UNIVERSALIZED **CONNECTIONS** FOR **PLANAR HEX** TIMBER PLATE STRUCTURES

Double Curvature Surfaces

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ABSTRACT

The thesis seeks to enhance the flexibility of fabricating and constructing timber plate structures with Planar Hex form for a double curvature surface. It focuses on solving connection(s) to develop a radical strategy to synthesize Timber plate structure with Planar Hex, such that it could be applied to any double curvature surface efficiently, to built a self-stable structure. Therefore, a systematic process has been followed to attain this connection design, which in combination of material and form enhancements allows for increase in reliability and precision of the assembly of this geometry easily on site. In order to achieve the desired connection design, physical & digital means of form-finding, analysis and fabrication techniques are used. This strategy proves that Planar Hex structures with this connection detail can be assembled on site rapidly with no reliability on high-tech machines and robotic technology and can be done using practical medium cost technology.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Timber Plate Structures

Self supporting
Structures

1° Load Bearing
Structures

Load Transfer
Plates? Joints?

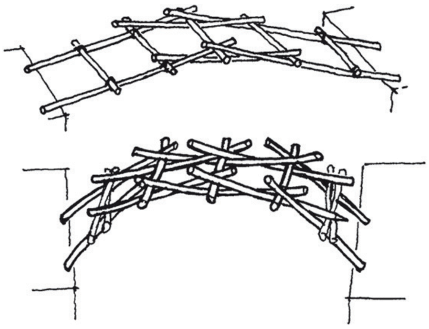


Figure 1.1.1 : reciprocal structure

Timber Plate structures can be organized such that the individual plates constitute the primary load bearing structure as the load transfer occurs through plates and joints.

1.2 Planar Hex Surfaces

Concave (K<0)
Anticlastic

Convex (K>0)
Synclastic

Rectangle (K=0)
Mixed

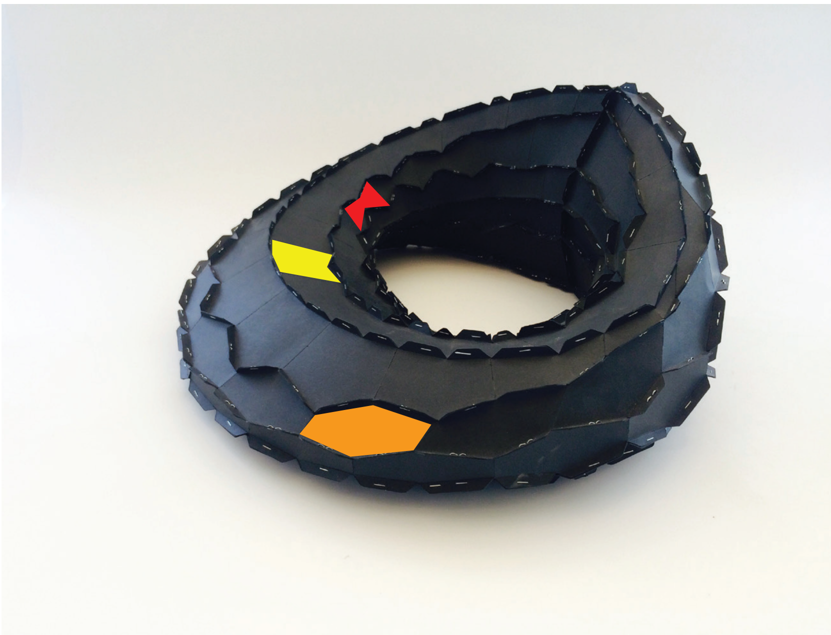


Figure 1.2.1 : Planar hex surface

1.3 Research Proposal

Timber Plate Structure	+	**Planar** Hex	=	?

