

**A few key facts**

- Building dimensions 177m x 177m x 30m
- 140mx120m main span
- 40m and 60m back-span on two sides
- Structure is cellular moment frame - no triangulation!
- 22000 beams and 190 load combinations
- 37 different beam sizes used
- Seismic design and detailing required
- Strength governs the design

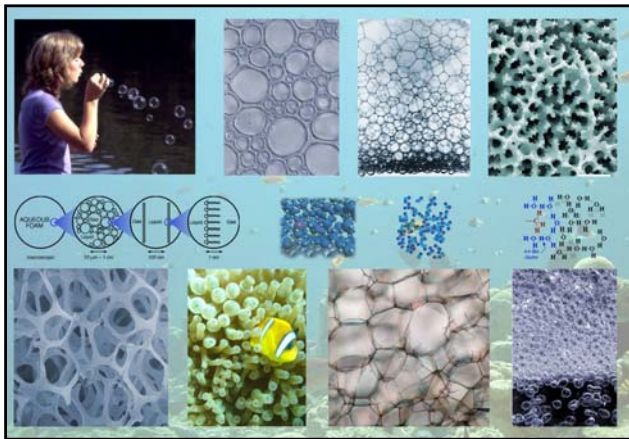
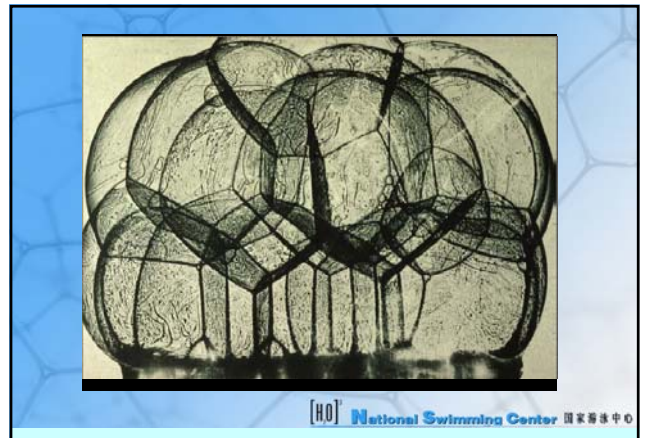
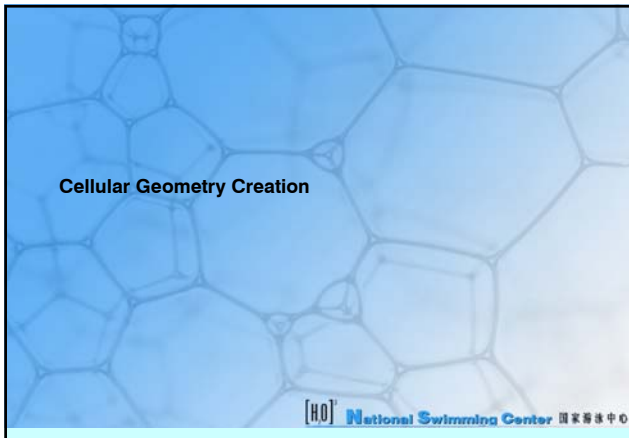
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**Design Timeframe**

Total Project Design Time = 7 months

DESIGN STAGES	Aug 07	Sept 07	Oct 07	Nov 07	Dec 07	Jan 08	Feb 08	Mar 08	Apr 08	May 08	Jun 08	Jul 08
Concept Development (2 wks)												
Design Development (3.5 mo)												
Construction Documents (12 wks)												
Construction (20.5 mo)												

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**Foam Theory**

- Lord Kelvin posed question and solution in 1887
- Weaire-Phelan Solution only 0.3% better in 1993

