Application of Evolutionary Structural Optimization to Architectural Design

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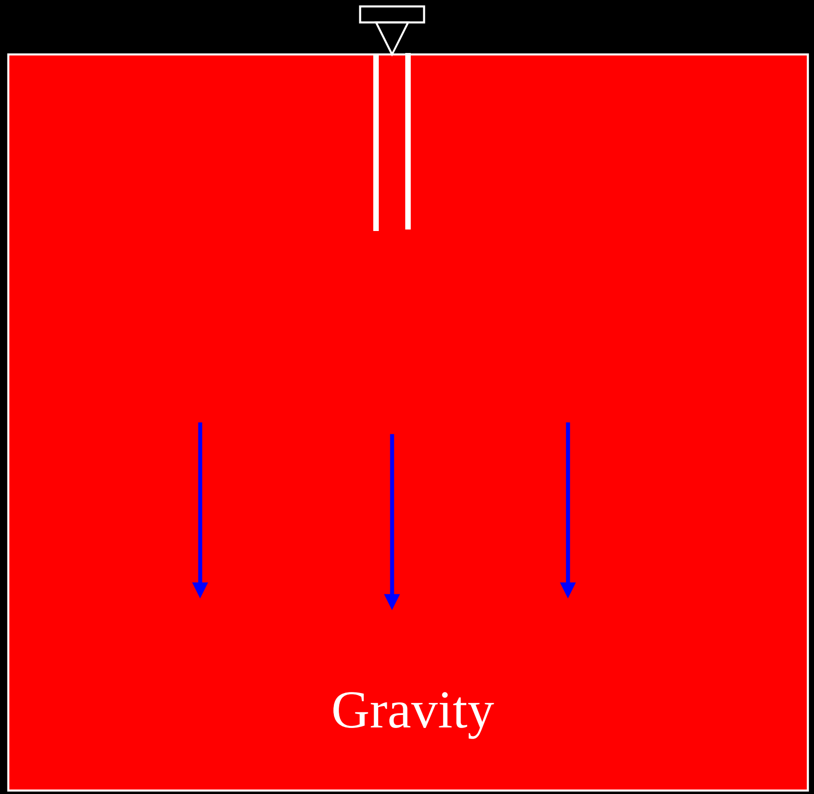
RMIT UNIVERSITY

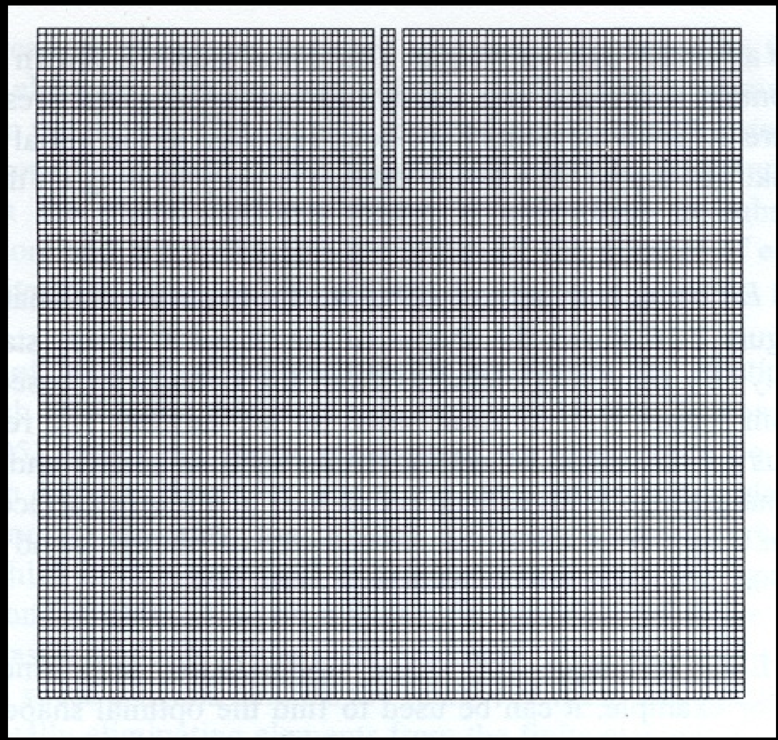
Evolutionary Structural Optimization (ESO)

- The Evolutionary Structural Optimization (ESO) technique, originally proposed in 1992 by Mike Xie and co-workers, was based on the simple concept of gradually removing unnecessary or inefficient material from a structure to achieve an optimum design
- The ESO method can be easily implemented and linked with existing structural analysis and CAD software packages (e.g. Abaqus, Ansys, Nastran, Strand7, Rhinoceros)

An ESO Example

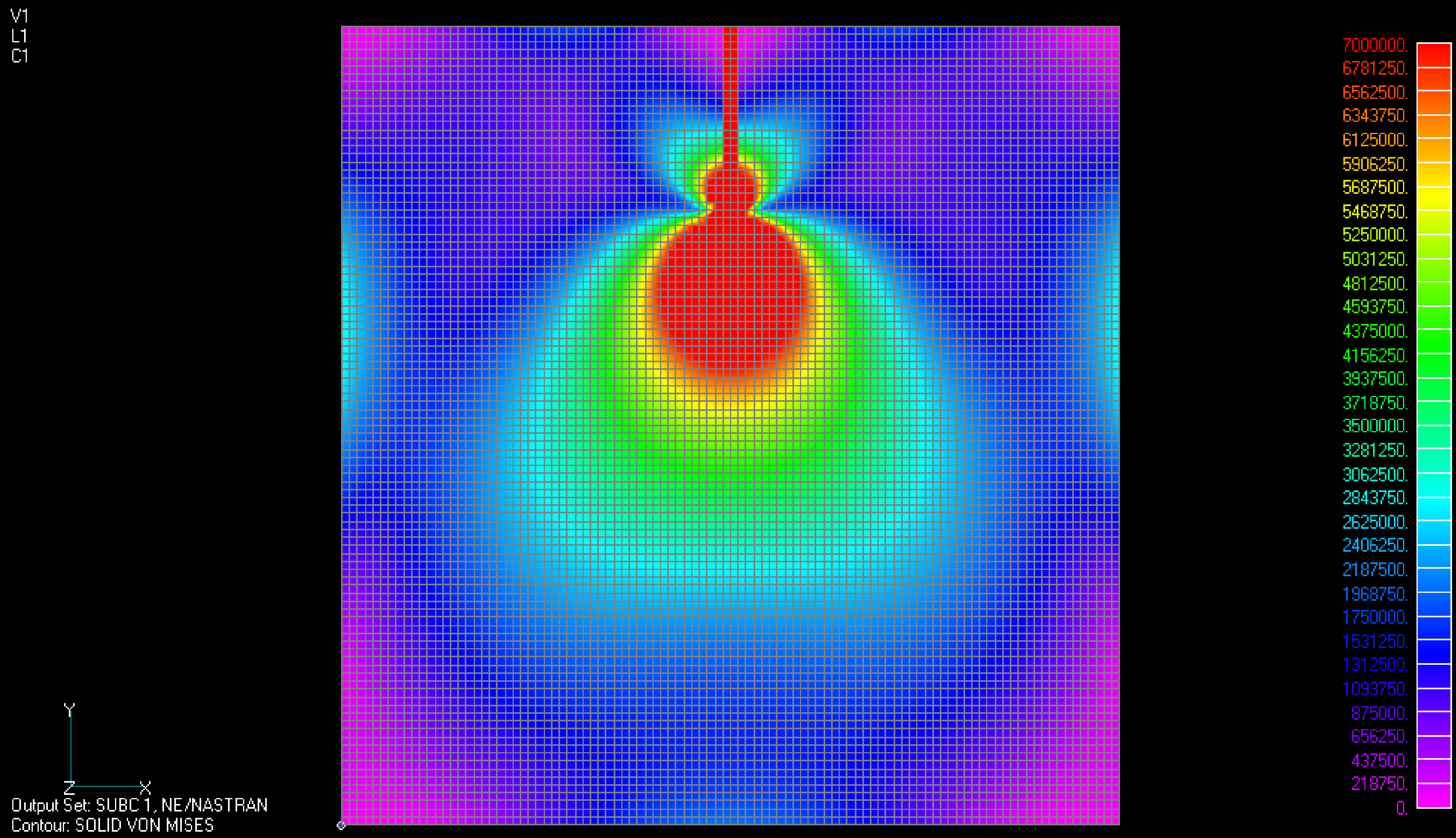


A hanging object under gravity

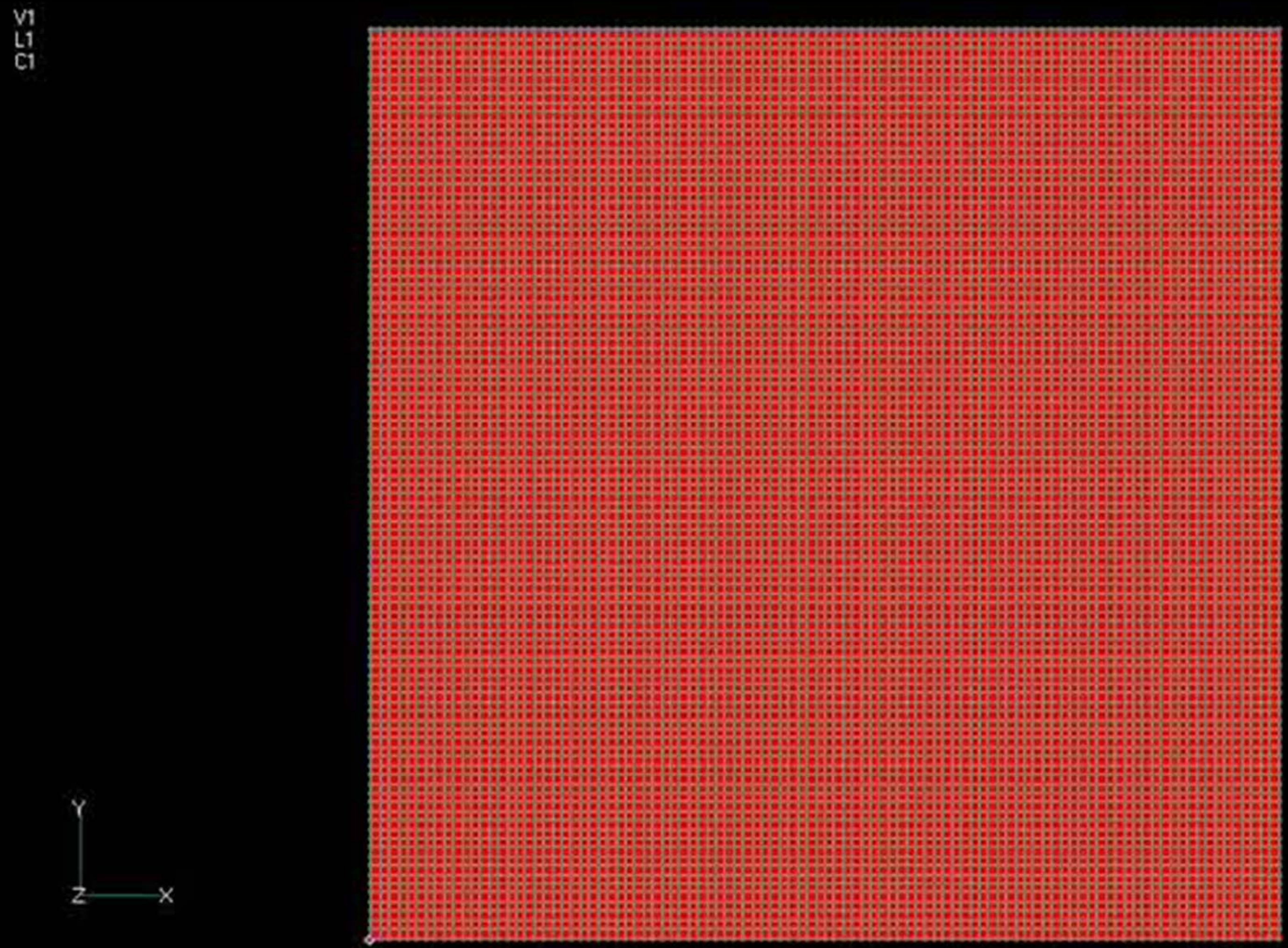


Finite Element Mesh

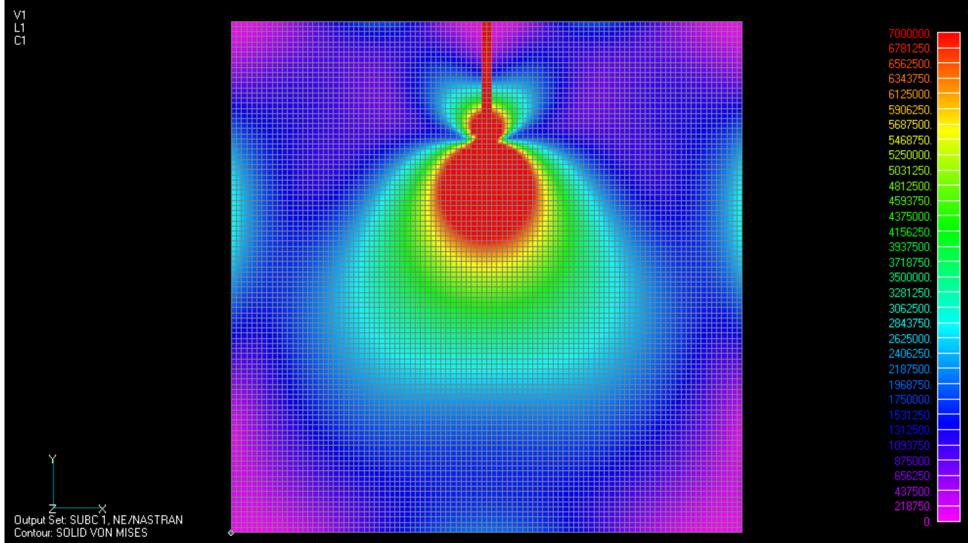
Stress Distribution of the Hanging Object