1.4 Hypothesis

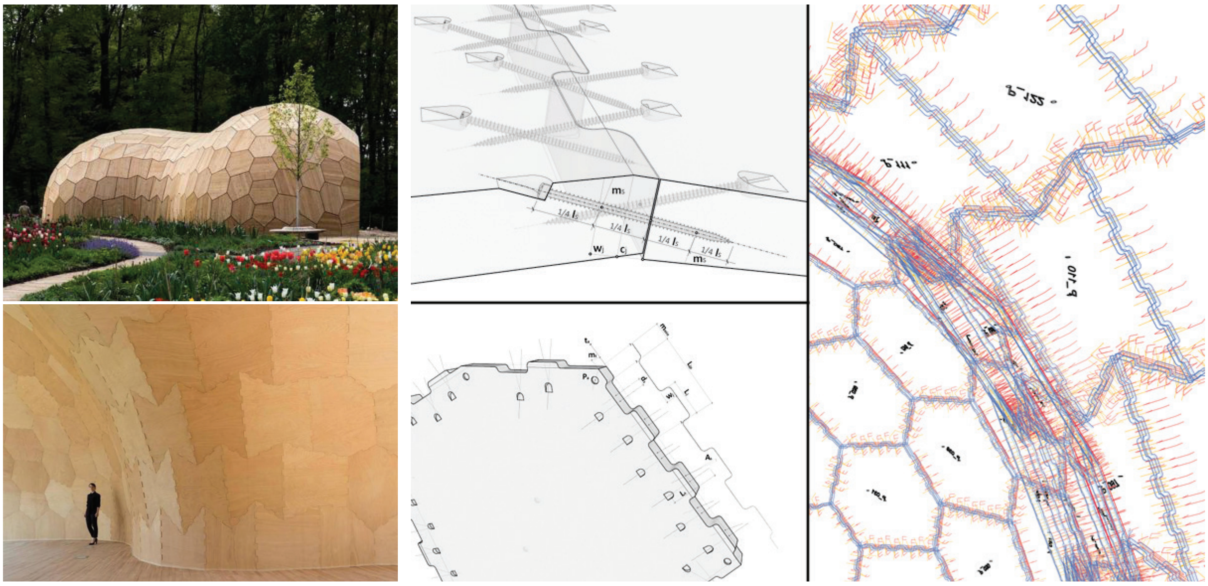
“ Develop a radical strategy to **solve connection(s)** in order to synthesize TPS with PHex, such that it could be applied to any double curvature surface efficiently, to built a self-stable structure “

1.5 Methodology

Form	**Analysis**	**Fabrication**
1) Surface Approximation 2) Topology Behaviour 3) **Planar clustering**	1) Structure Optimization 2) Analysis for various **cross-section and thickness**	1) **Joint Geometry** Generation 2) **Connection** Generation 3) Fabrication process 4) 3 plate Assembly 5) 3 Plate Finished prototype