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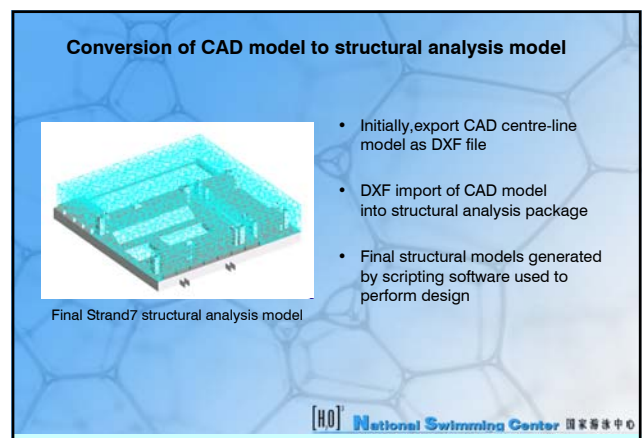
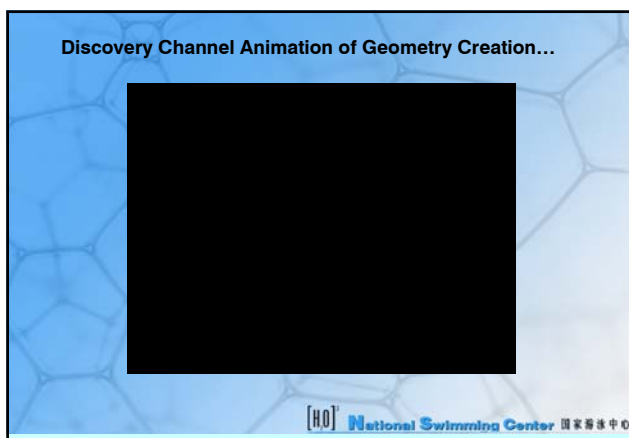
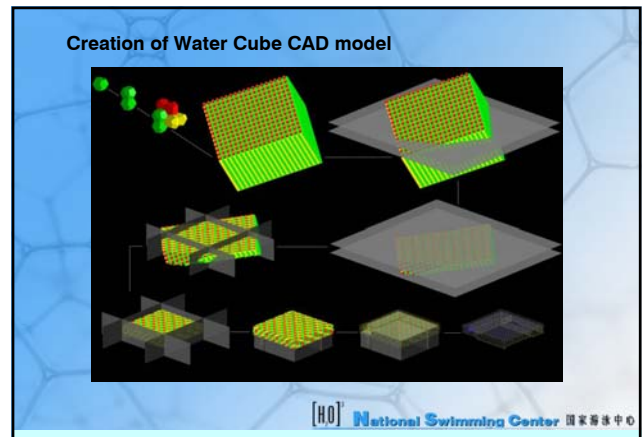
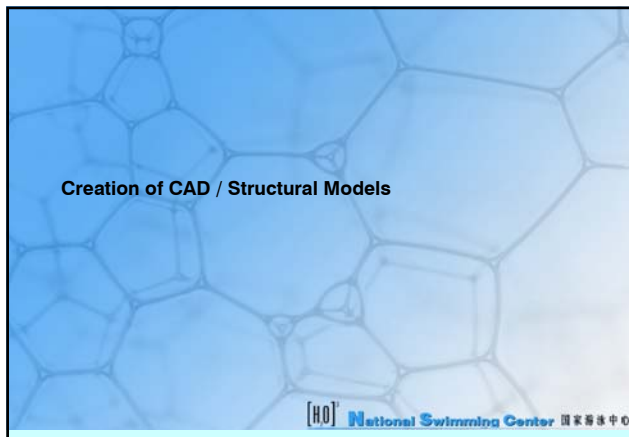
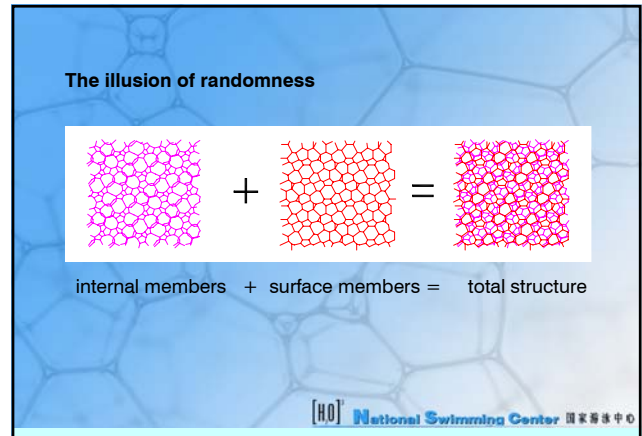
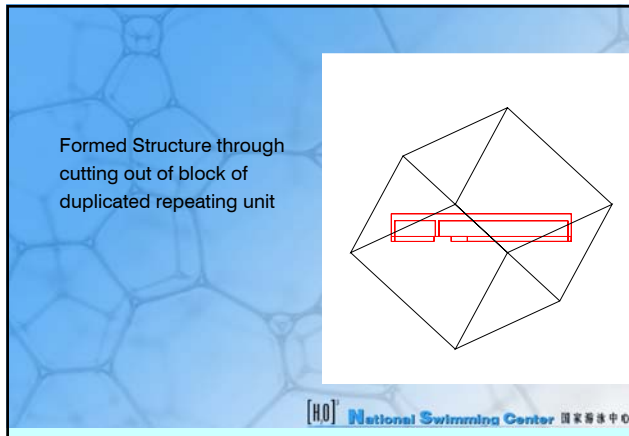
**The repeating unit**

- Cells: 12-sided polyhedron  
14-sided polyhedron
- Translation Unit:  
2X12-sided polyhedron  
+6X14-sided polyhedron

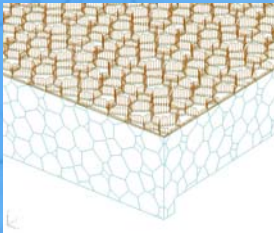
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- Duplicate the Weaire-Phelan repeating unit
- Rotate 60° around vector  $(0,0,0) \rightarrow (1,1,1)$

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### Application of structural loadings



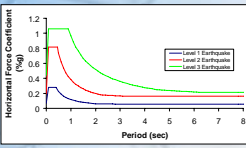
- Define pressures on façade surfaces
- Complex loading on steel from Façade ETFE pillows
- Automatic conversion of pressures to distributed beam loads
- 750,000 beam loads in 55 basic load cases

