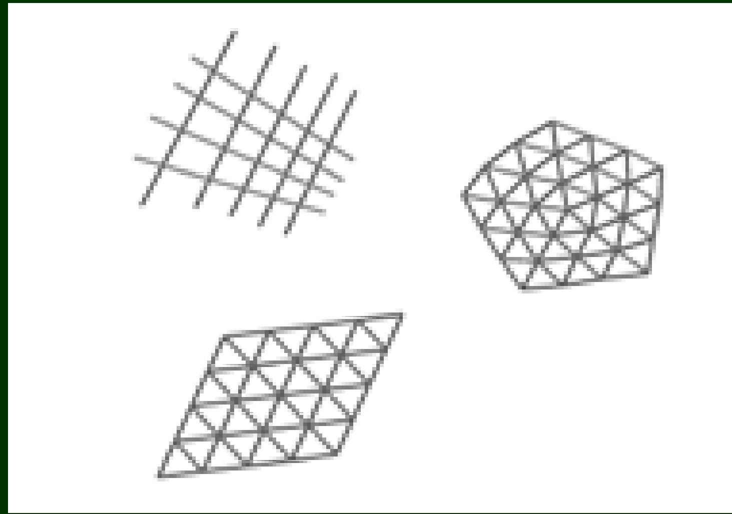


Defining the Roof Grid

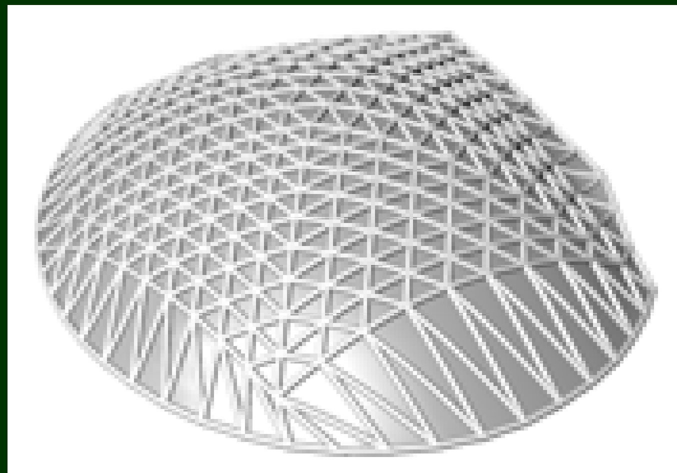


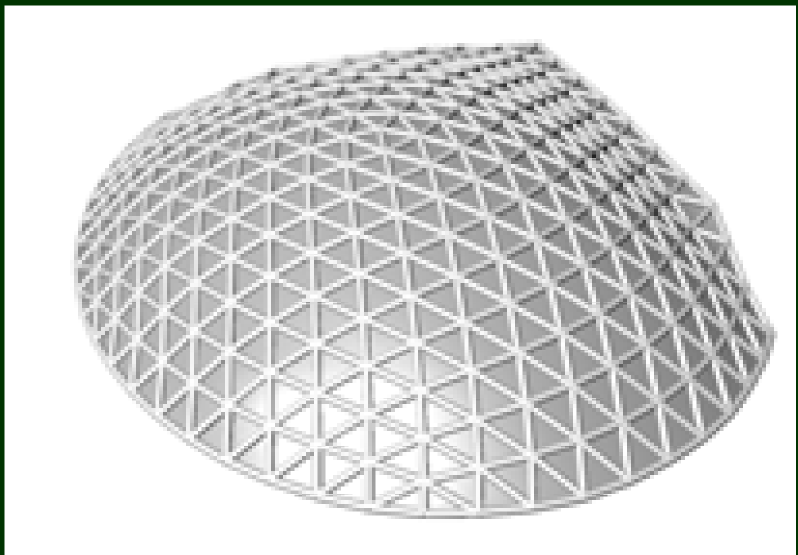