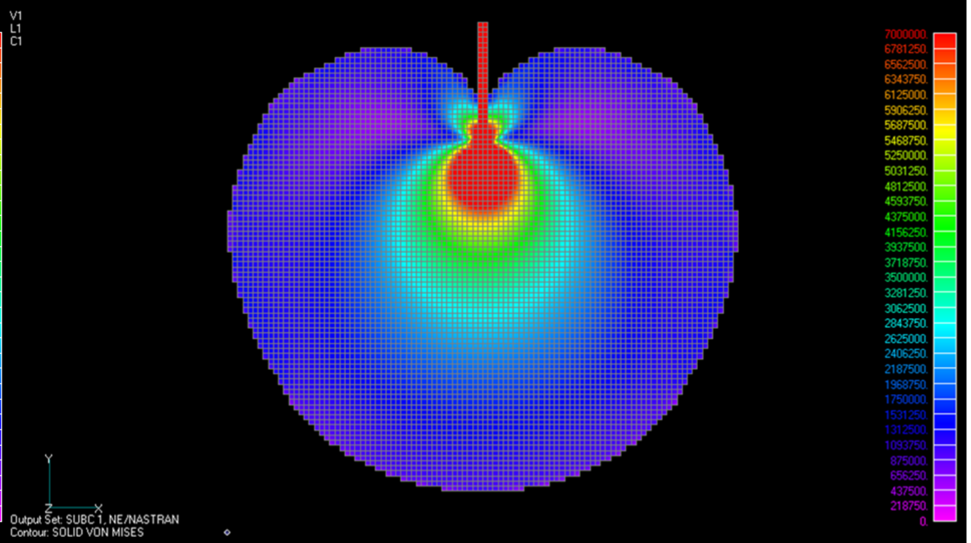


Evolution of the Hanging Object



Comparison of Stress Distributions





General Applicability of ESO

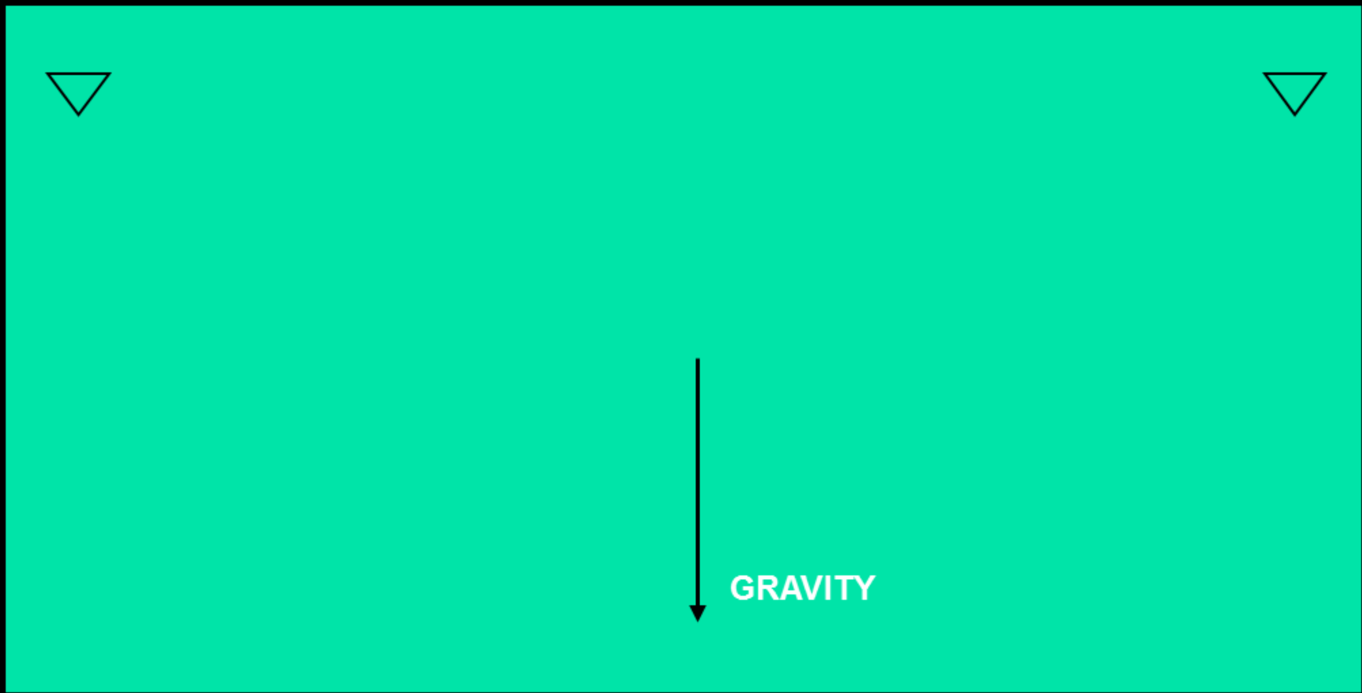
ESO has been successfully applied to a wide range of engineering optimization and architectural design problems, including:

- *maximizing stiffness*
- *minimizing displacement*
- *maximizing natural frequency*
- *maximizing buckling load*
- *minimizing temperature in heat transfer*
- *minimizing contact stresses, etc.*

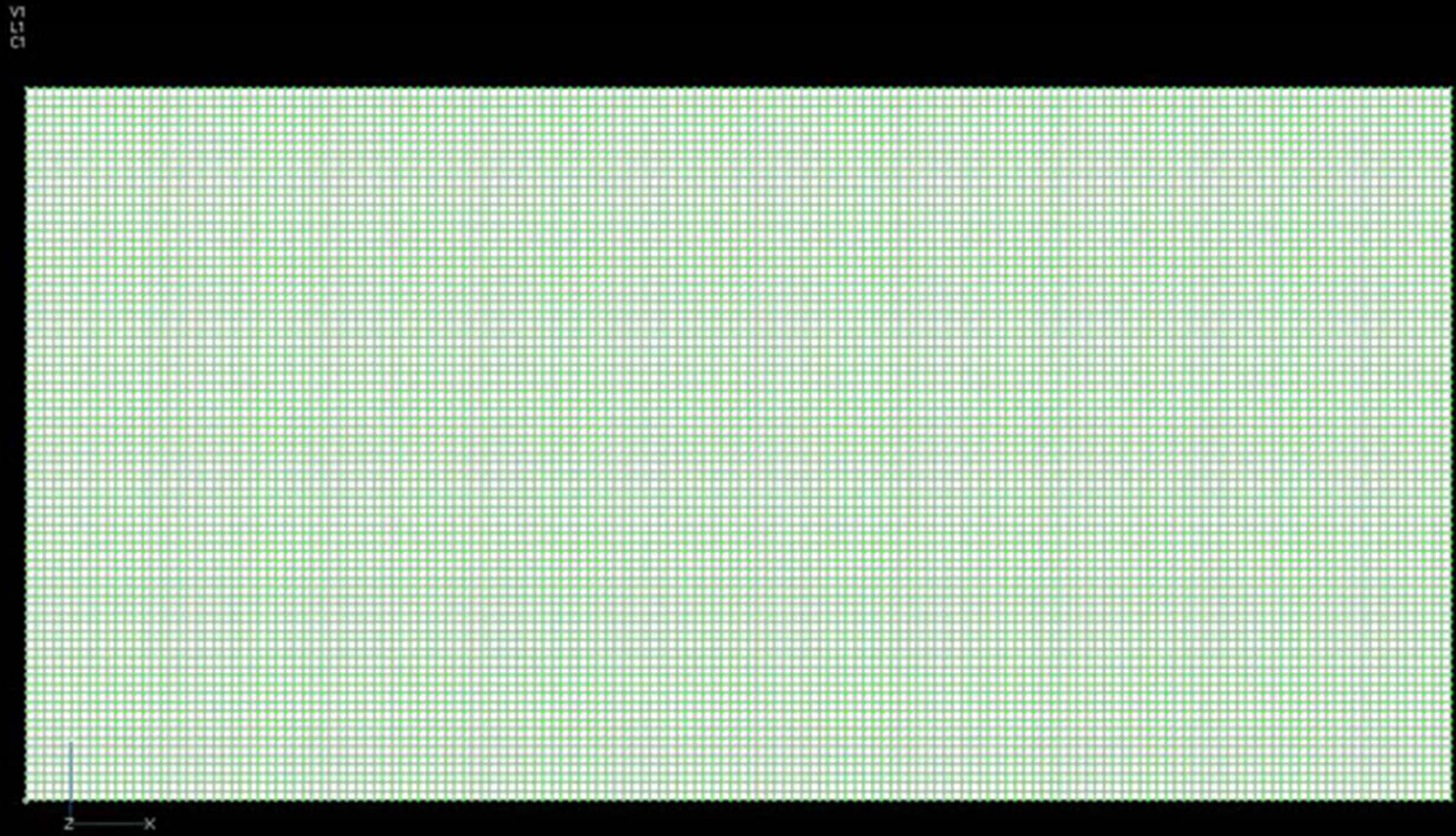
Design for Tension-only Structure

Elements with the highest compressive stresses will be deleted from the structure step-by-step

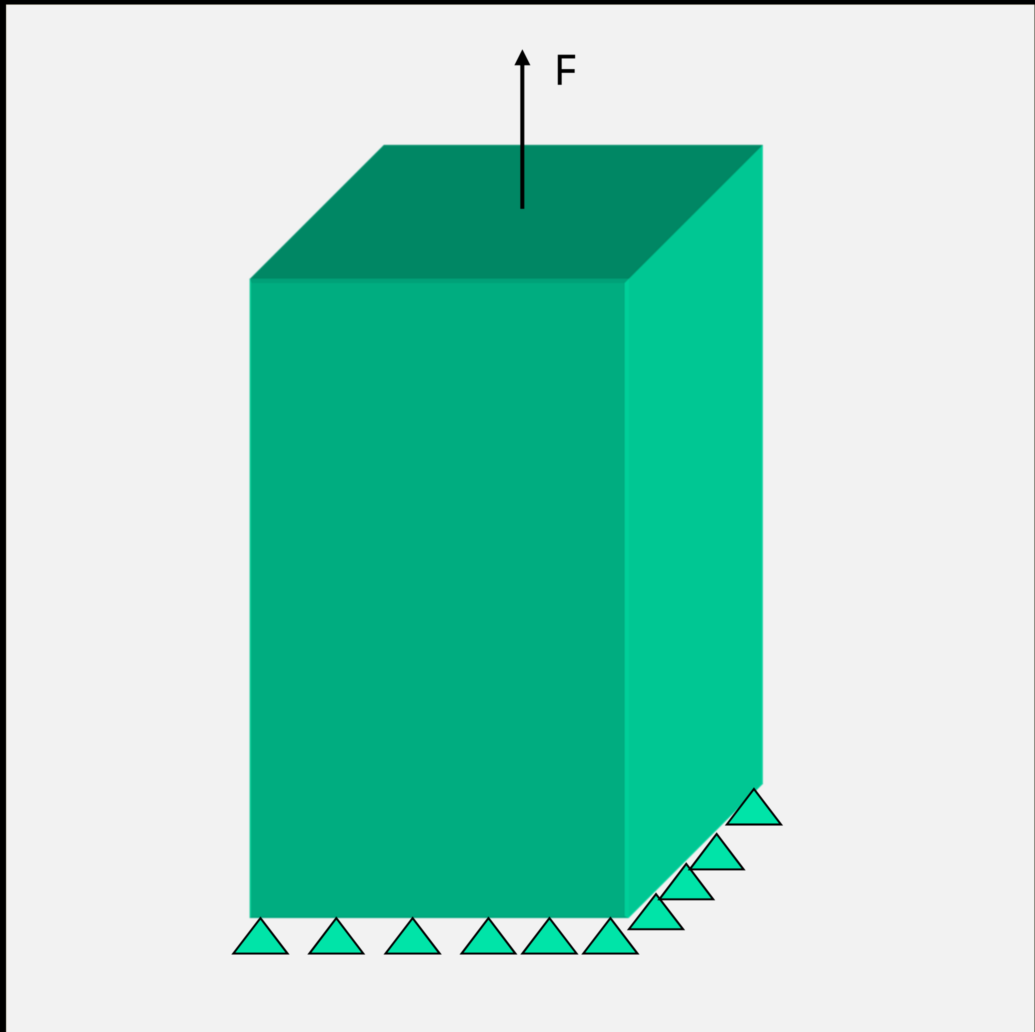
An Example of Tension-only Structure: Catenary



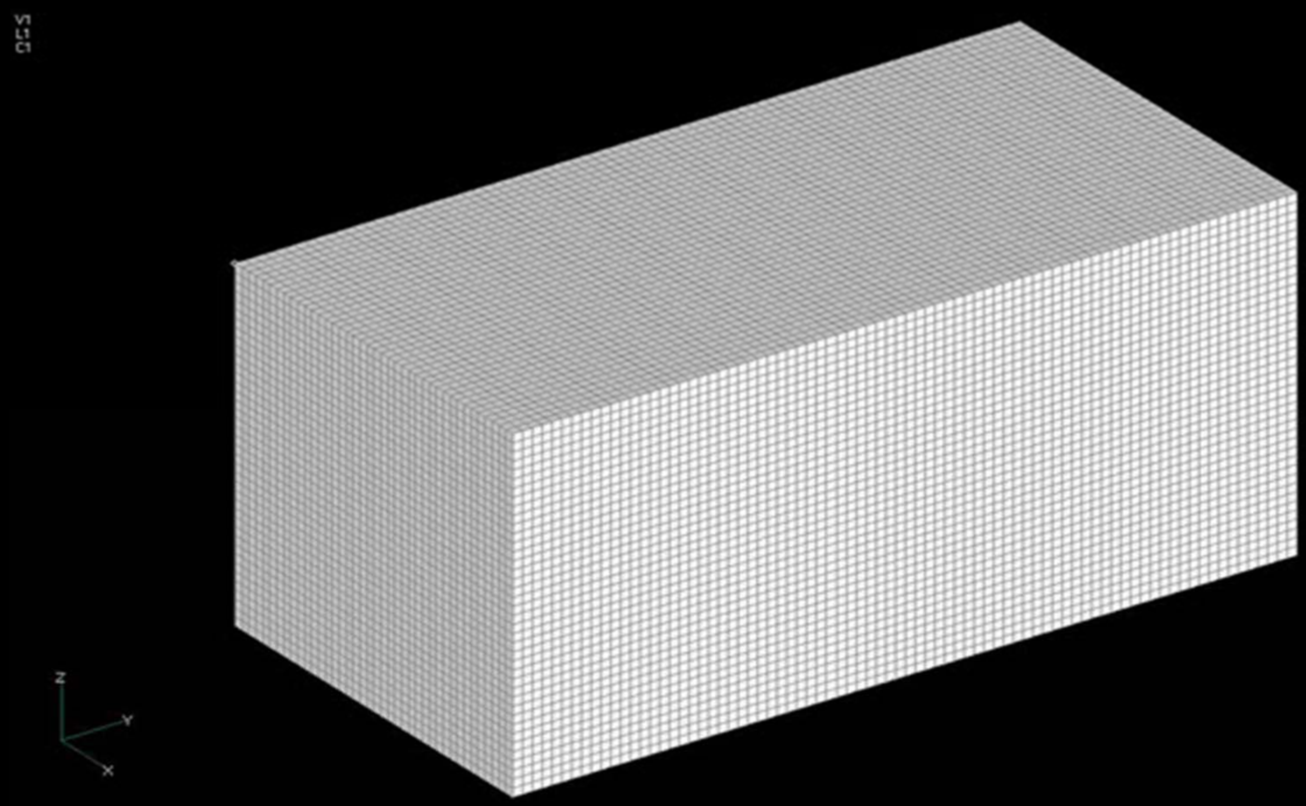
Evolution of a Catenary



A 3D Tensile Example



Evolution of a 3D Tensile Structure



Design for Compression-only Structure

Elements with the highest tensile stresses will be deleted from the structure step-by-step