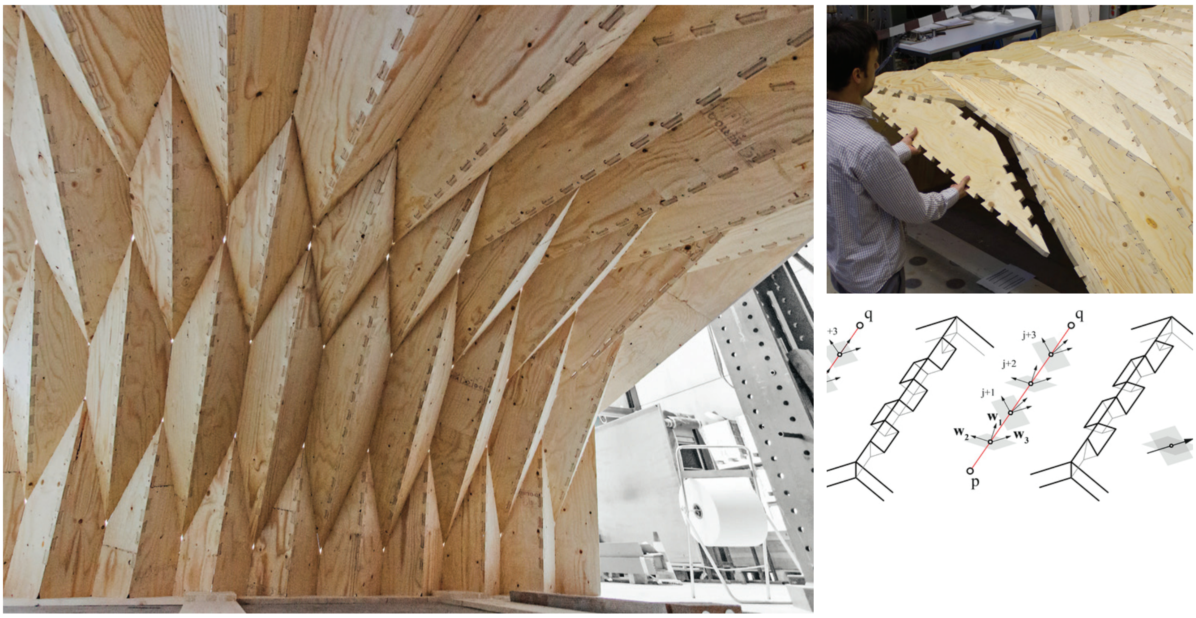
2. STATE OF ART

2.1 Landesgartenschau Exhibition Hall / ICD/ITKE/ IIGS University Of Stuttgart, 2014



- Beech Plywood - 12 sqm, 50mm thickness
- Robotic manufacturing tools (7 axis)
- Finger Joint

2.2 Interlocking folded plates - integral mechanical attachment for structural wood plates; Christopher Robellor and Yves Weinand



- Timber Folded Plate structure with dovetail joint
- 21mm thick plywood , 2.5 X 1.5m
- Joint Fabrication : 5 axis CNC Router

2.3 ICD/ITKE/University Of Stuttgart, Research Pavilion, 2011


- 6.5mm thick Plywood sheet
- The plates and finger joints of each cell were produced with CNC 7 axis robotic fabrication system.

2.4 Roskilde Dome, Denmark, 2012


- 240 panels made form plywood CNC cutting machine
- Brackets were attached around the window holes, in vertical position on the spherical surface. In this way, transparent and waterproof membranes could be attached to the windows.

3. CONNECTIONS DESIGN

3.1 Strategy to find the right connection

The appropriate connection detail has to be kept in mind while working with timber plate structures. Being a reciprocal structure, the plates and joints together gives binding strength to the structure. The plates helps in surface curvature control and joints helps in load transfer. Therefore, a self supporting structure can be created with no frame and cladding system.