take surface

define a grid



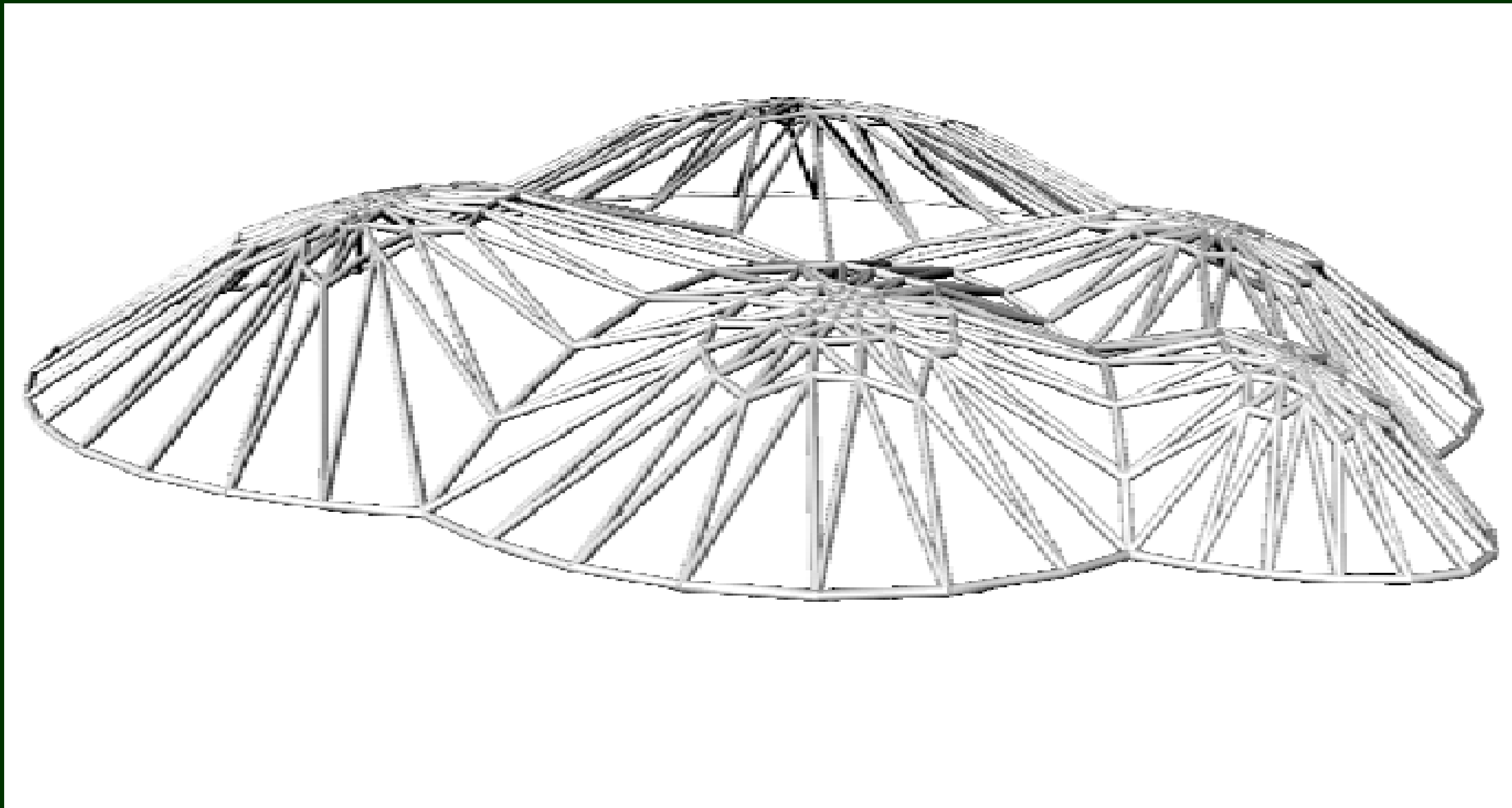
map grid onto surface



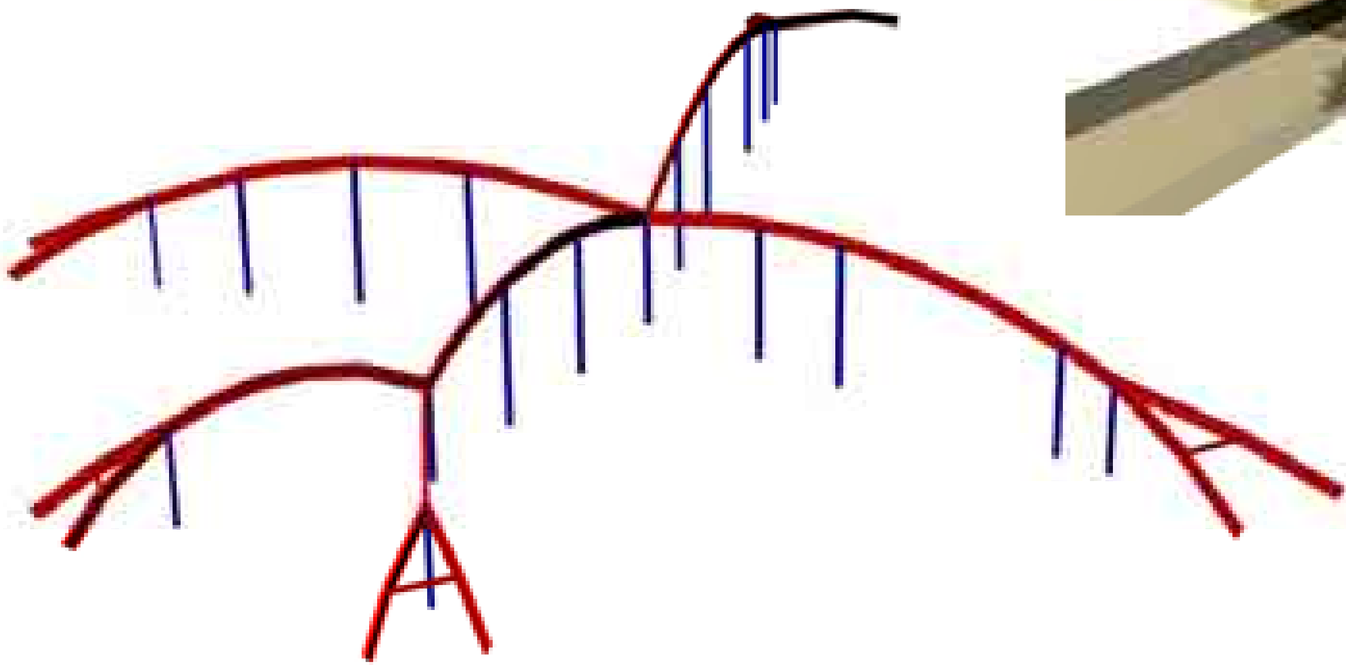