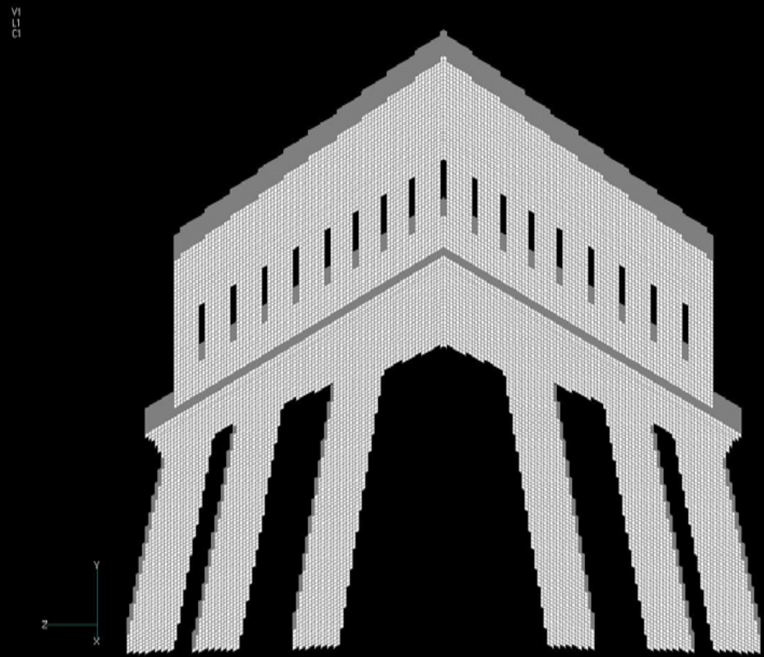
Example of Compression-only Structure

Sagrada Familia Church Façade
Barcelona, Spain

Antonio Gaudi's hanging
chain model

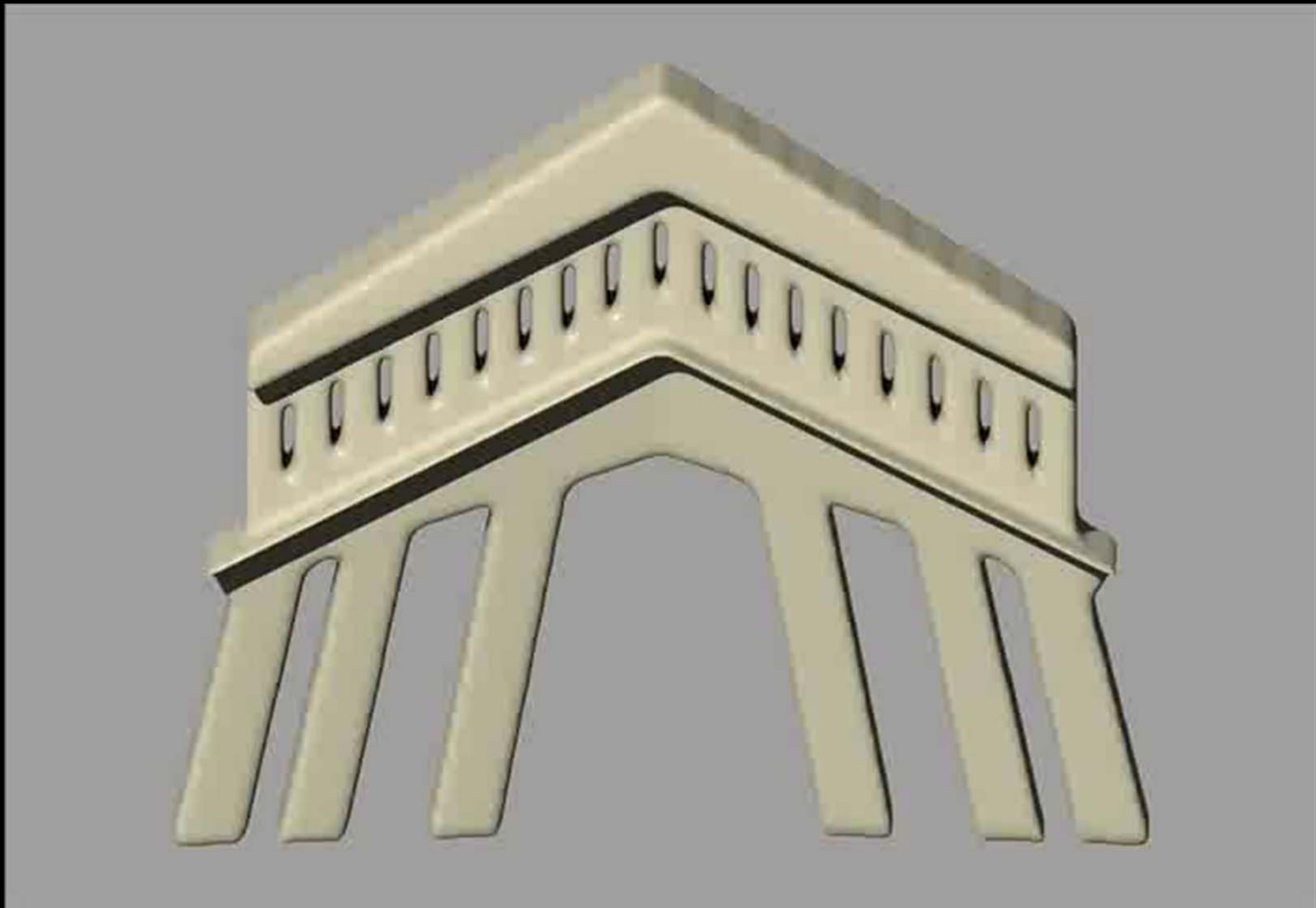
Example of Compression-only Structure

Sagrada Familia Church Façade
Barcelona, Spain

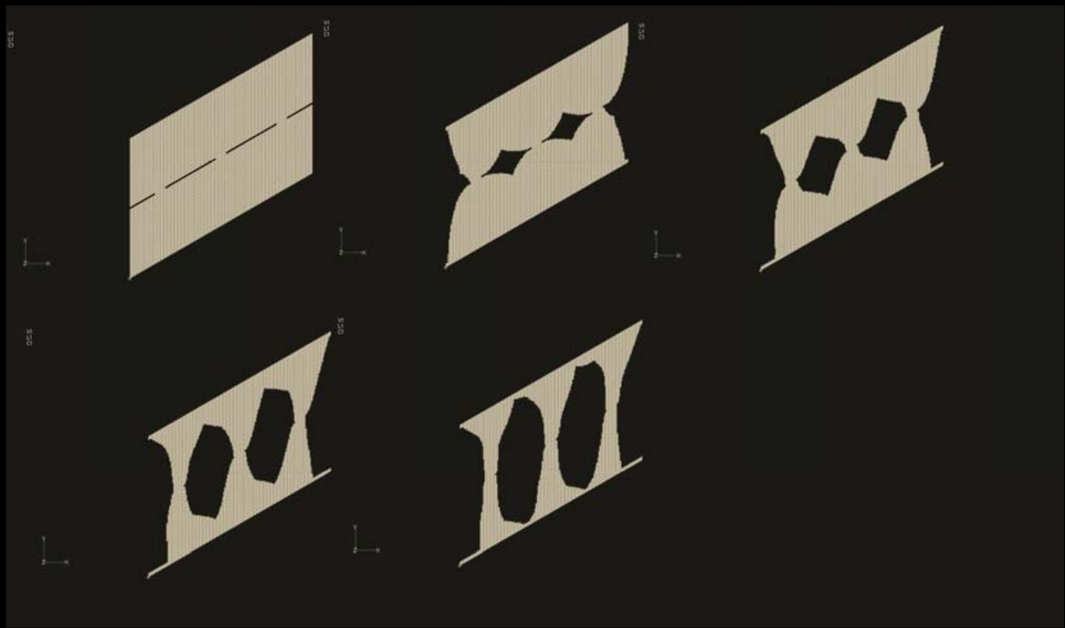


Finite Element Model of Initial Design

Evolution of a Structure in Compression



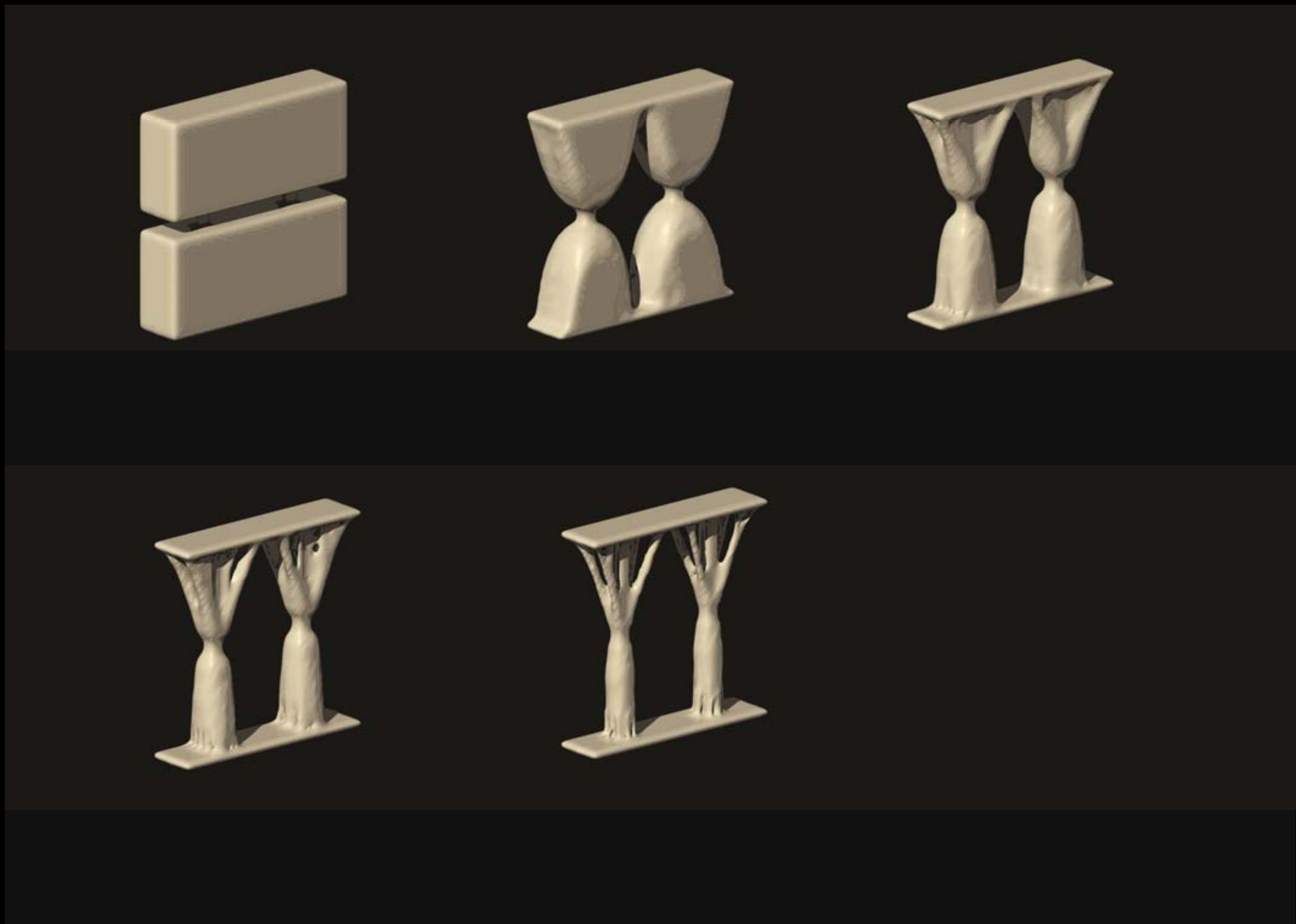
Three Columns on a Sloping Surface



ESO process

Actual structure
in Barcelona

Evolution of Two Columns Resulting in Branching Elements at Top



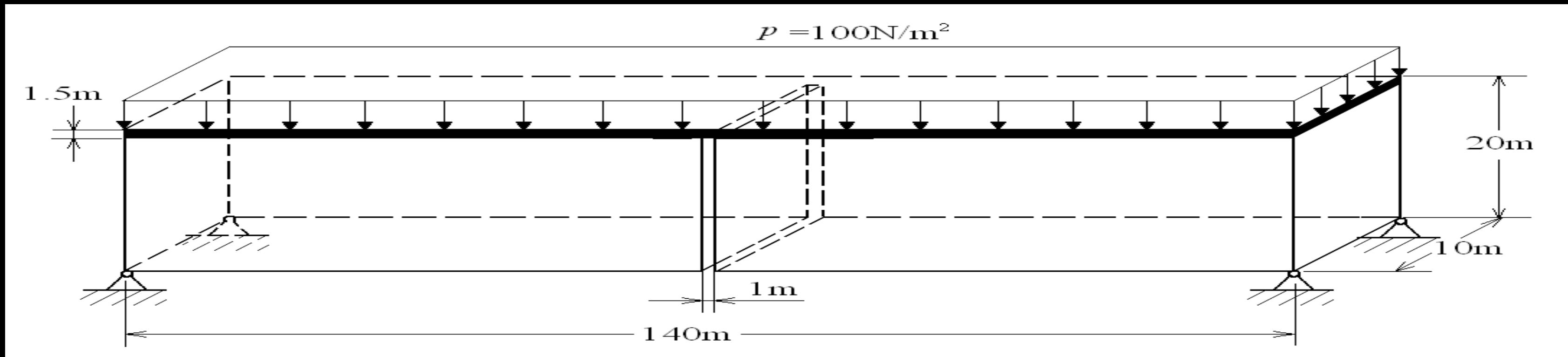
Examples of Columns with Branching Elements and a Real Tree

Bi-directional Evolutionary Structural Optimization (BESO)

- Inefficient material is removed from the structure and, at the same time, material is added to where it is most needed

- Algorithm is more robust and efficient

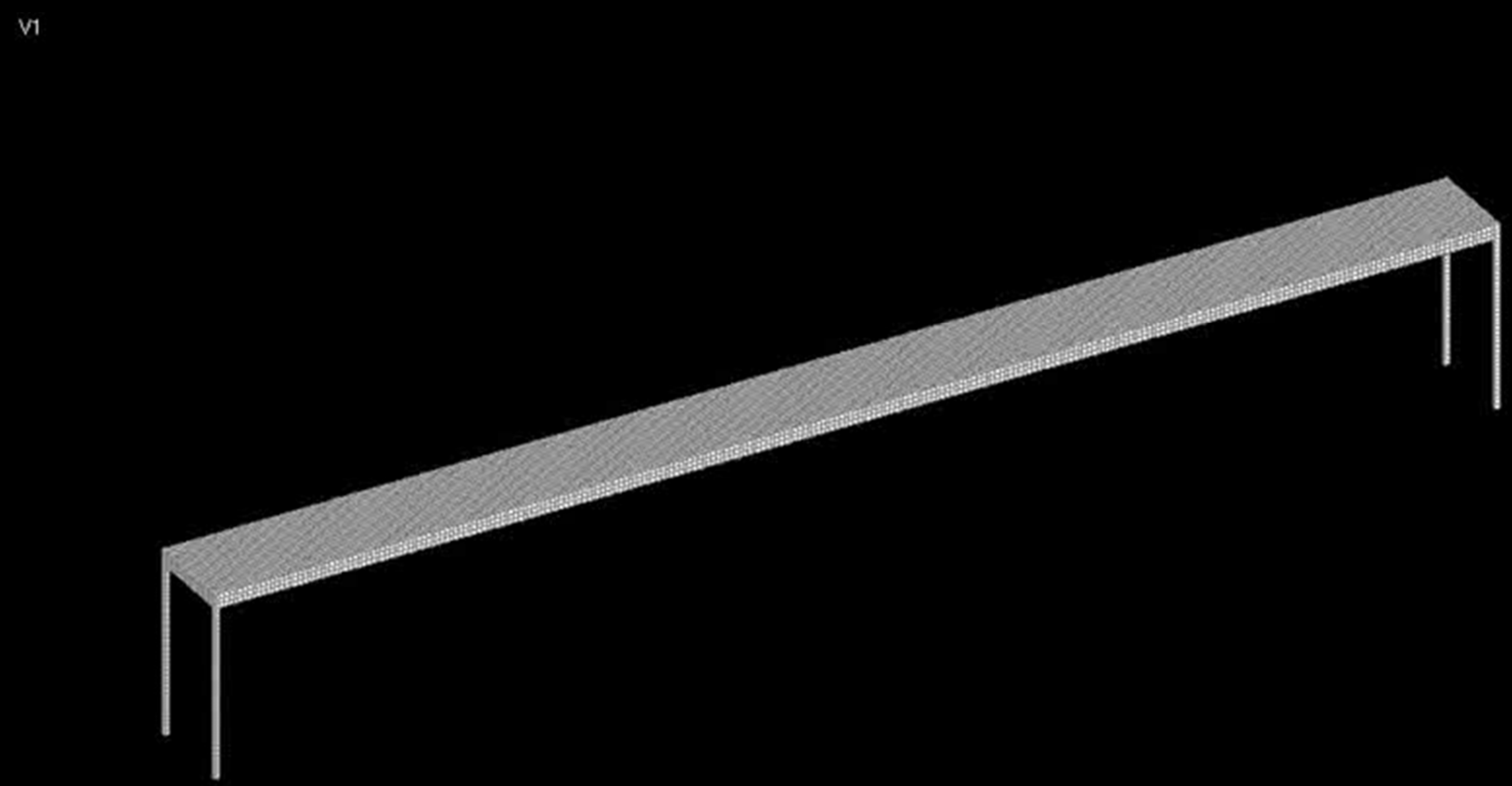
A BESO Example –
A Bridge-type Structure