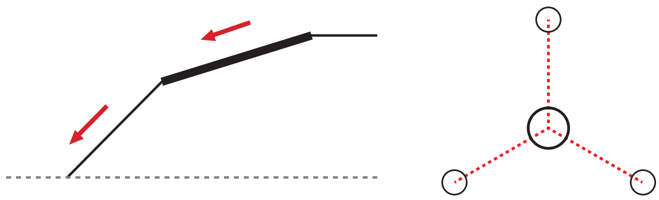
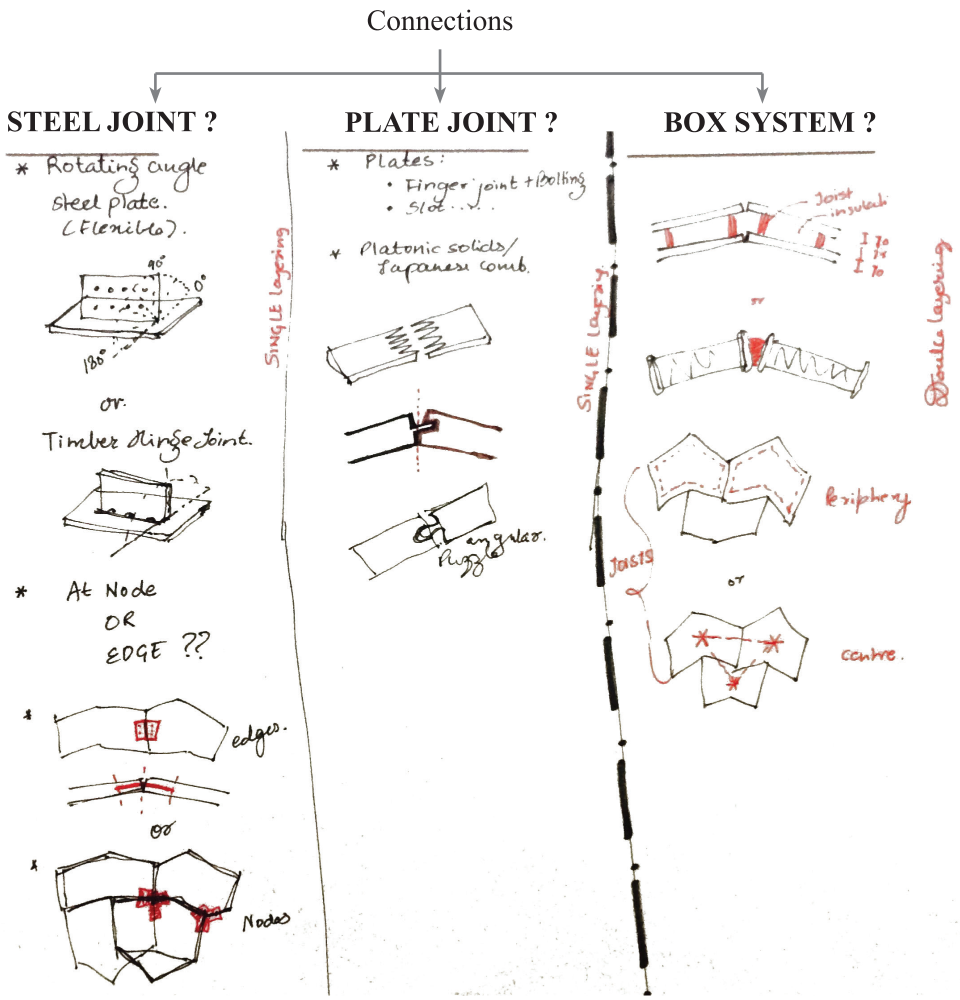


Figure 3.1.1: load transfer from plates to ground at every node

3.2 Properties



There are 3 ways to solve the connection. The first way is to solve the steel Joint. As the timber plates will be joined together at an angle, a rotating angle steel plate or a timber hinge joint might be a solution due to its flexibility to rotate from 0° to 180°. It can be placed either at the node or at the edge depending on the connection design. The second way is to solve the timber plates as puzzle, as in case of platonic solids or Japanese combs. By using any of these methods, single layering can be done. The third way is to solve the timber plates as a box system, where plates are joined to each other as a box, by placing joists either at the periphery or at the center of the plates and then joined individually box to box. With this method, double layering can be done.

3.3 **Finding solutions**

To find solutions for the connections, few pointers needs to be kept in mind. Few examples are :
- Which type of connection to use i.e. will it be a steel joint, plate joint or combination of both or a box system?
- Are the connections made in timber, metal or adhesives?
- How the load transfer takes place in the structure? What all forces acts upon the structure; compression, shear forces, bending moments, stresses?
- Type of timber wood to use? plywood, CLT, LVL or ghulam?

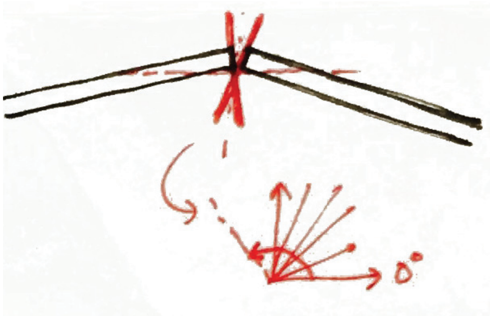


Figure 3.3.1: for 100 plates; 100 different angles. Therefore, find that 1 connection with changeable angles.