Beam distributed loads created

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### Structural loadings

- Steel self weight
  - Member weight
  - Node weight
- Superimposed dead load
  - Down cases (0.54kPa)
  - Uplift cases (0.15kPa)
- Live load (0.3kPa)
  - Uniform
  - Out of Balance cases
- Snow Load (0.45kPa)
  - Uniform
  - Out of Balance cases
- Wind Load
  - 100 year, 10min avg, h=10m
  - $q_w = 0.5kPa$  basic wind pressure
  - Roof pressure = +0.17 kPa ult
- Seismic Load
  - Level 1 (pga=0.07g, Tg=0.45s)
  - Level 2 (pga=0.20g, Tg=0.45s)
  - Level 3 (pga=0.44g, Tg=0.90s)



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### Structural Design Issues and Methods

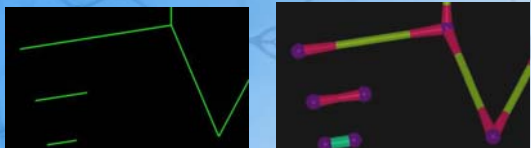
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### Structural design issues and methods – Key topics

- CAD automation, visualisation and documentation
  - Rapid prototyping visualisation
- Structural design automation
- Global structure optimisation
- Cross section optimisation
- Seismic modal analysis

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### CAD automation and visualisation – Competition stage

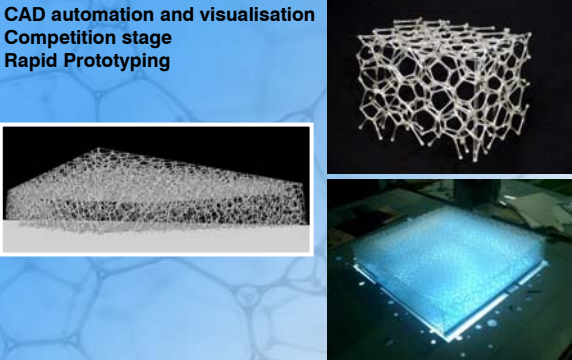


Centre-line CAD model. Tags define beam sizes from structural analysis

CAD visualisation of beam sizes using VBA Scripting

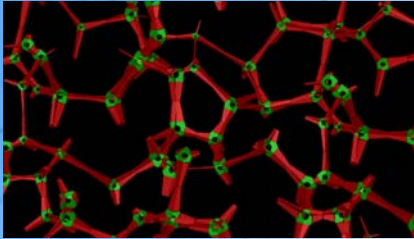
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### CAD automation and visualisation Competition stage Rapid Prototyping

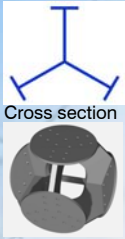


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### CAD automation and visualisation – Design stage options



Partially run CAD VBA script



Cross section  
Connection

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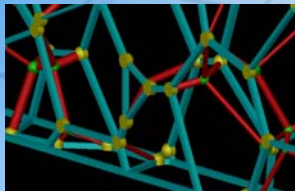
### CAD automation and visualisation – Final VBA scripting

```

Exported from Strand 7 for input into Microstation vba script
TotalNodes 10001
TotalEdges 21007
TotalFlags 507
NodeType 500

MODEL
1 00200.00 -13002.74 9216.177
2 00210.00 -10728.000 9216.177
3 00220.00 -10015.4 9216.180
4 00230.00 -9302.8 9216.183
5 00240.00 -8590.2 9216.186
6 00250.00 -7877.6 9216.189
7 00260.00 -7165.0 9216.192
8 00270.00 -6452.4 9216.195
9 00280.00 -5739.8 9216.198
10 00290.00 -5027.2 9216.201
11 00300.00 -4314.6 9216.204
12 00310.00 -3602.0 9216.207
13 00320.00 -2889.4 9216.210
14 00330.00 -2176.8 9216.213
15 00340.00 -1464.2 9216.216


```



- Member sizes set from Structural Analysis
- Node size, type, & orientation set by VBA scripting
- All CAD and VBA scripting performed on project

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### Automated Tender documentation delivery

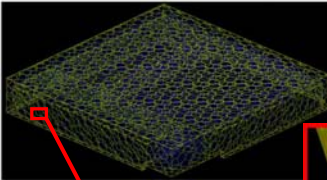
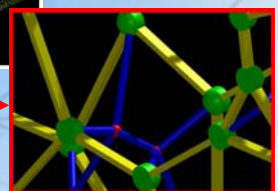


Node Number	Node Type	Radius	Sphere (or Hemisphere) Thickness	Cylinder and Top/Bottom Plate Thickness
1	1 External (Sphere+Cylinder)	411.75	17.55	13
2	2 External (Sphere+Cylinder)	411.75	13.5	10
3	3 Internal (Sphere)	210.025	9.45	-
4	4 Internal (Sphere)	210.025	12.55	-
5	5 External (Sphere+Cylinder)	411.75	17.55	13
6	6 External (Sphere+Cylinder)	411.75	17.55	13
7	7 Internal (Sphere)	211.35	14.55	-