A 3D beam with a solid deck at the top and a gap in the middle

Initial design for the above structure

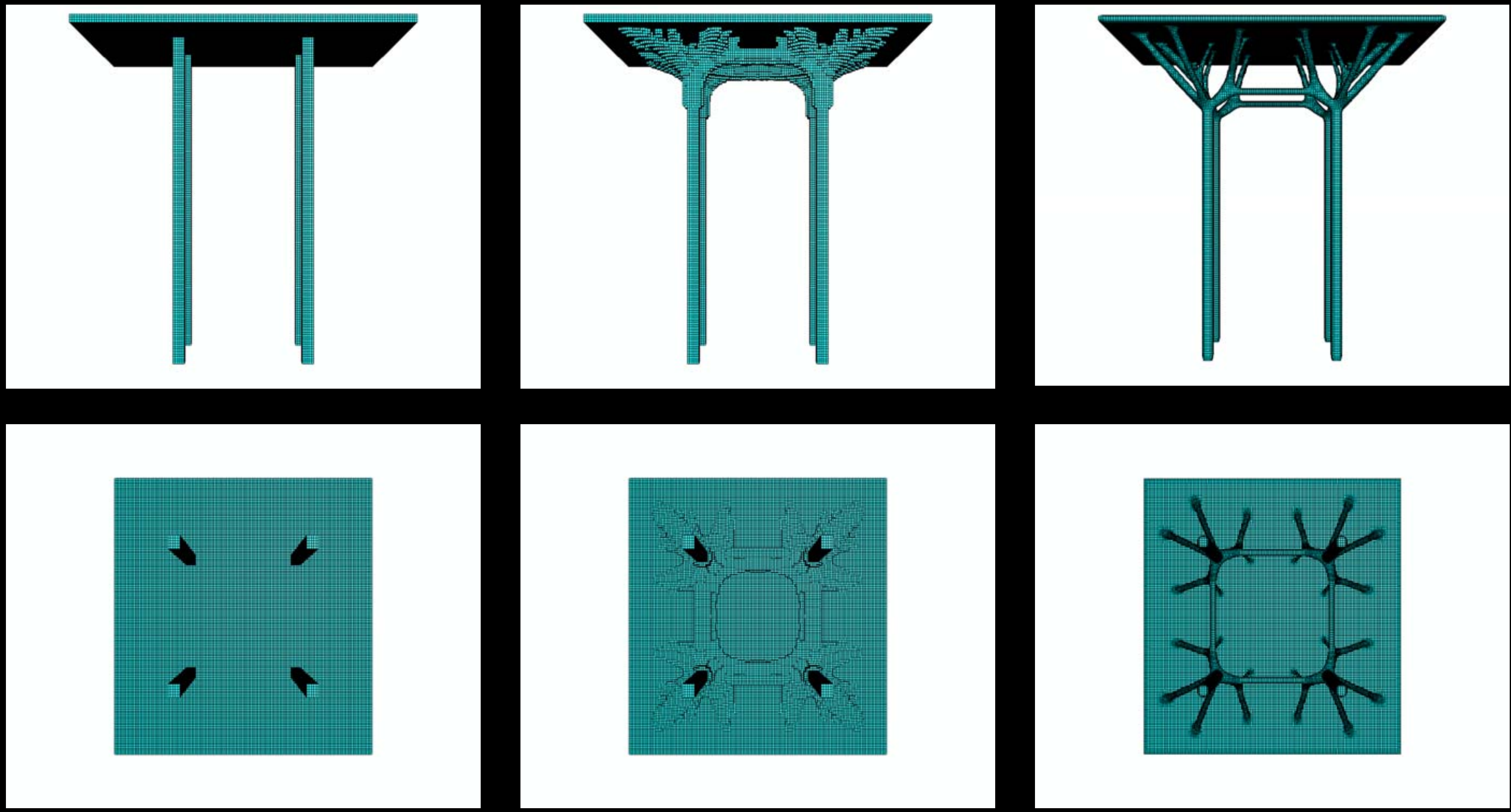
Evolution of a Bridge



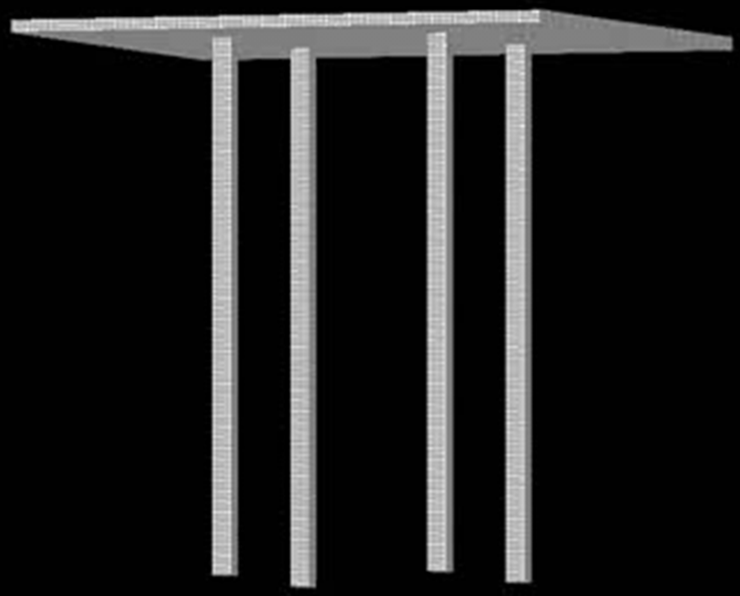
An Optimal Bridge-type Structure

Compared to the initial design

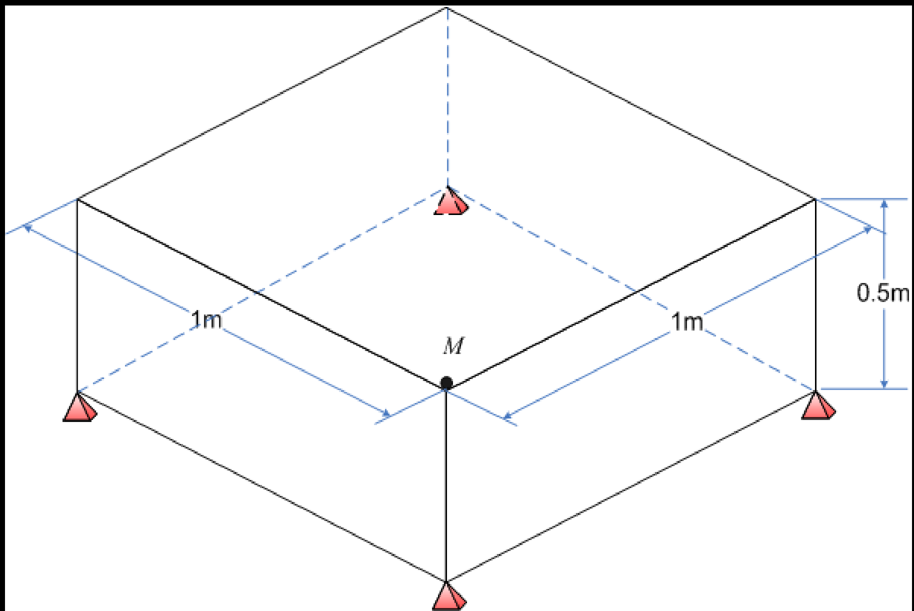
Load Transfer Structure for a Building

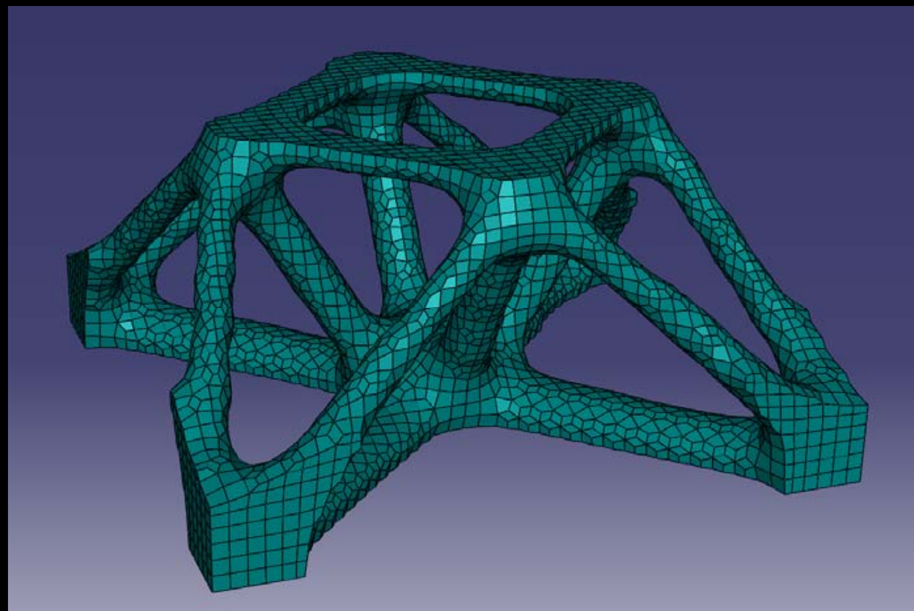


Evolution of a Load Transfer Structure for a Building Atrium



A Simply Supported Structure with a Concentrated Mass M = 5000kg at the Center of the Bottom Surface





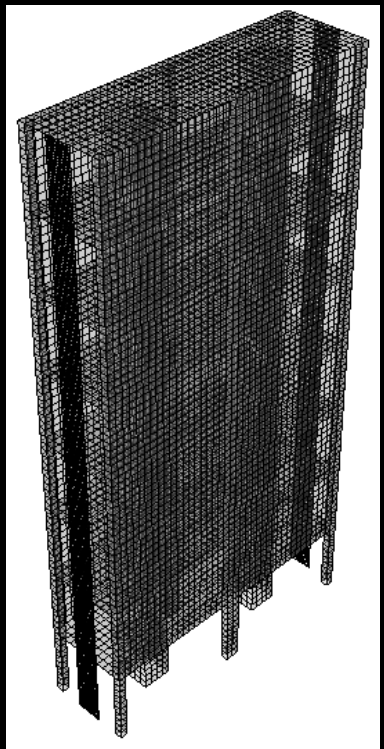
Objective: To maximize the fundamental frequency ω_1

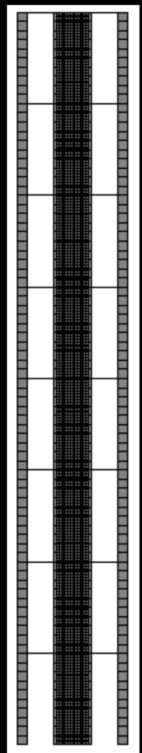
Constraint: Volume of the final structure to be 15% of the whole design domain

Optimal design with the highest possible fundamental frequency

Design with Multiple Constraints

Initial building under wind load





Perspective   Side

Objective:

To maximize the overall stiffness of the building

Constraints:

(i) Volume of bracing to be 30% of the design domain

(ii) Displacement at top less than 68mm

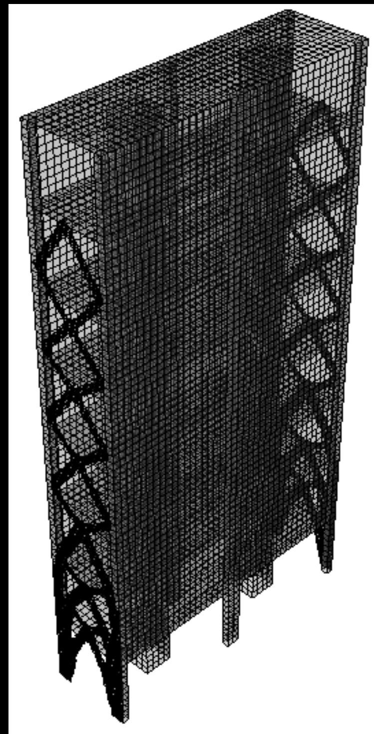
(iii) Fundamental frequency greater than 12 rad/s

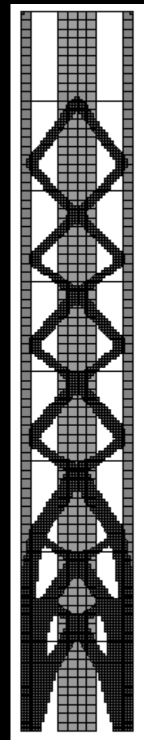
C= 3.7x10^5 Nm

ω_1= 5.2rad/s

d_{top} =416mm

Optimized bracing





Perspective   Side

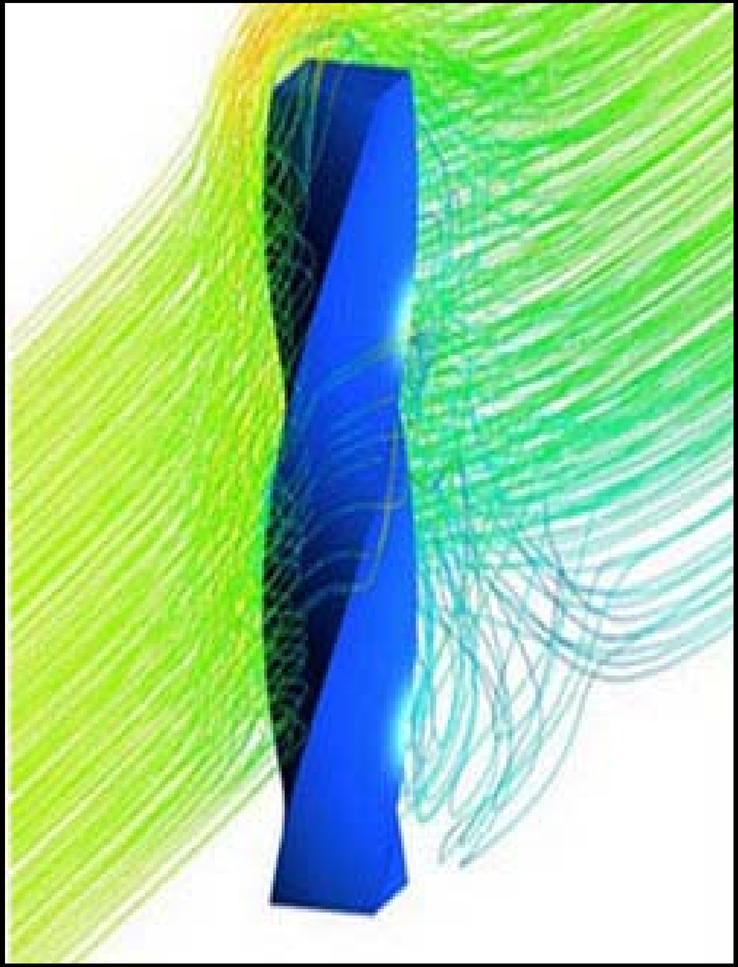
C= 1.1x10^5 Nm

ω_1= 12.01rad/s

d_{top} =67.9mm

Building Design Considering Wind Loading

(Mike Xie's team in collaboration with Felicetti Pty Ltd)