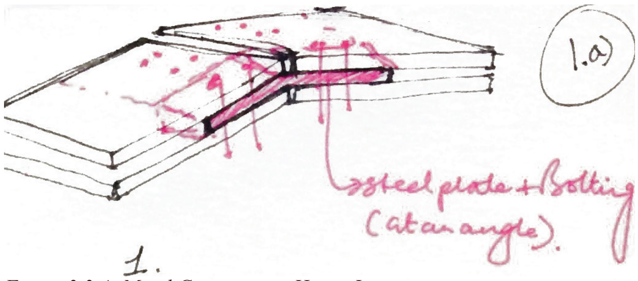


Figure 3.3.4: Metal Connection - Hinge Joint

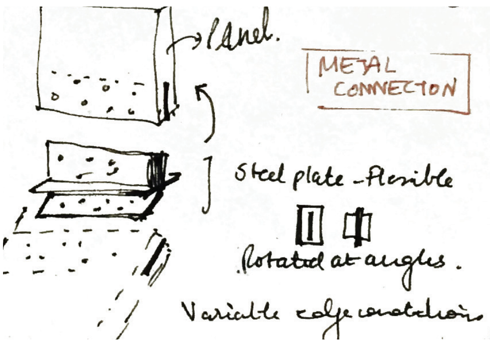


Figure 3.3.2: Metal Connection - Hinge Joint

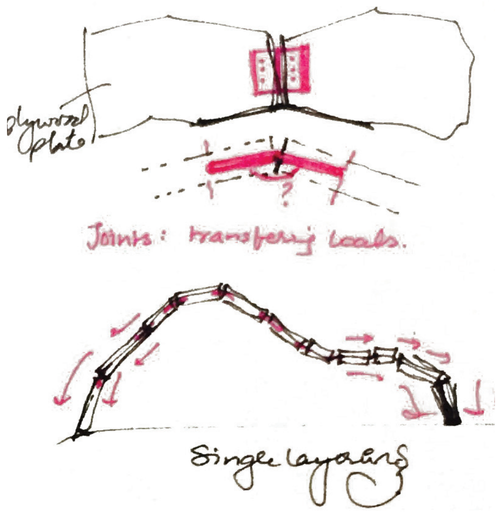


Figure 3.3.5: Metal Timber Connection - single layering

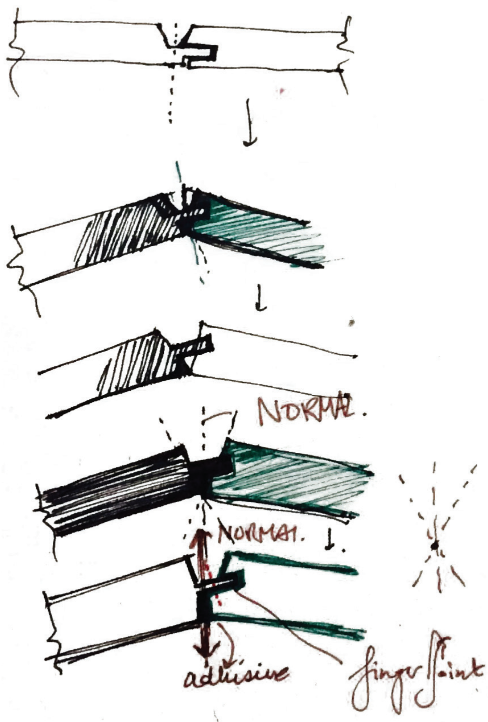


Figure 3.3.3: Timber Connection - Hinge Joint

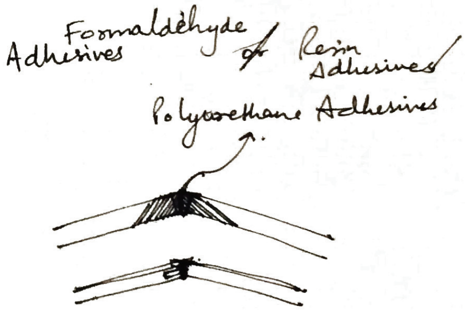


Figure 3.3.6: Adhesive Connection