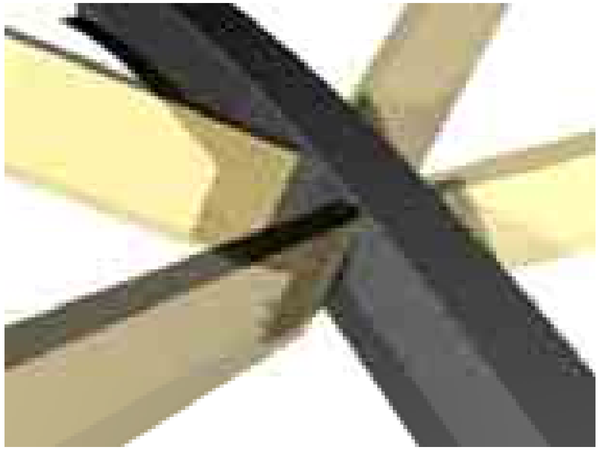
relax grid using dynamic relaxation

Defining the Roof Grid

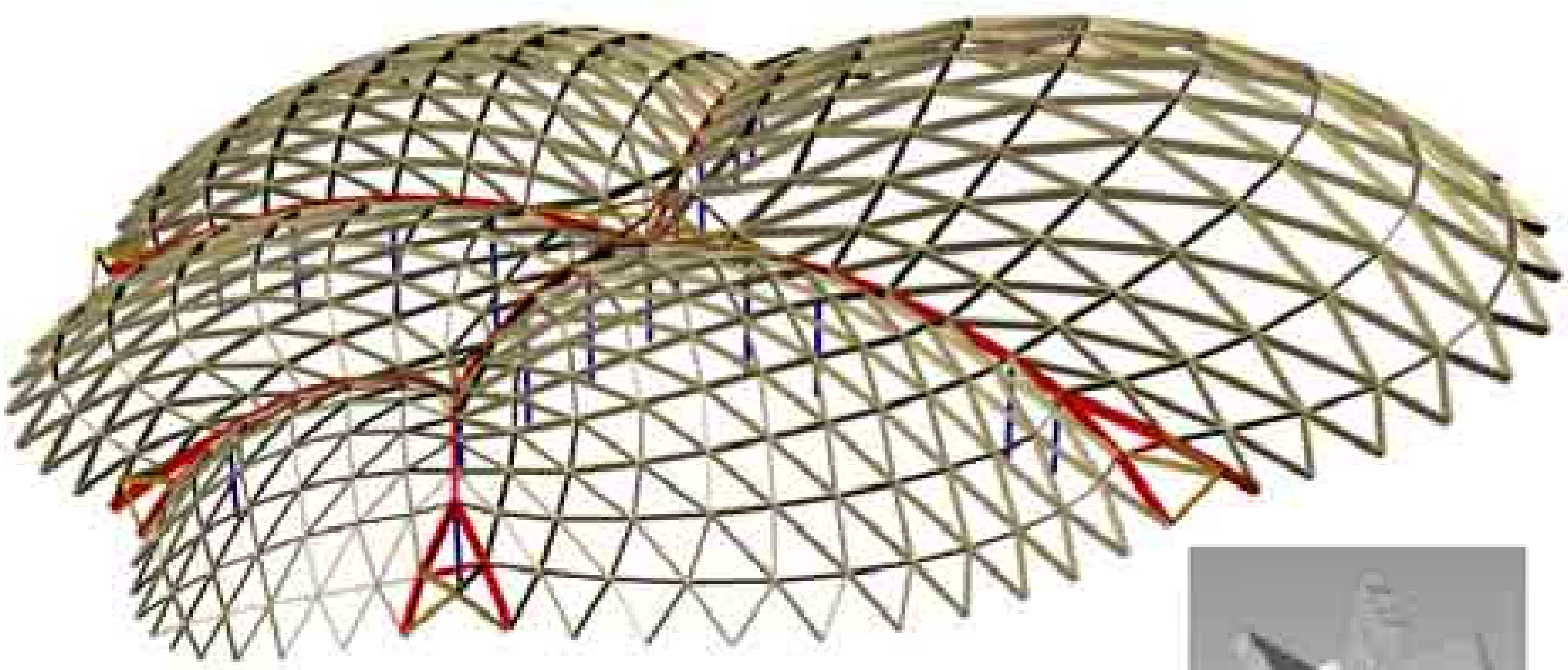


The Structural Solution - Roof