- Drawings created by VBA scripting
- 3000+ lines of VBA code in Microstation
- Approx 25 minutes run-time
- Creates 30Mb CAD file
  - Members drawn and trimmed for connections
  - Connections drawn
  - Members tagged with design information
- Excel spreadsheet of node connections data

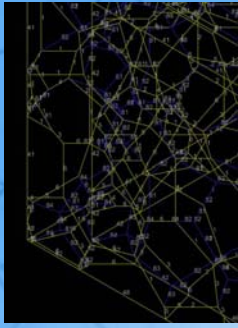
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### Microstation 3d CAD model generated for Tender

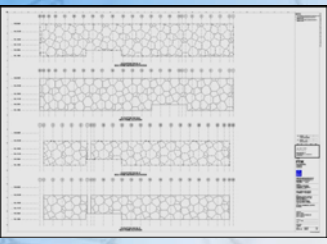



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### Microstation wireframe 3d CAD model generated for Tender

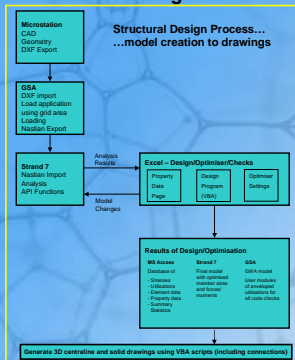


- Wireframe tagged with design information
- 2d drawings created from 3d CAD models



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### Structural design automation developed on Project



```

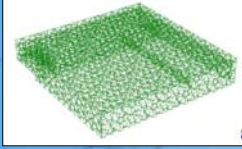
Microstation CAD Geometry DXF Export
  |
  v
GSA DXF Import Load application using grid area Loading Nasion Export
  |
  v
Strand 7 Nasion Import Analysis API Functions
  |
  v
Excel - Design/Optimise/Checks
  |
  v
Results of Design/Optimization
  |
  v
Generate 3D centreline and solid drawings using VBA scripts (including connections)

```

- Produce complete Tender design documents for steel superstructure in only 7 months
- To meet the Tender issue date design options need fast and reliable assessment methods.
- Automation/integration of Structural Design and CAD drawings ensured :
  - Rapid design option assessment
  - CAD drawings consistent with structural design
- Other benefits
  - 3d CAD visualisation of design solution
  - Rigorous structural design/optimisation
  - Confidence in design solution

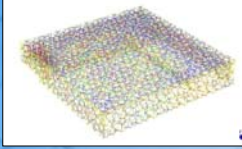
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### Global structure optimisation process (Constraint satisfaction)



- Too many variables for gradient optimisation methods (22000 beam size variables)
- Large number of constraints (Chinese design code) (22000 beam sizes) x (190 load cases) x (11 code equations) Total constraints = 230 million
- Not all constraints are active
- Structural design governed by strength requirements
- Try to choose beam sizes to satisfy all constraints
- CONSTRAINT SATISFACTION USED FOR DESIGN
- Setup automated design/optimisation routines to find beam sizes that satisfy all constraints

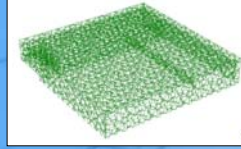
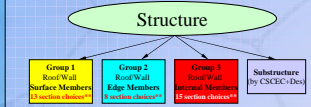
All members start in one of 3 groups...



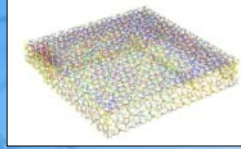
...Member selections after optimisation process.

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### Global structure optimisation process (Constraint satisfaction)

All members start in one of 3 groups...


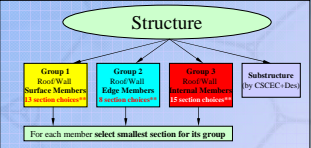


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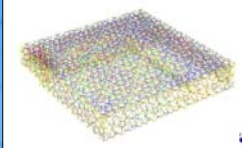
**\*\* Cross section choices determined by maximising strength/mass ratio**

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All members start in one of 3 groups...


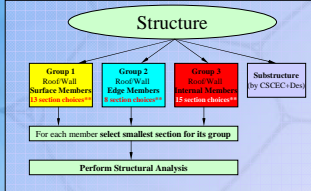


...Member selections after optimisation process.

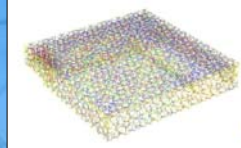
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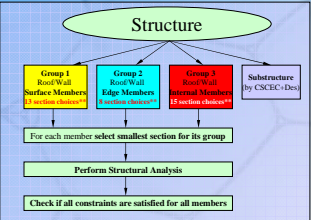


...Member selections after optimisation process.


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All members start in one of 3 groups...