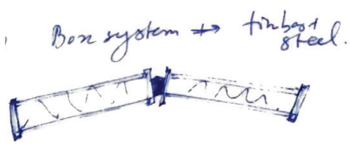


Figure 3.3.7: Box System-double layering

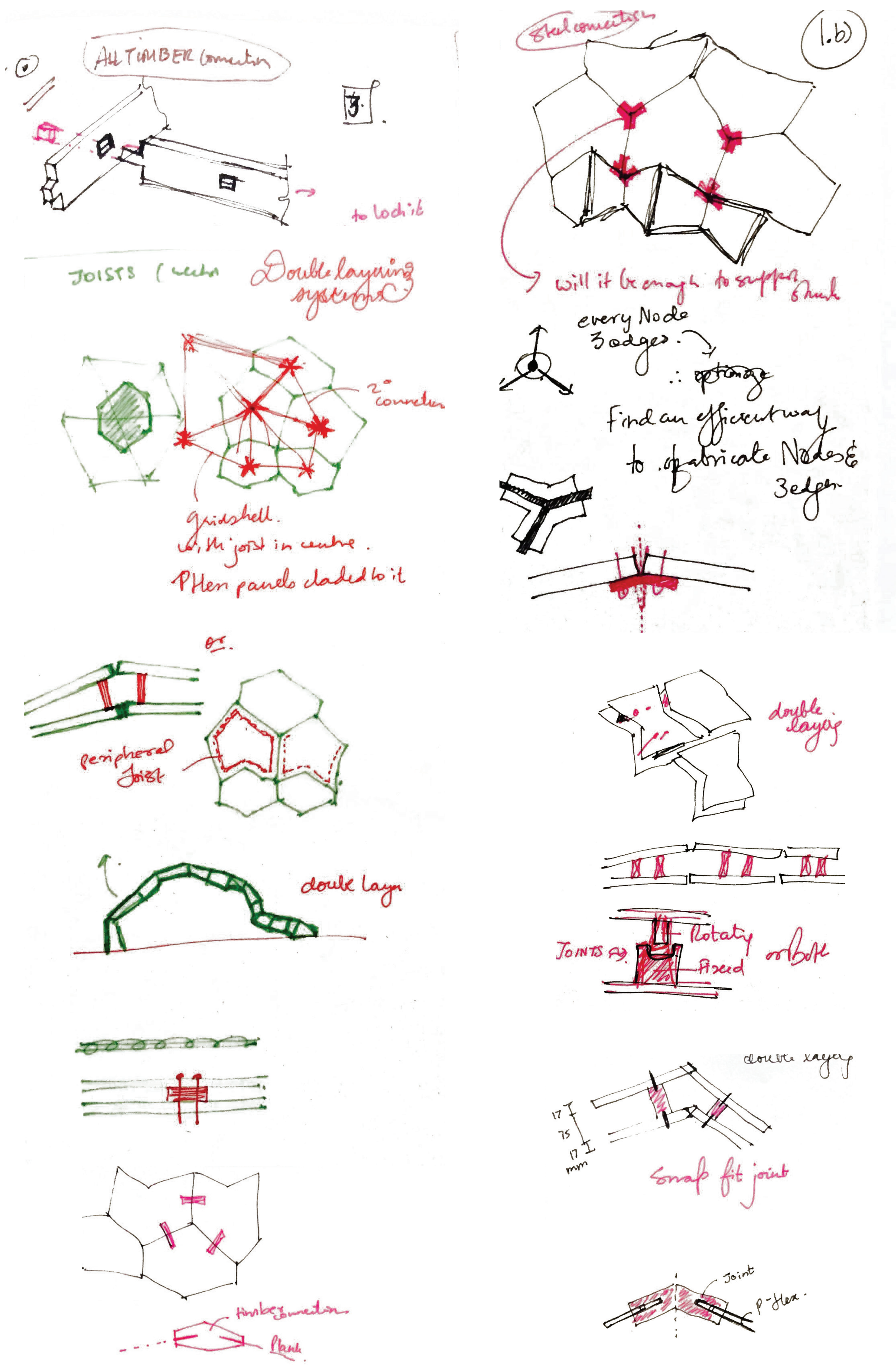


Figure 3.3.8: Timber Connections

3.4 Physical Experimentation - Testing on 3 adjacent plates

3.4.1 Experiments conducted to study type of connection

To understand the behavior of the structure, 3 adjacent plate from PHex double curvature surface is chosen. These plates shows synclastic properties with convex curvature where K>0.