CFD simulation

3D printing of optimized design

Periodic Structures

- **Structures with repetitive geometrical patterns**
- **Cost-saving of mass production of identical components**
- **Simplifying assembly process**
- **Distinctive aesthetic appeal**

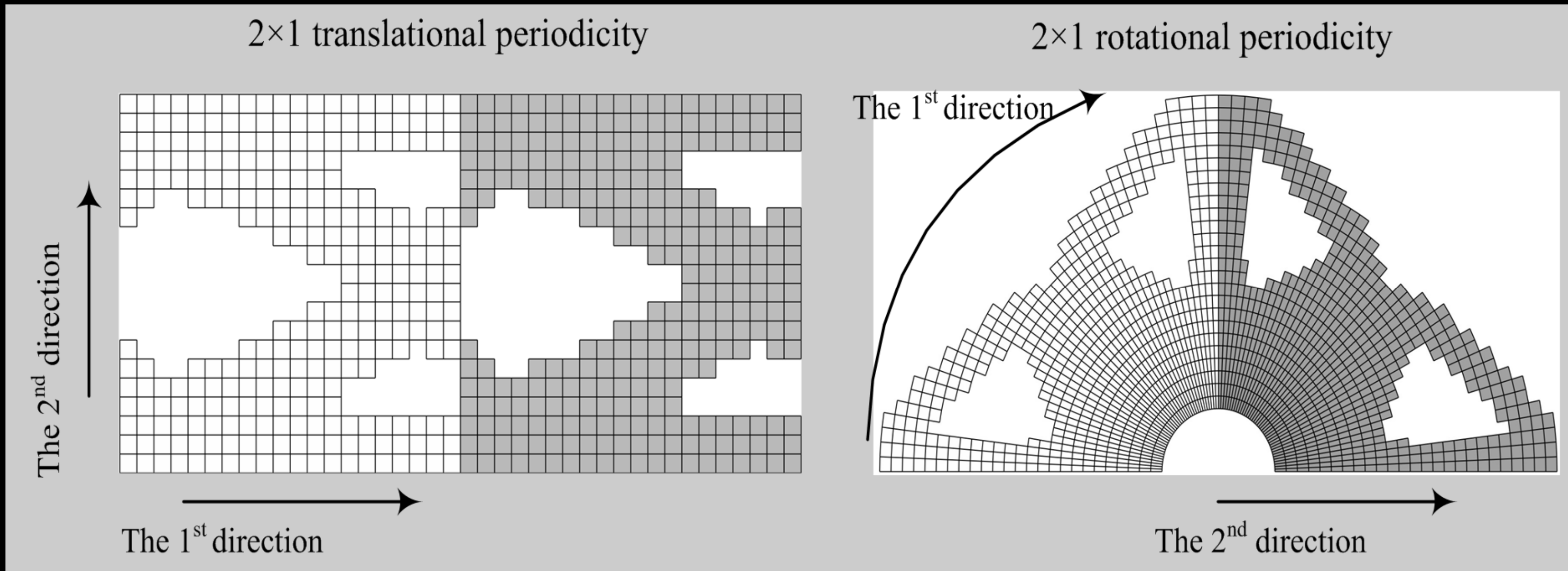
(a) Building in Melbourne

(b) Bridge by Santiago Calatrava

(c) Building by Norman Foster

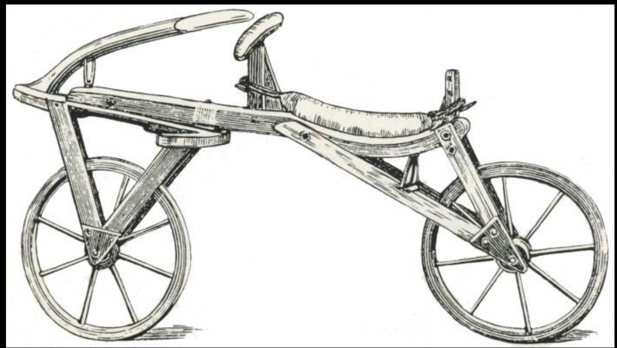
Realizing Topological Periodicity

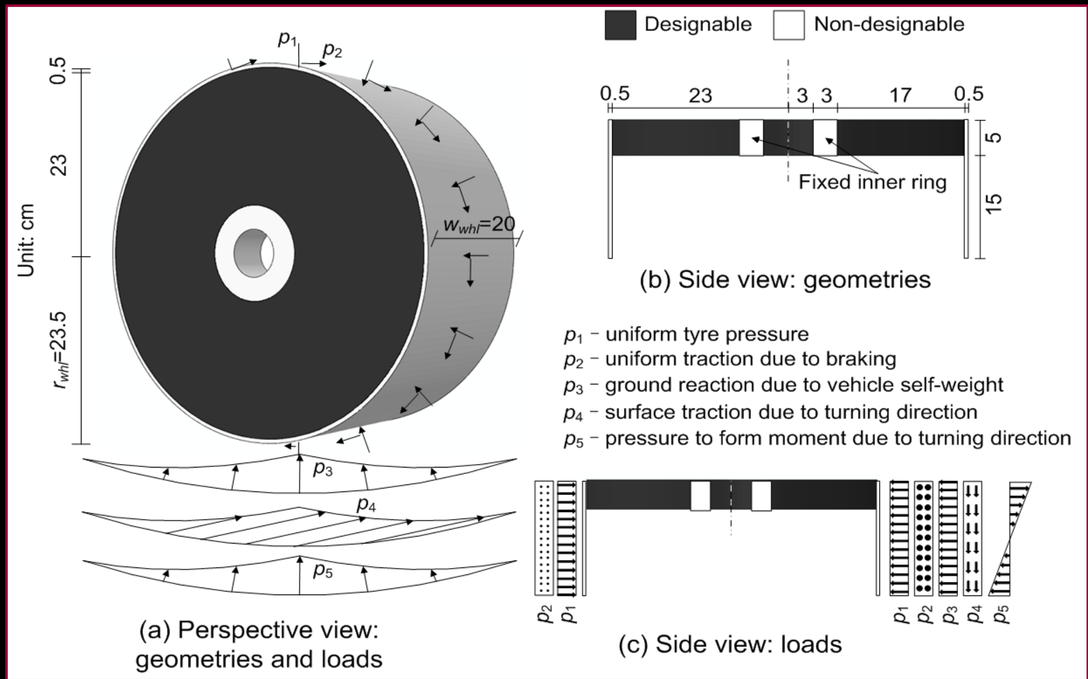
- The sensitivity of a *representative cell* is determined by averaging the strain energies of corresponding elements of all cells.
- The corresponding elements in all cells will be deleted or added simultaneously.



Examples of *translational periodicity* and *rotational periodicity*

A Case Study of Rotational Periodic Structure: Wheel Design



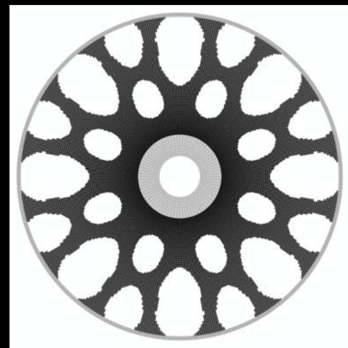


Wheel Designs with Various Cell Numbers


2 cell


4 cell

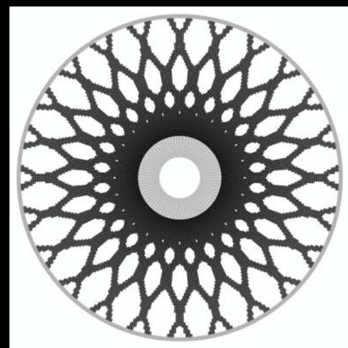

6 cell


8 cell


10 cell

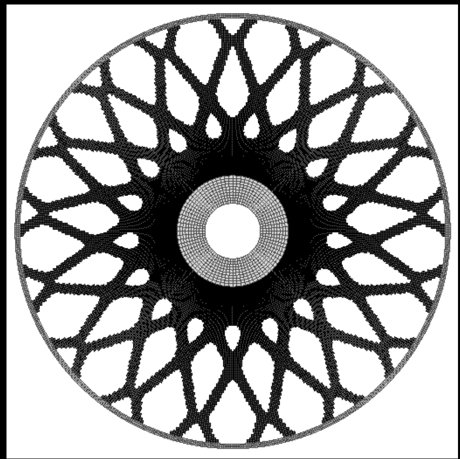

12 cell


15 cell


24 cell

Similarity Between BESO Designs and Real Wheels

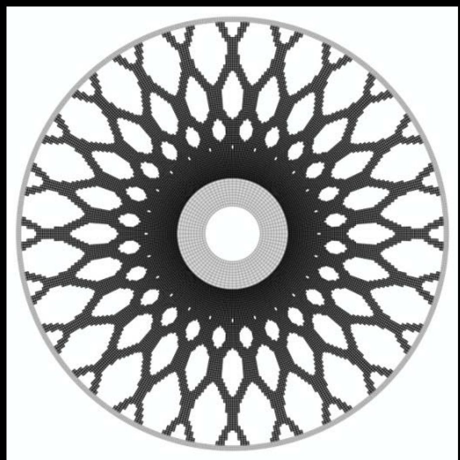
17 cell



17 cell

BMW

24 cell



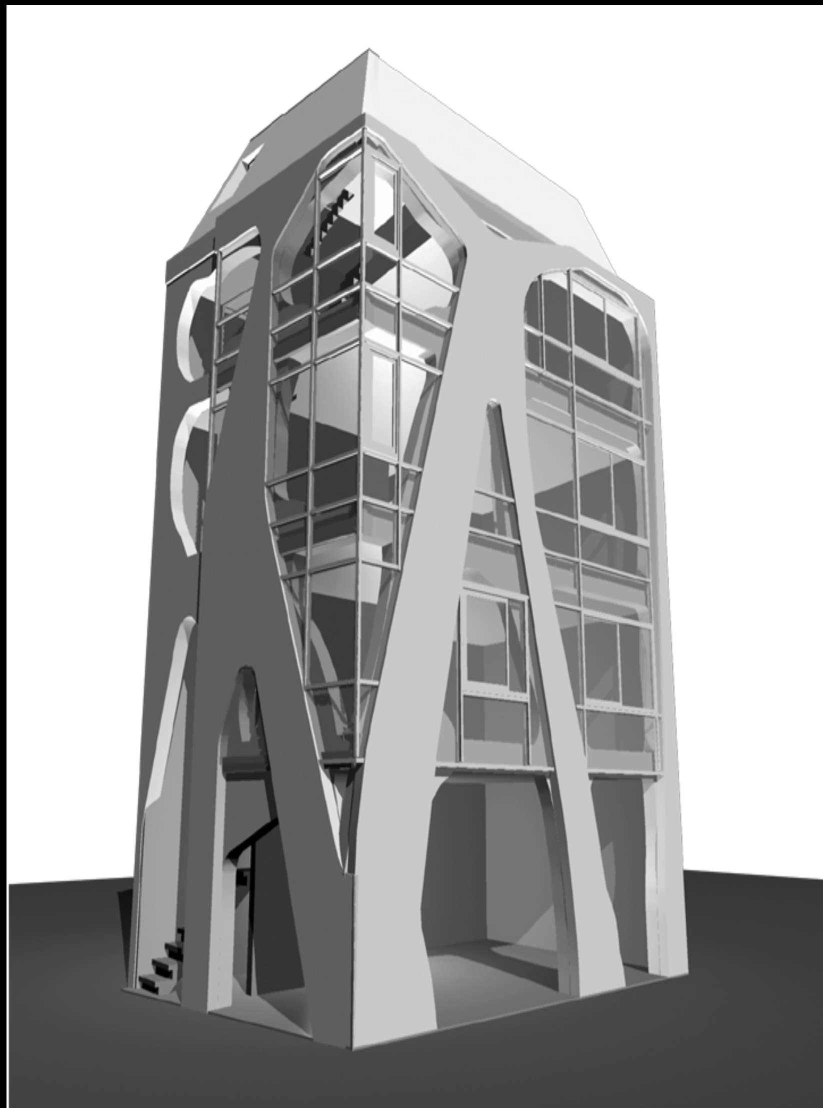
24 cell

Cadillac

BESO Optimal Designs

Real Wheels

Real Buildings Designed Using BESO



(An office building in Japan designed by Ohmori et al.)