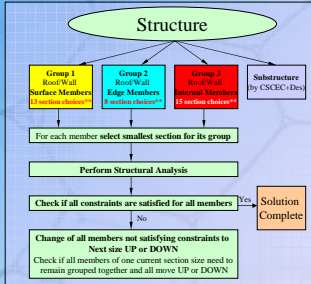


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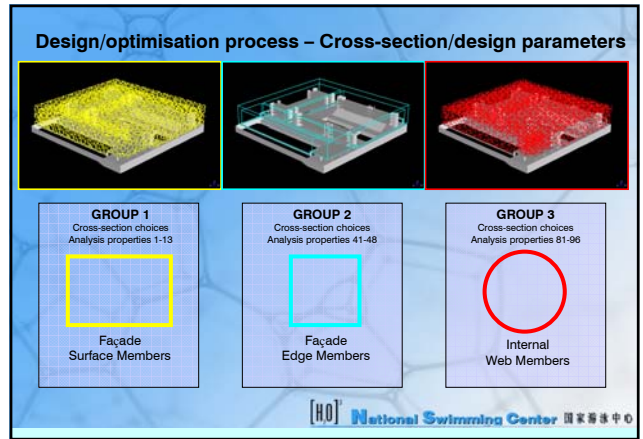
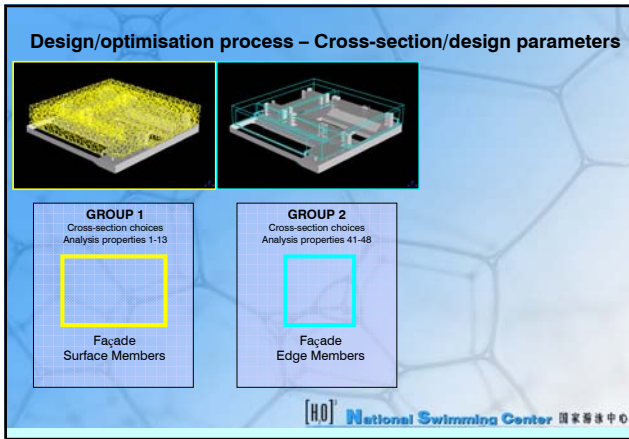
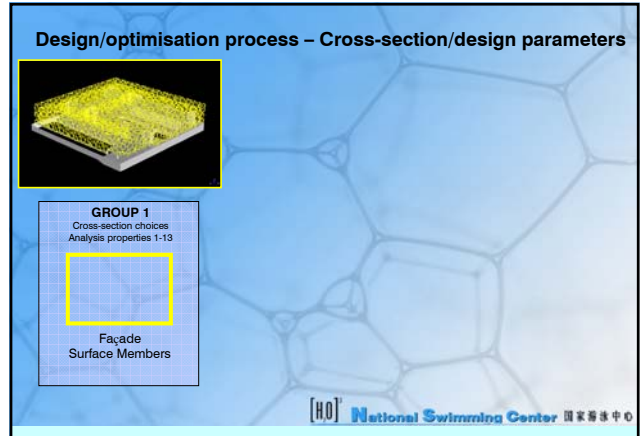
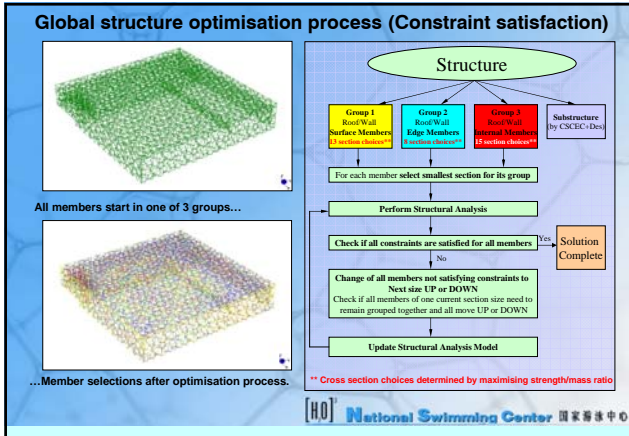
All members start in one of 3 groups...



...Member selections after optimisation process.

**\*\* Cross section choices determined by maximising strength/mass ratio**

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### Design/optimisation process – Cross-section/design parameters

GENERAL DATA		GENERAL TECHNOLOGY				GENERAL		STRUCTURE				LIMIT			
STRANDY PROPERTY	GROUP OR PROPERTY DESCRIPTION	Material Type	σ <sub>yk</sub> /N/mm <sup>2</sup>	E/10 <sup>4</sup> /N/mm <sup>2</sup>	ρ <sub>k</sub> /%	ρ <sub>s</sub> /%	ρ <sub>l</sub> /%	ρ <sub>l,lim</sub> /%	ρ <sub>l,max</sub> /%	ρ <sub>l,min</sub> /%	ρ <sub>l,max</sub> /%	ρ <sub>l,min</sub> /%	ρ <sub>l,max</sub> /%	ρ <sub>l,min</sub> /%	ρ <sub>l,max</sub> /%
1	S500 300 x 110 x 6 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
2	S500 300 x 110 x 7 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
3	S500 300 x 110 x 8 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
4	S500 300 x 110 x 9 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
5	S500 300 x 110 x 10 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
6	S500 300 x 110 x 11 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
7	S500 300 x 110 x 12 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
8	S500 300 x 110 x 13 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
9	S500 300 x 110 x 14 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
10	S500 300 x 110 x 15 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
11	S500 300 x 110 x 16 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
12	S500 300 x 110 x 17 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
13	S500 300 x 110 x 18 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
14	S500 300 x 110 x 19 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
15	S500 300 x 110 x 20 RHBS	SM490	490	205	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25