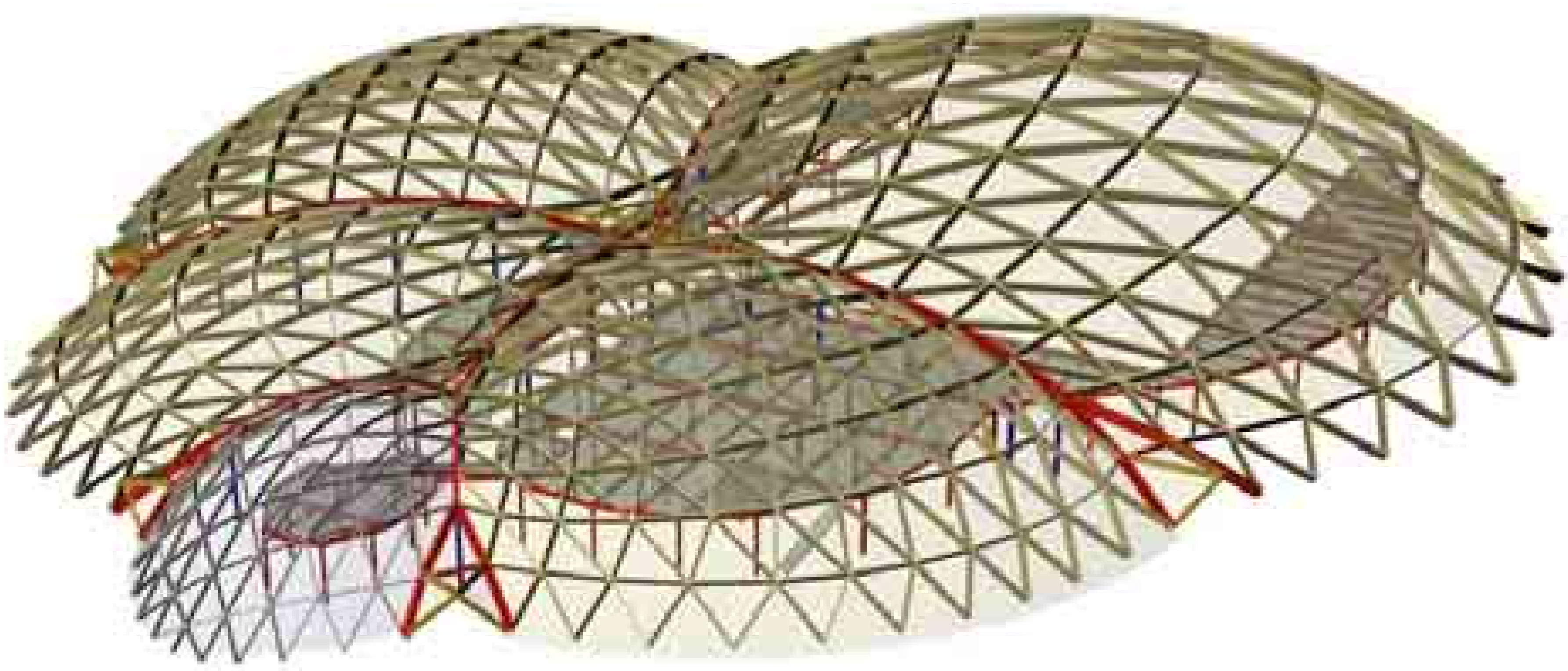




The Structural Solution - Roof



The Structural Solution



The Structural Solution - Cladding