West Side View

South-west Side View

Fab-Union Space, Shanghai

(by Philip Yuan)

Qatar Convention Centre

(by Arata Isozaki, Mutsuro Sasaki and co-workers)

Qatar National Convention Centre During and After Construction

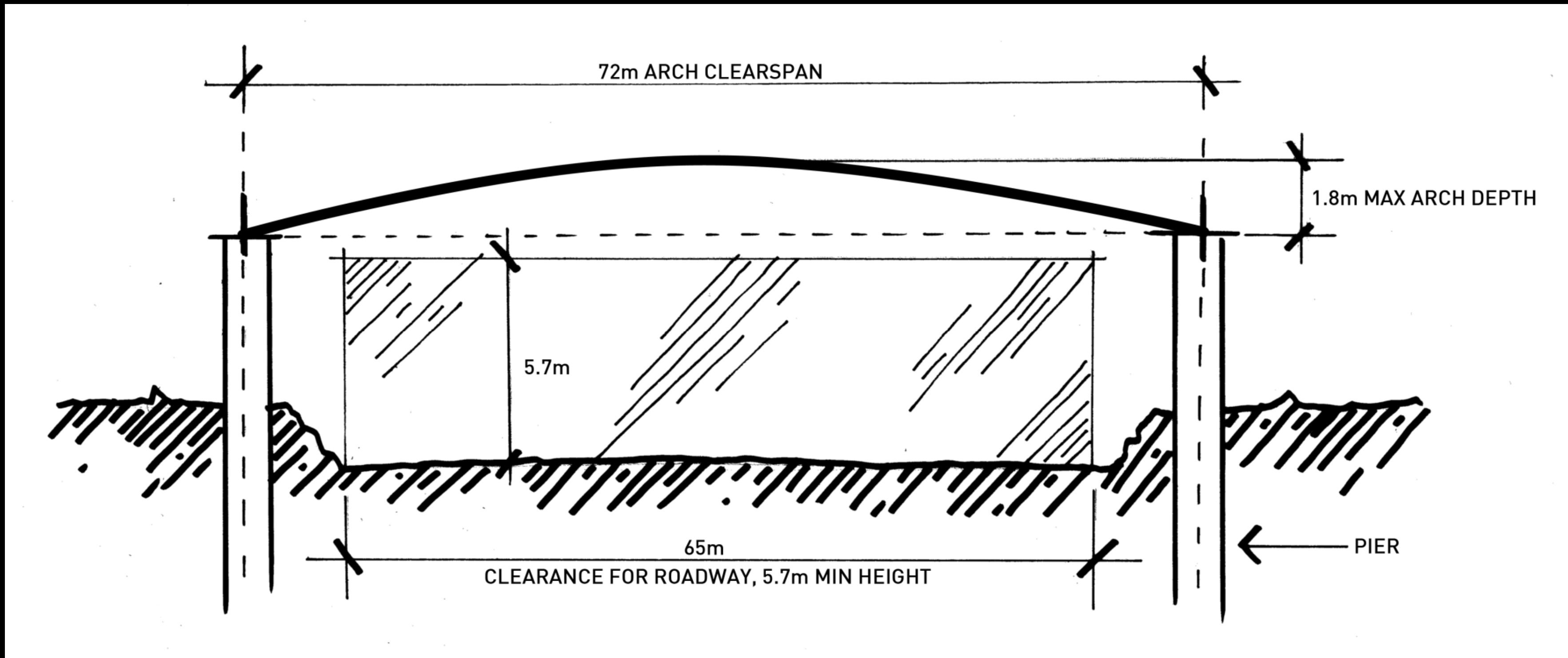
Pedestrian Bridge Design Proposal

(Mike Xie’s team in collaboration with BKK Architects)

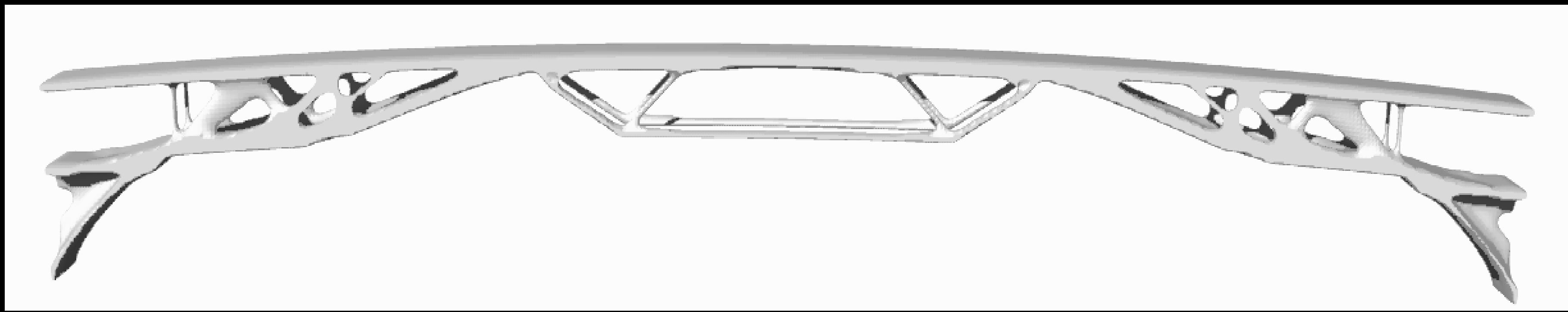
- **To design a series of pedestrian bridges for a major metropolitan freeway in Australia**

- **Simple sculptural gestures providing visual interest for the freeway and surrounding environment**

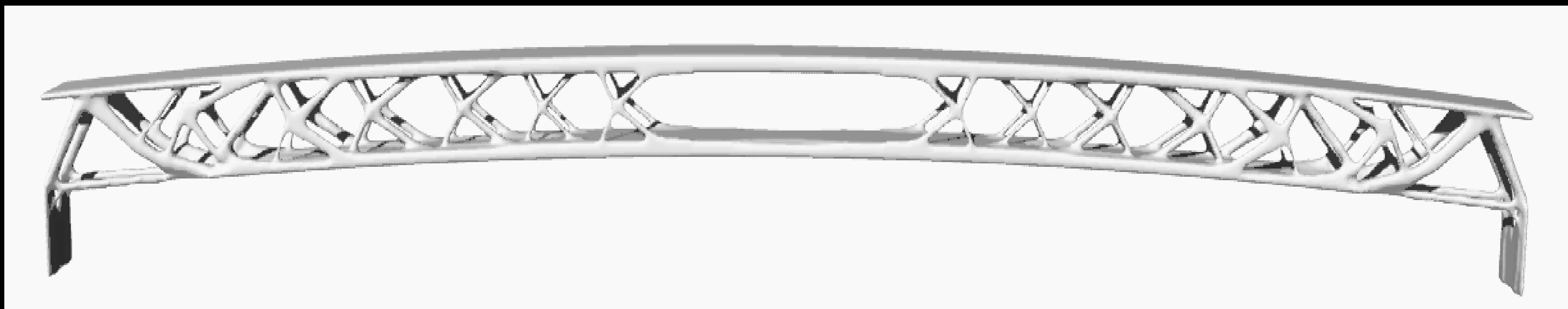
Initial Sketch from Architect



BESO Results Using 3D Elements

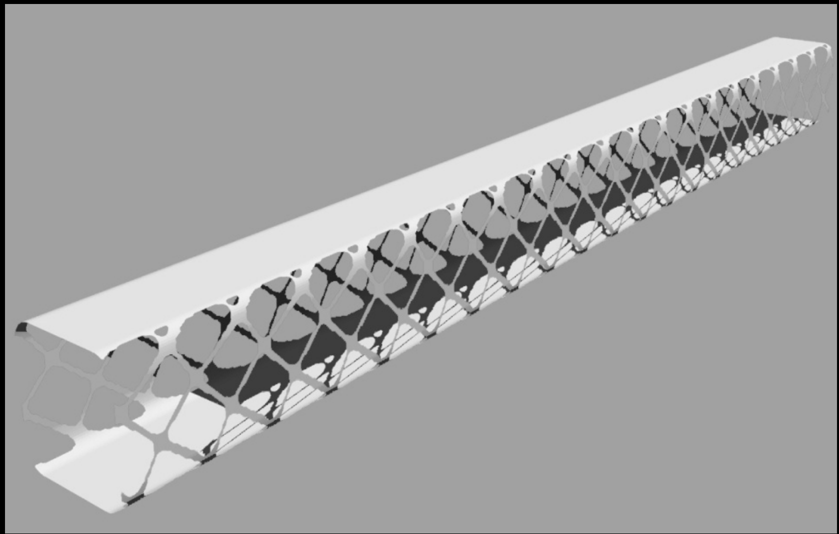


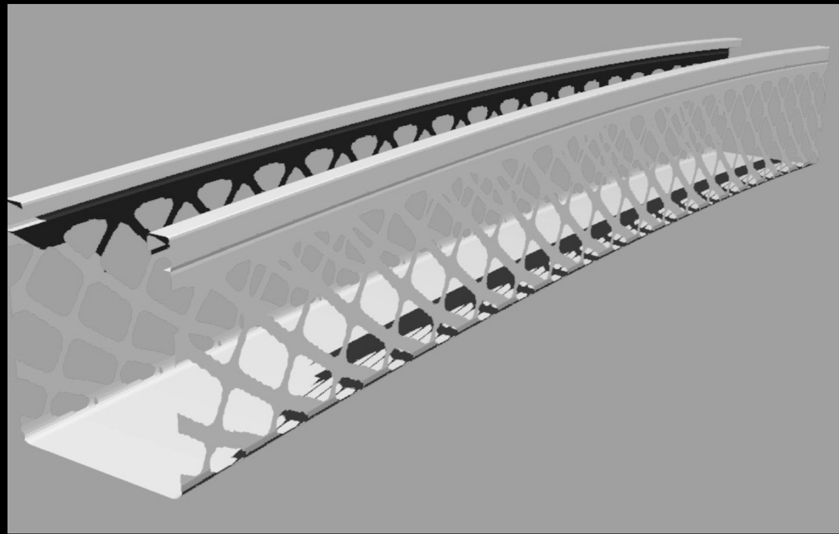
(a) Two end planes fixed

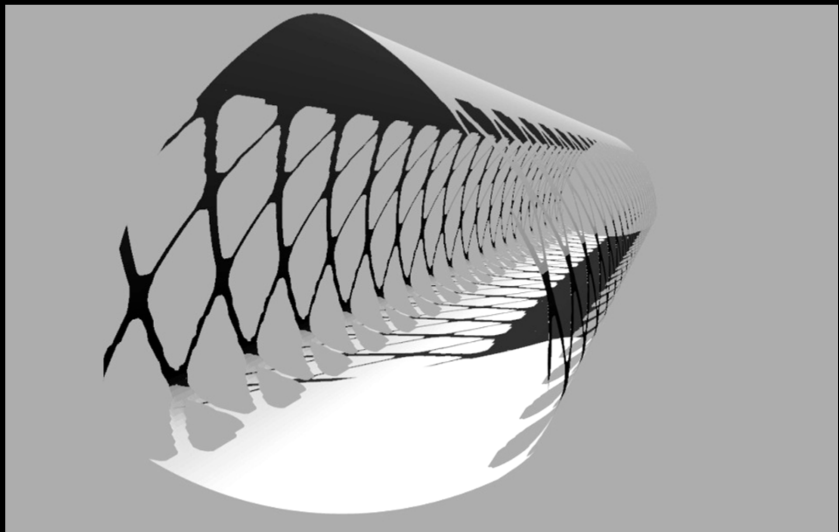


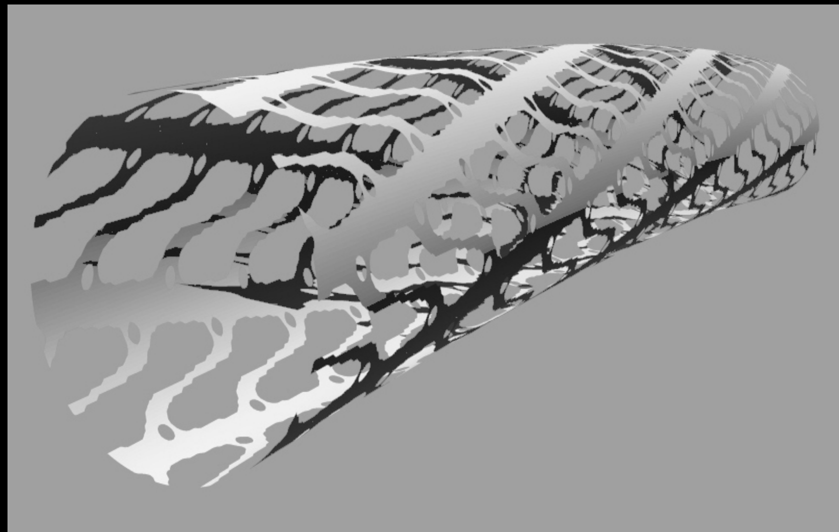
(b) Pin and roller at bottom corners

Periodically Perforated Bridge Designs with Various Cross-sections and Numbers of Cells









3D Printout of a Circular Section

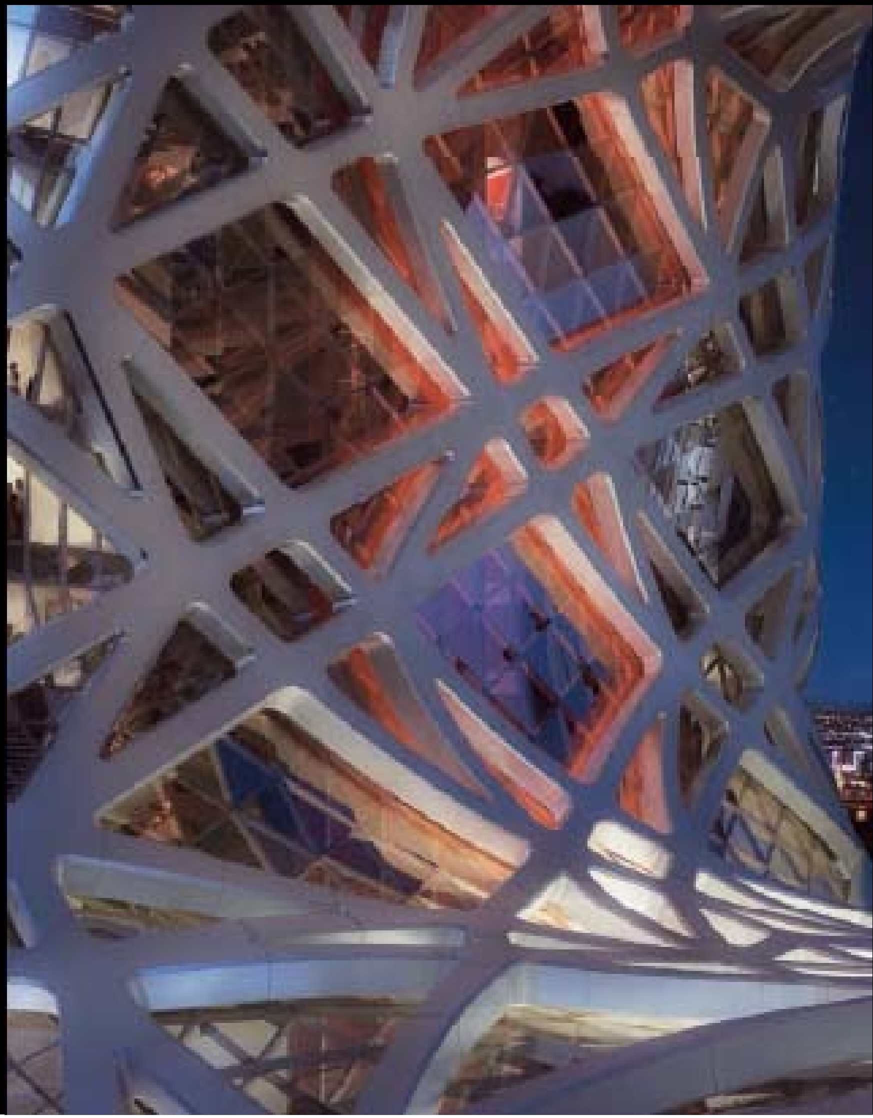
Reusable Mould for Fabricating One Section of the Footbridge Using Reinforced Concrete

Six Identical Reinforced Concrete Sections Joined Together

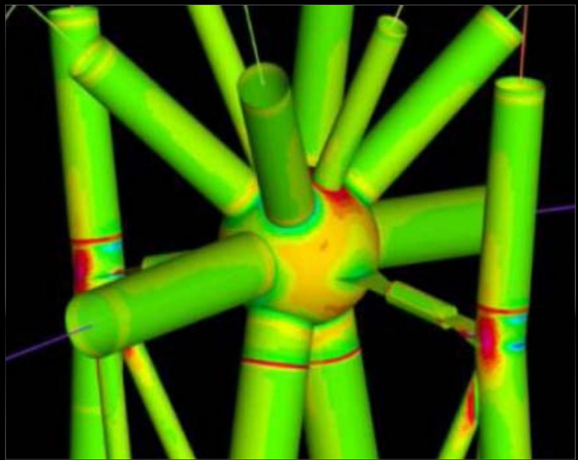
How it looks like…

Design Proposal for a Footbridge in Suzhou, China
(Mike Xie's team in collaboration with BKK Architects)