STRANDY PROPERTY	Steel Grade	Min Property	Max Property
1	S500	1.25	1.25
2	S500	1.25	1.25
3	S500	1.25	1.25
4	S500	1.25	1.25
5	S500	1.25	1.25
6	S500	1.25	1.25
7	S500	1.25	1.25
8	S500	1.25	1.25
9	S500	1.25	1.25
10	S500	1.25	1.25
11	S500	1.25	1.25
12	S500	1.25	1.25
13	S500	1.25	1.25
14	S500	1.25	1.25
15	S500	1.25	1.25

GROUP 1	GROUP 2	GROUP 3
Cross-section choices Analysis properties 1-13	Cross-section choices Analysis properties 41-48	Cross-section choices Analysis properties 81-96
Façade Surface Members	Façade Edge Members	Internal Web Members

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### Design/optimisation process – Cross-section Choice Controls

Strandy/Original Element Property	Element Group Description	Min Property Number to choose from	Max Property Number to choose from	Max Allowable Utilisation to limit to	Lower target limit of Utilisation before reducing property	Keep Property Together (Y/N)
1	S500 300 x 110 x 6 RHBS	1	13	0.8	0.4	Y
2	S500 300 x 110 x 7 RHBS	1	13	0.8	0.4	Y
3	S500 300 x 110 x 8 RHBS	1	13	0.8	0.4	Y
4	S500 300 x 110 x 9 RHBS	1	13	0.8	0.4	Y
5	S500 300 x 110 x 10 RHBS	1	13	0.8	0.4	Y
6	S500 300 x 110 x 11 RHBS	1	13	0.8	0.4	Y
7	S500 300 x 110 x 12 RHBS	1	13	0.8	0.4	Y
8	S500 300 x 110 x 13 RHBS	1	13	0.8	0.4	Y
9	S500 300 x 110 x 14 RHBS	1	13	0.8	0.4	Y
10	S500 300 x 110 x 15 RHBS	1	13	0.8	0.4	Y
11	S500 300 x 110 x 16 RHBS	1	13	0.8	0.4	Y
12	S500 300 x 110 x 17 RHBS	1	13	0.8	0.4	Y
13	S500 300 x 110 x 18 RHBS	1	13	0.8	0.4	Y
14	S500 300 x 110 x 19 RHBS	1	13	0.8	0.4	Y
15						
16						
17						
18						
19						
20						

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### Design/optimisation process - Seismic ductility factor control

Category Num	Category Name	Min Property	Max Property	Active (Y/N)
1	Roof Box Sections	1	13	Y
2	Wall Box Sections	41	48	Y
3	CHS webs	81	96	Y
4				N

← Beam categories of unique seismic ductility factor defined by Strand7 Property

LOAD COMBINATION	1	2	3	4
Category num	Roof Box Sections Ductility Factor	Wall Box Sections Ductility Factor	CHS webs Ductility Factor	Ductility Factor
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1

186	3	3	3	1
187	3	3	3	1
188	3	3	3	1
189	3	3	3	1
190	3	3	3	1

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### Design/optimisation process - Seismic ductility factor control

Category Num	Category Name	Min Property	Max Property	Active (Y/N)
1	Roof Box Sections	1	13	Y
2	Wall Box Sections	41	48	Y
3	CHS webs	81	96	Y
4				N

← Beam categories of unique seismic ductility factor defined by Strand7 Property

LOAD COMBINATION	1	2	3	4
Category num	Roof Box Sections Ductility Factor	Wall Box Sections Ductility Factor	CHS webs Ductility Factor	Ductility Factor
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1

← Each category has ductility factor defined for each load combination  
R=1 for non-seismic cases

186	3	3	3	1
187	3	3	3	1
188	3	3	3	1
189	3	3	3	1
190	3	3	3	1

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### Design/optimisation process - Seismic ductility factor control

Category Num	Category Name	Min Property	Max Property	Active (Y/N)
1	Roof Box Sections	1	13	Y
2	Wall Box Sections	41	48	Y
3	CHS webs	81	96	Y
4				N

← Beam categories of unique seismic ductility factor defined by Strand7 Property

LOAD COMBINATION	1	2	3	4
Category num	Roof Box Sections Ductility Factor	Wall Box Sections Ductility Factor	CHS webs Ductility Factor	Ductility Factor
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1

← Each category has ductility factor defined for each load combination  
R=1 for non-seismic cases