Figure 3.4.1.1: Testing on 3 adjacent plates on double curvature PHex Surface

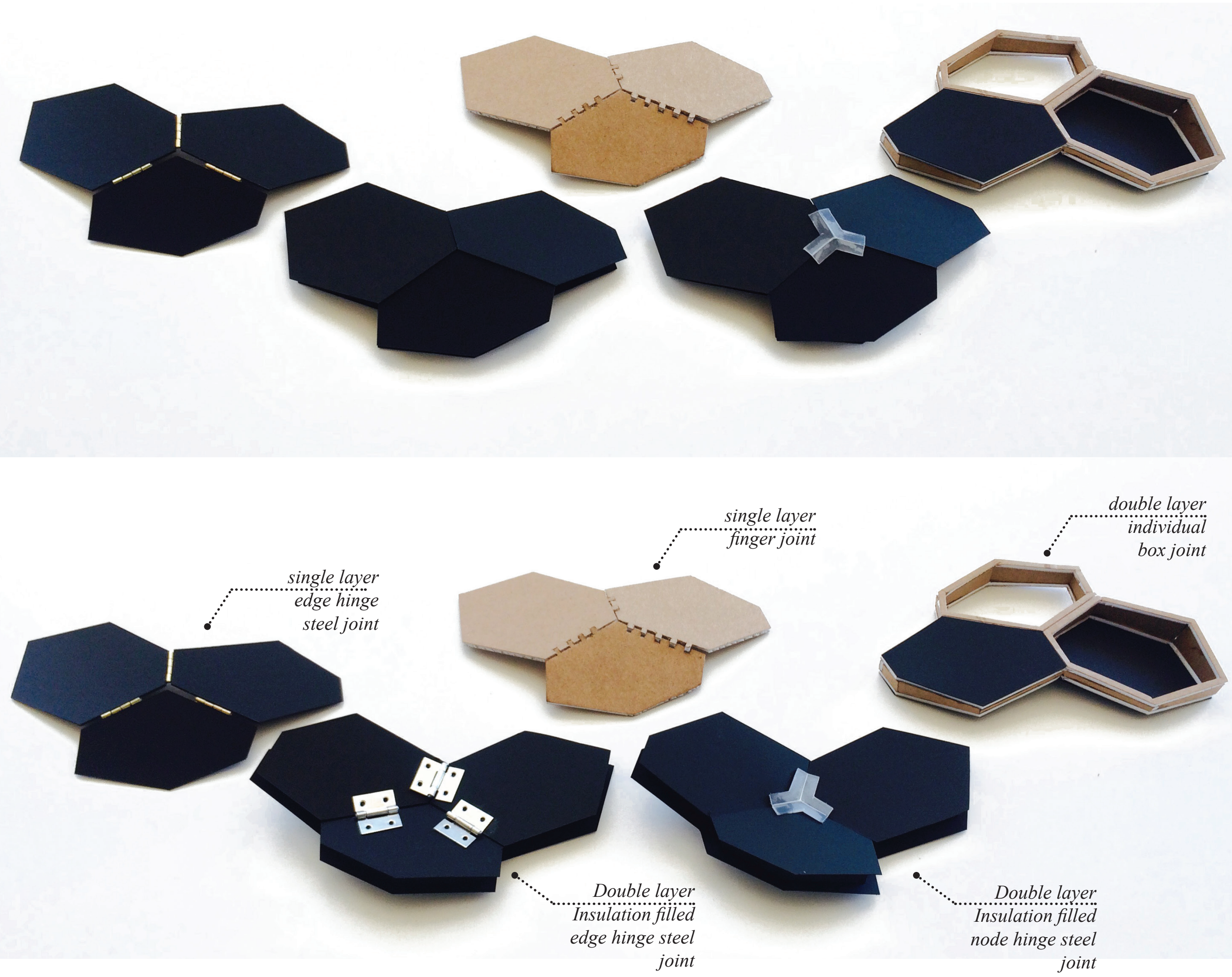


Figure 3.4.1.2: 5 connection options

3.4.2 Joint Systems

Option 01- the plates for both interior and exterior sides can be joined together either by a hinge steel joint at the edge or at the node. The exterior