Design and Fabrication of Complex Structural Nodes



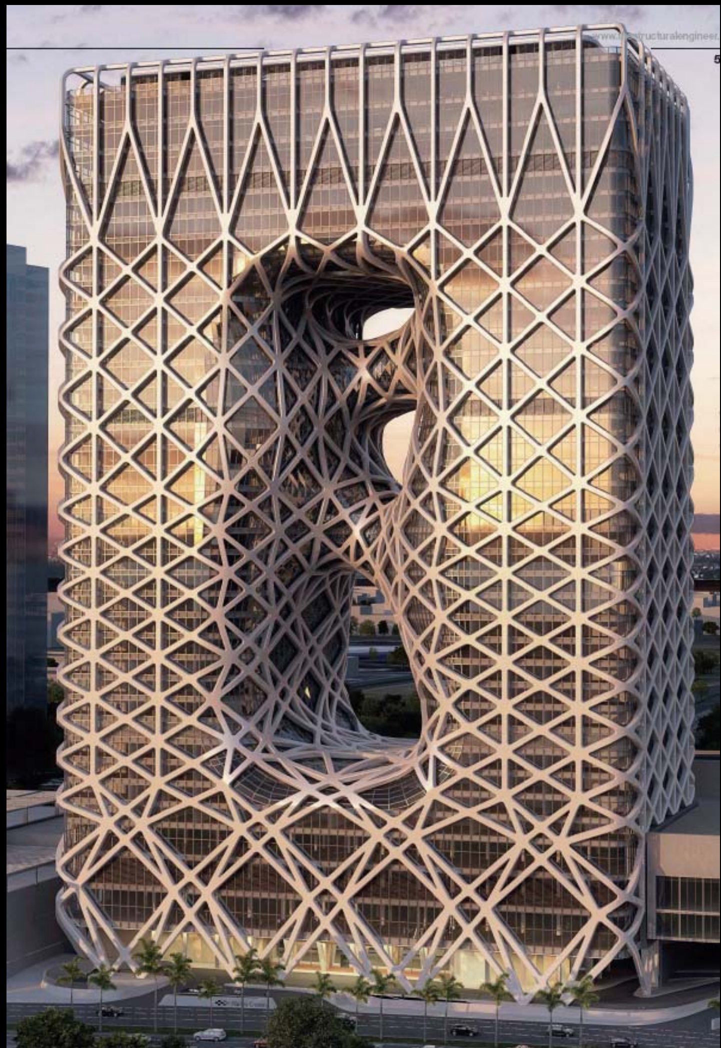
Traditional approach to "designing" and fabricating nodes



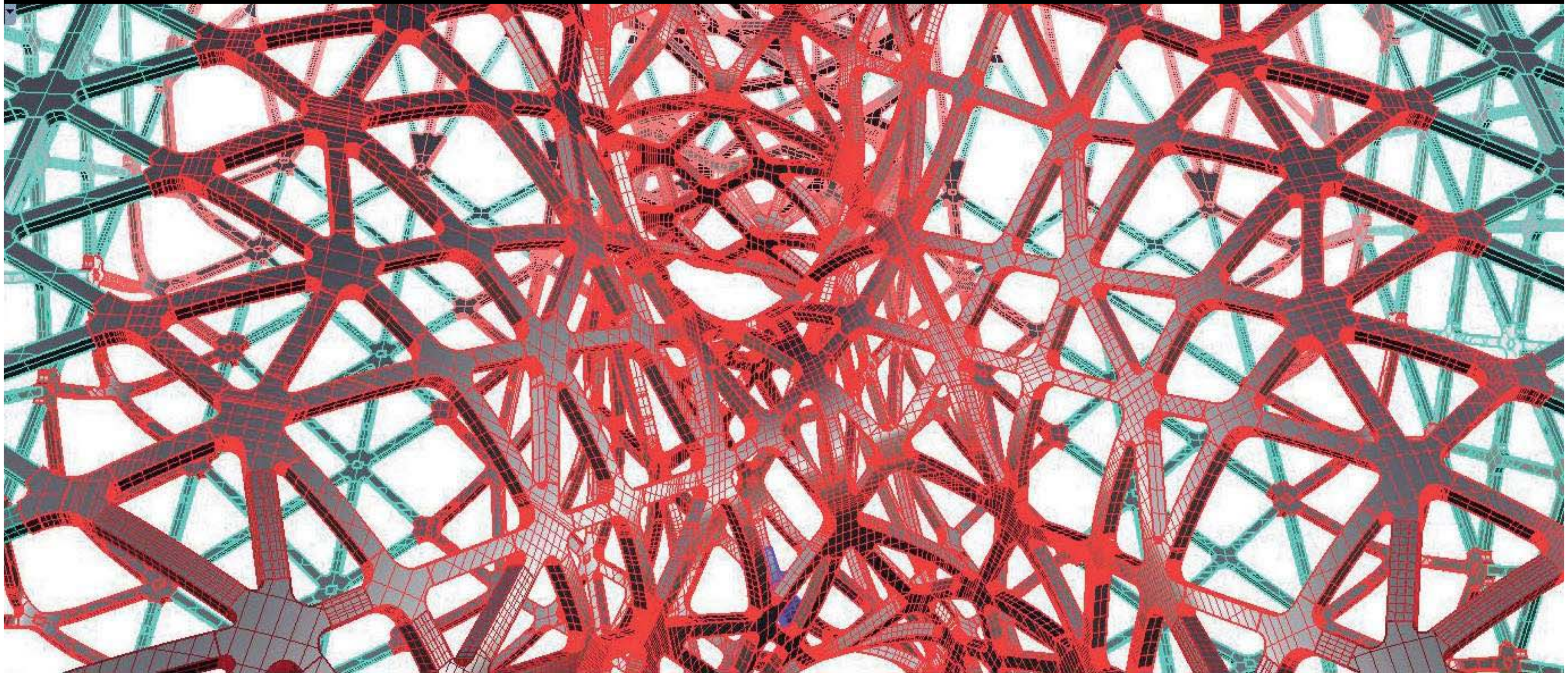
City of Dreams, Macau

Architecture: Zaha Hadid

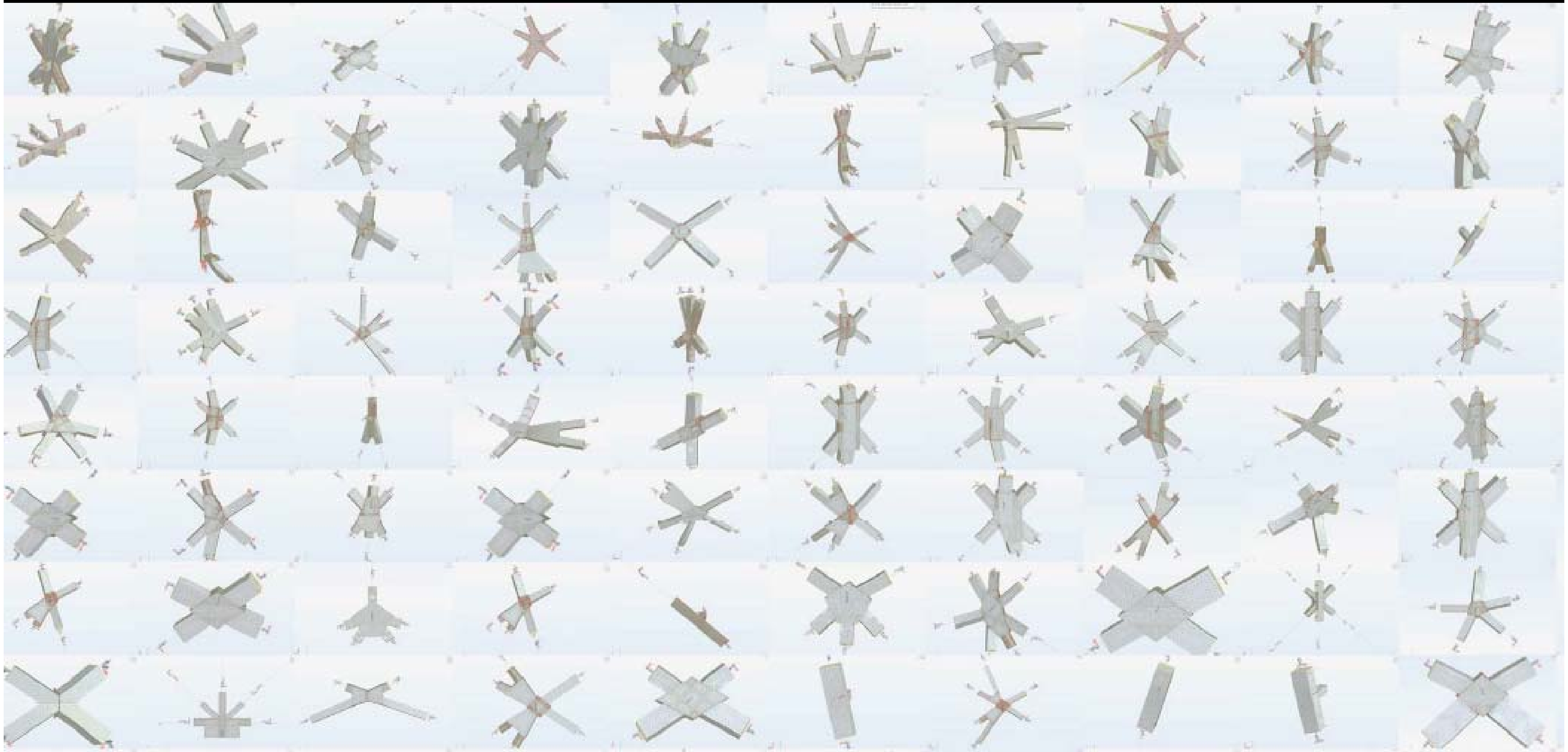
Structural Engineering: BuroHappold



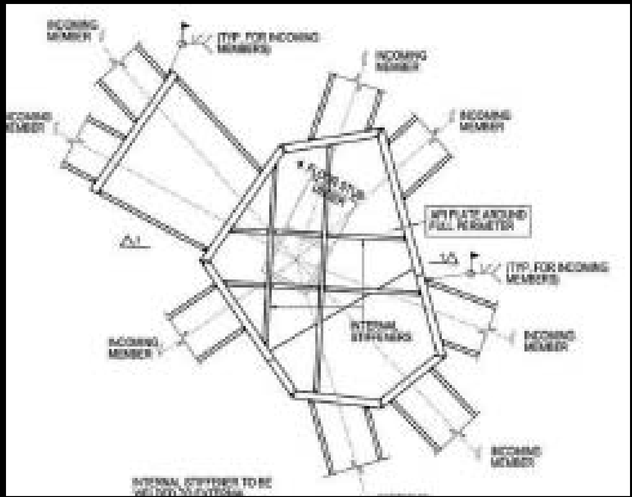
2500 Complex Nodes in Exoskeleton

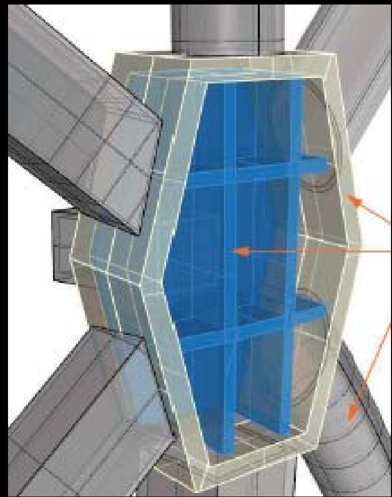


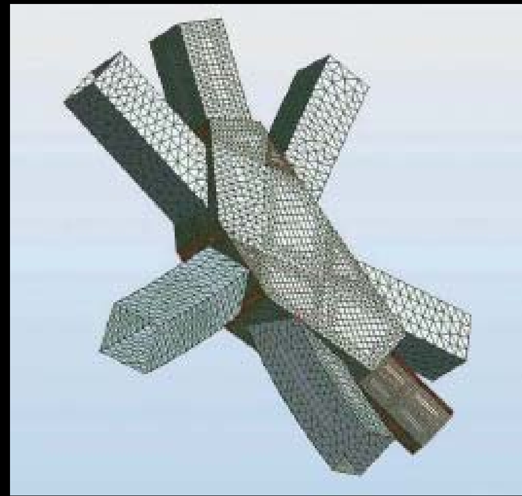
2500 Nodes Simplified into 400 Different Types