186	3	3	3	1
187	3	3	3	1
188	3	3	3	1
189	3	3	3	1
190	3	3	3	1

← Seismic load combinations  
Ductility factor R=3

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### Design/optimisation process - Seismic ductility factor control

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← Seismic load combinations  
Ductility factor R=3

Automated Forced Reduction in Design/optimisation process

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### Automated structural analysis and design/optimisation tool developed by Arup

Design Checks and optimisation for Chinese Steel Code GB50017-2003

START CHINESE STEEL CHECK/OPTIMISER

- Control page calls VBA code
- Complete integration and automation of:
  - VBA design code (Excel)
  - Analysis (Strand7)
  - Calculations (MS Access)
- 12000 lines of VBA code
- Full design/optimisation run takes 2 days
- Outputs are:
  - Final structural model
  - Full calculation set
  - Input data for CAD VBA scripts to generate drawings

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### Optimised solution convergence

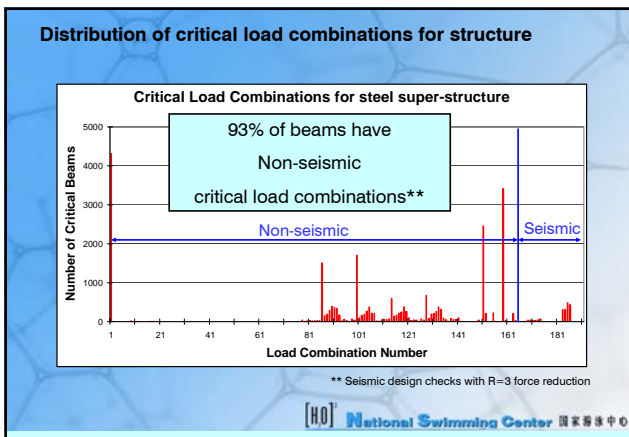
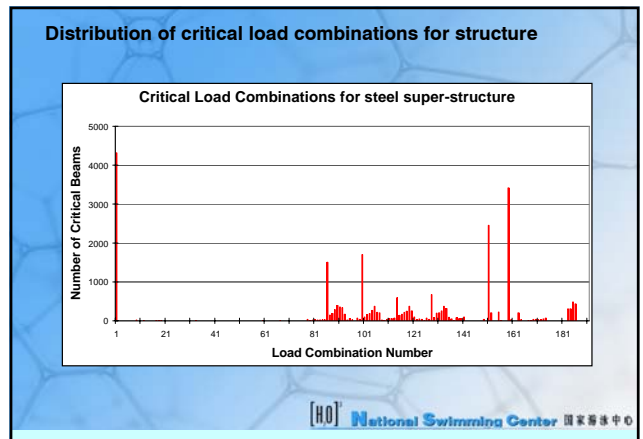
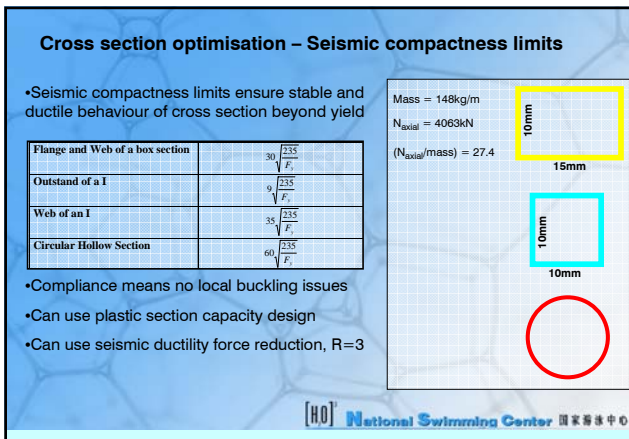
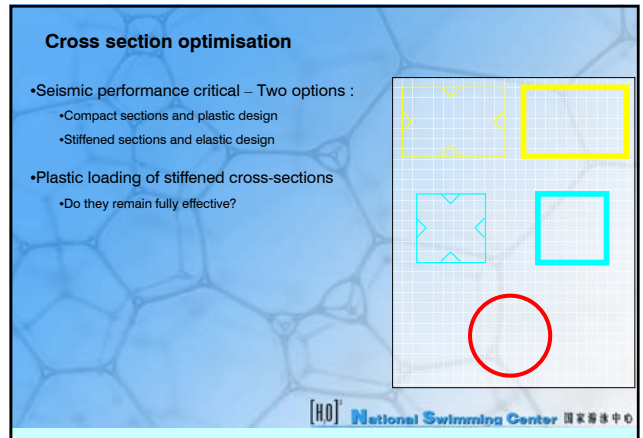
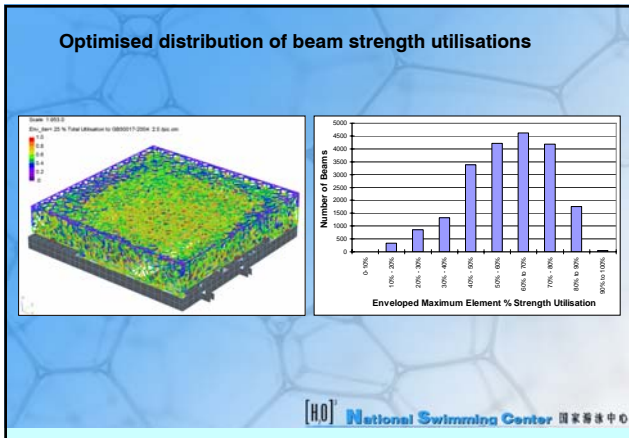
•Solution is sensitive to:

- starting position
- cross-section choices
- utilisation limits

•Minimum tonnage from:

- starting at minimum possible weight
- using optimised cross-section choices
- maximising utilisation limits

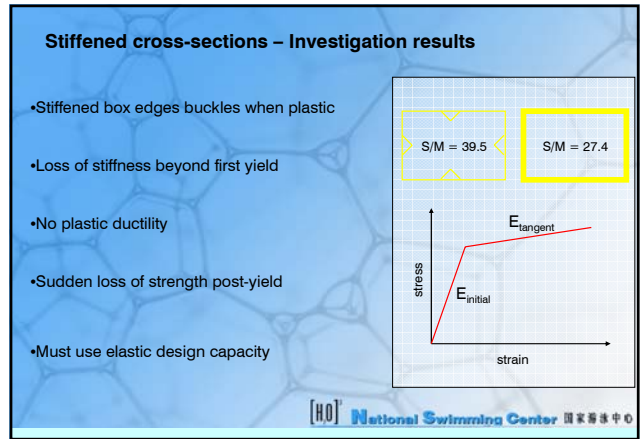
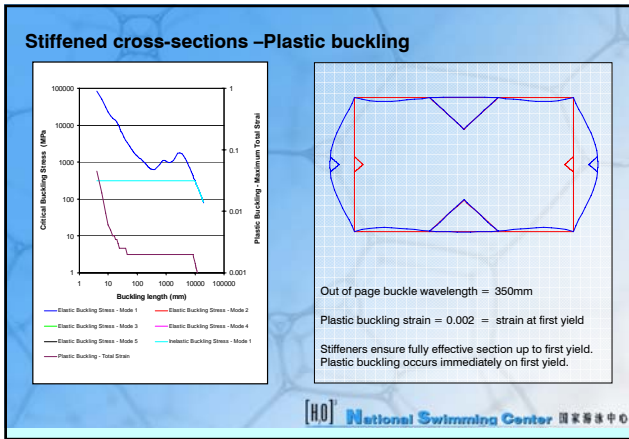
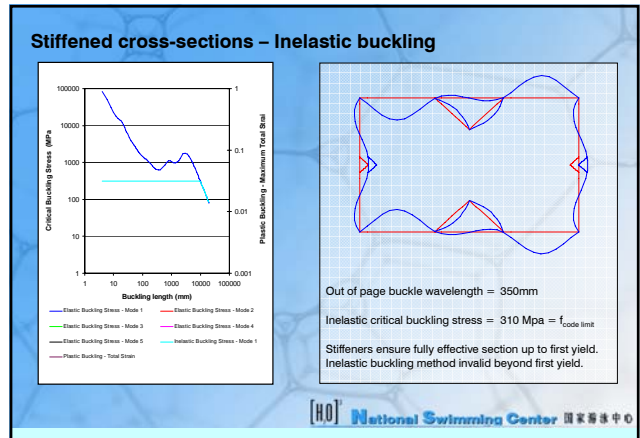
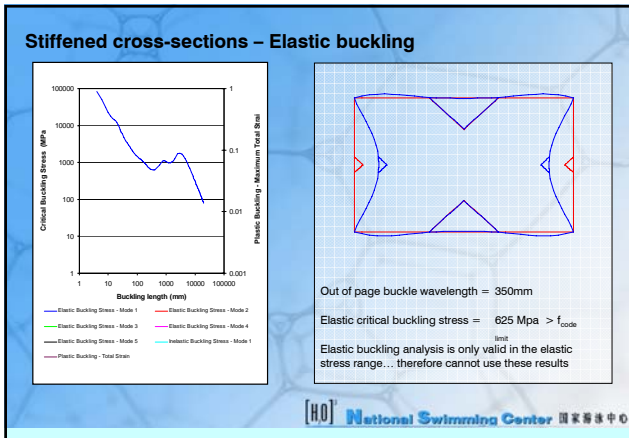
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### Could we use longitudinally stiffened cross-sections?

- Potential steel-tonnage savings, but...
- What are the design implications?

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### Cross-section optimisation study conclusions

- Stiffener steel tonnage saving not enough
- Cannot design stiffeners plastically
- Stiffener fabrication more complex and costly
- Locked in construction stresses important.... Ideally want ductility for force redistribution
- Final tender design adopted compact cross-sections

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### Modal dynamic analysis to determine seismic design forces

- Investigated super-structure sensitivity to sub-structure stiffness variation
- Final super-structure Tender design included CSCEC+Design sub-structure
- Response spectrum analysis performed (90% mass participation from 4424 modes)

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