Design and Fabrication of Nodes

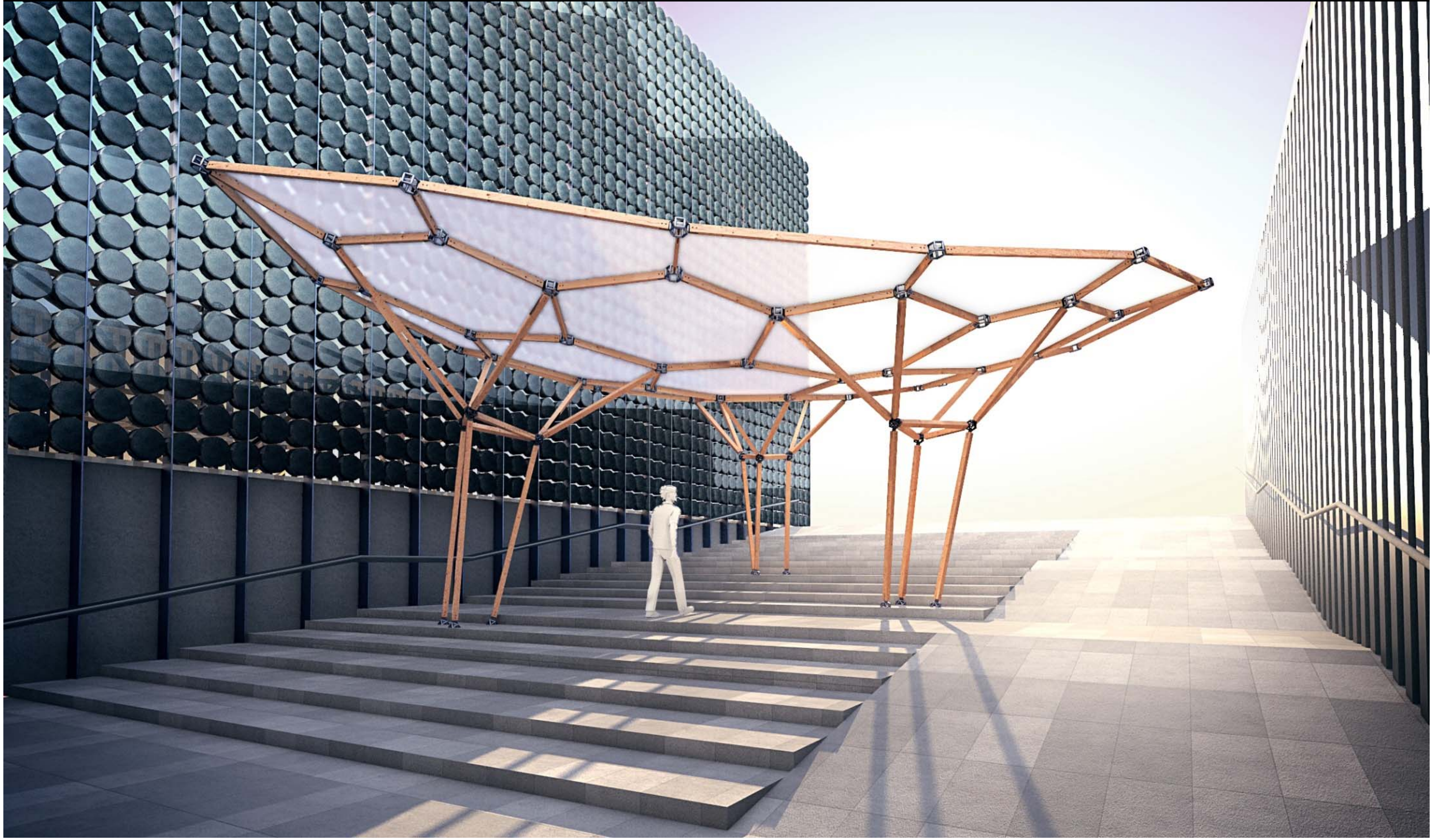




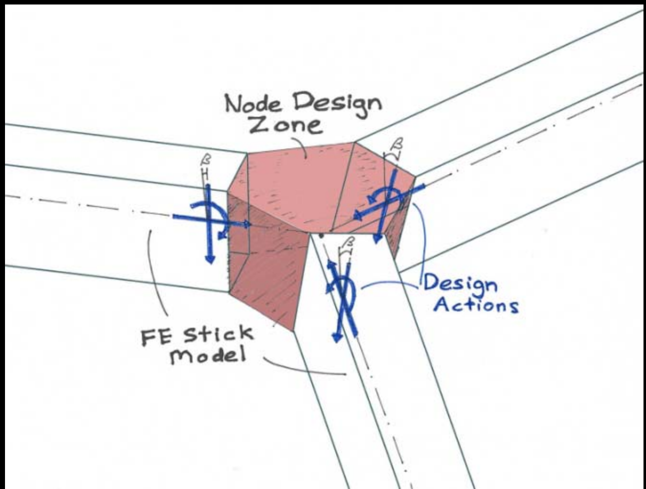


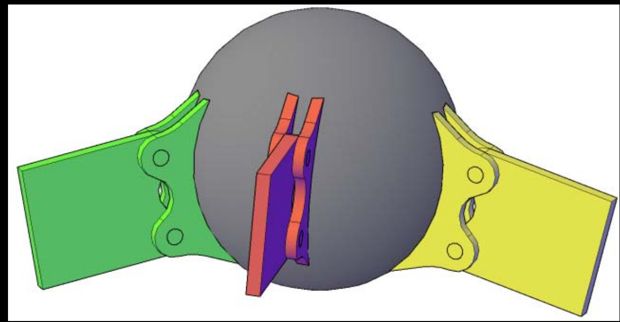
Designing Nodes Using BESO

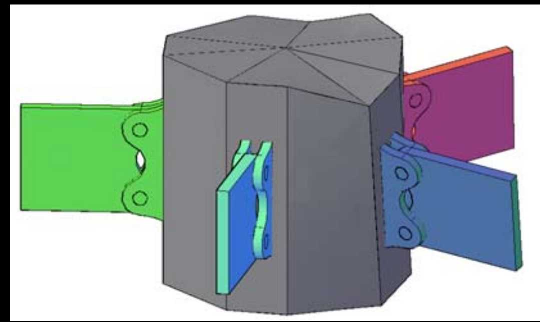
(RMIT team in collaboration with LEAD and Arup)

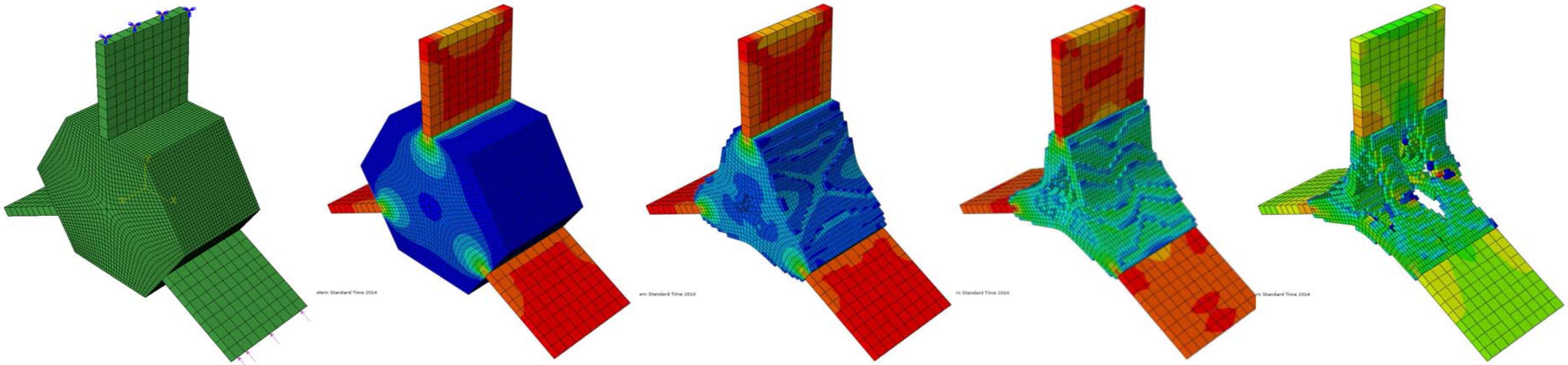


Topology Optimization of Nodes Using BESO

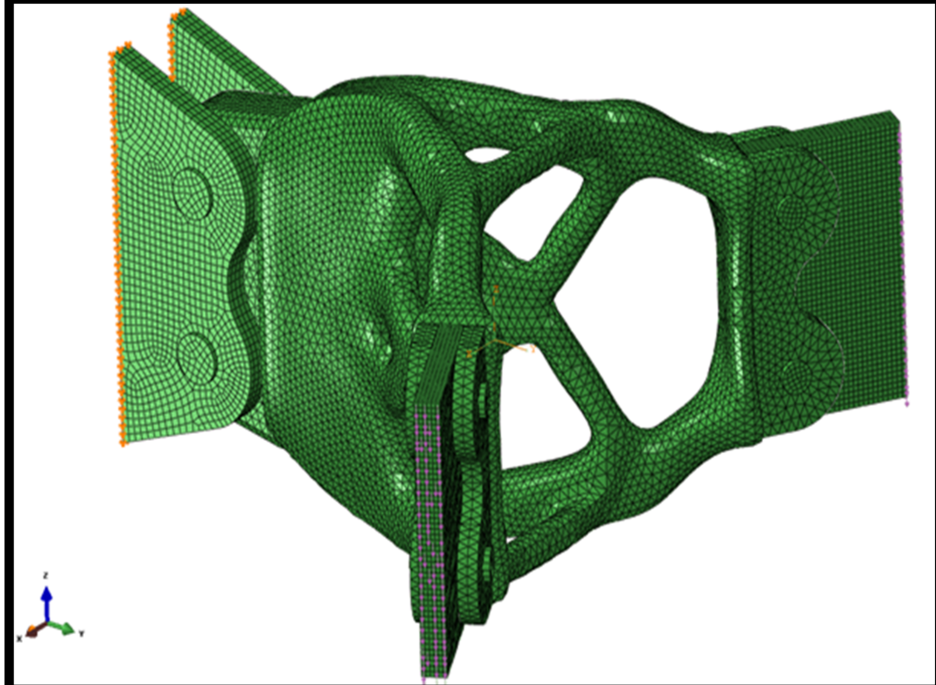


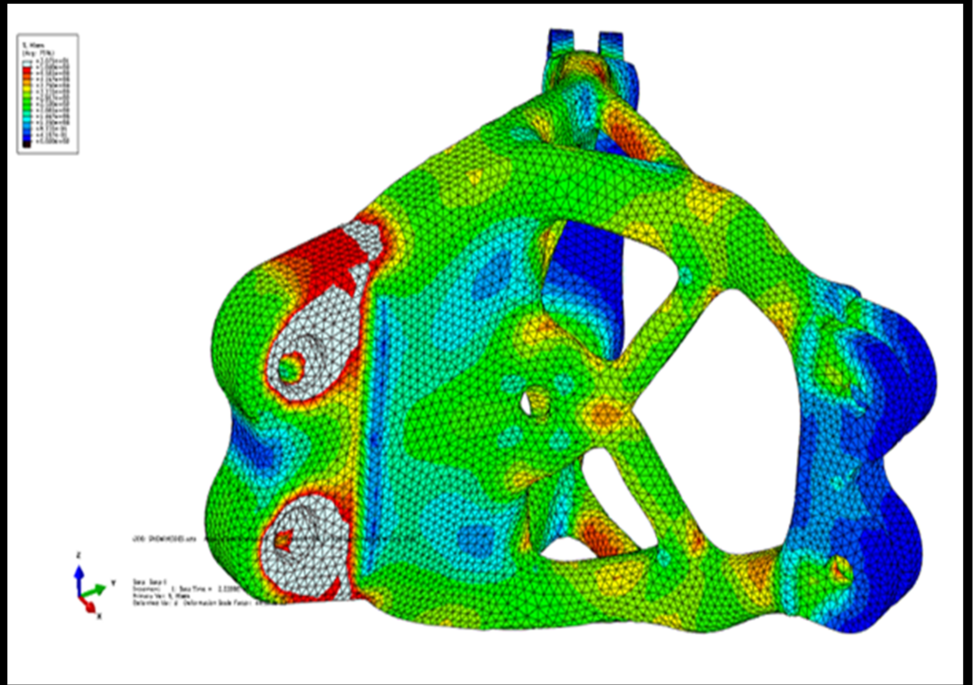




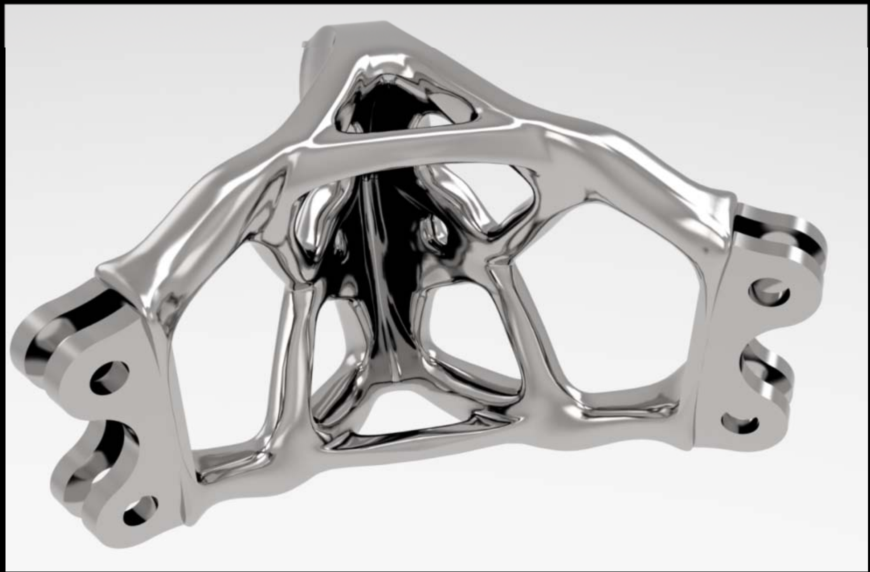


An Example of Node Designed Using BESO

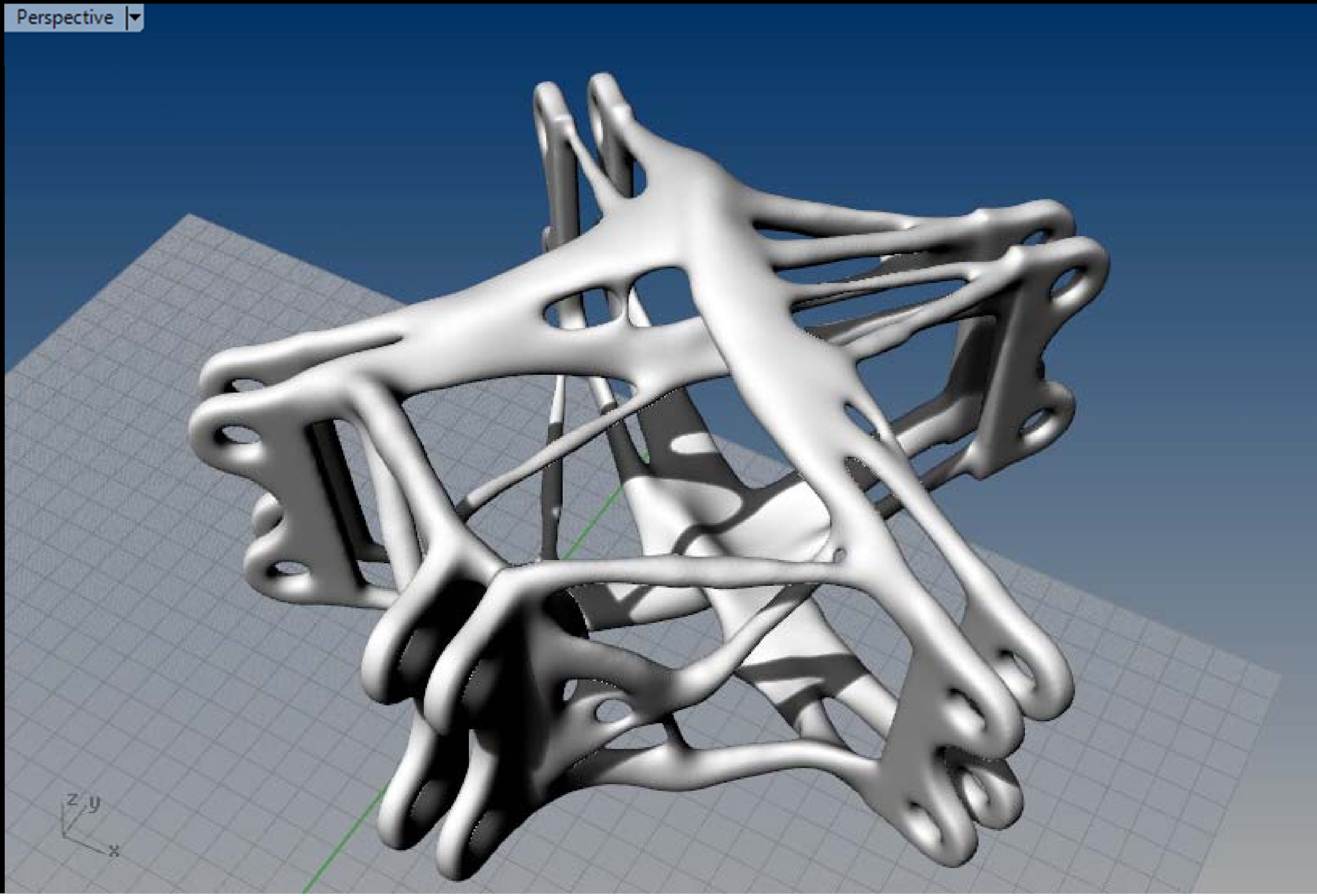




Rendering and 3D Printing of the Node Optimized by BESO



Another Example of Node Designed Using BESO



3D Printed Metal Nodes

Integrating Digital Technology with Traditional Casting

(Mike Xie's team in collaboration with HUST)

Direct 3D printing
in stainless steel

3D printing
in wax 3D

Cast node
in stainless steel

Acknowledgement of Collaborators

Tim Black, Milan Brandt, Jane Burry, Mark Burry, Kristof Crolla, Peter Felicetti, Martin Leary, Xiaodong Huang, Andrew Maher, James O'Donnell, Hamed Seifi, Ben Sitler, Jiwu Tang, Qingsong Wei, Shifeng Wen, Nicholas Williams, Zhihao Zuo, and others

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