plate can have an extended surface for waterproofing, placed such that the water follows the drainage route. It can be filled with insulation for weather and thermal protection. In this way, a double layering box system can be formed.

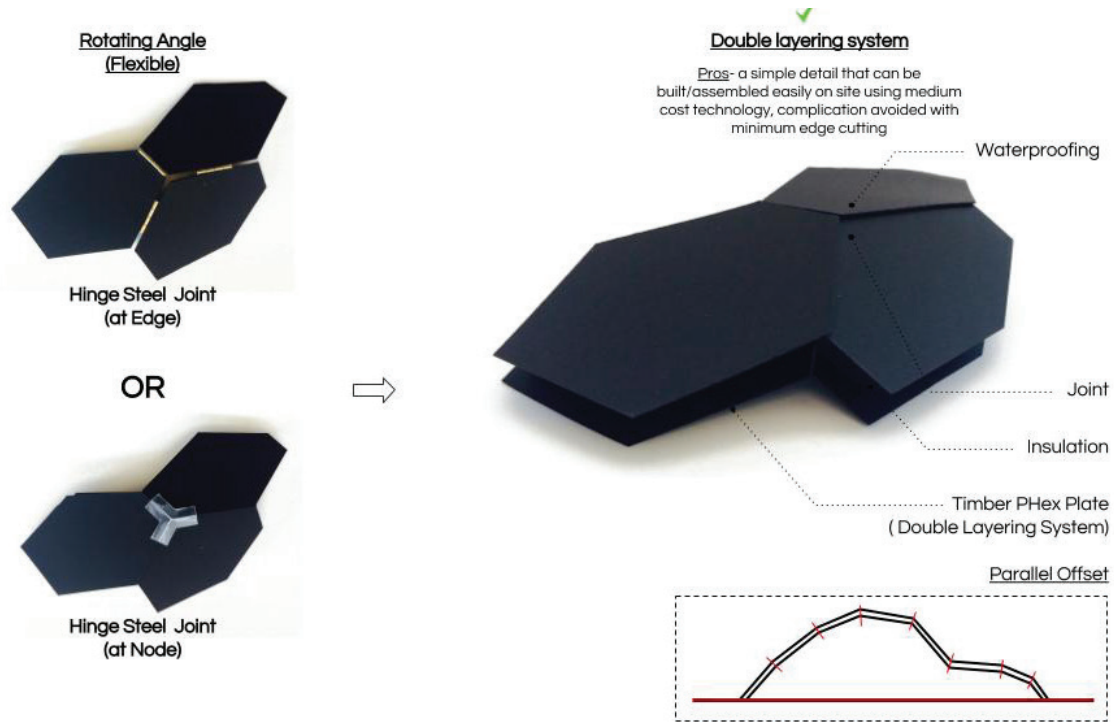


Figure 3.4.2.1: Option 01, double layering box system

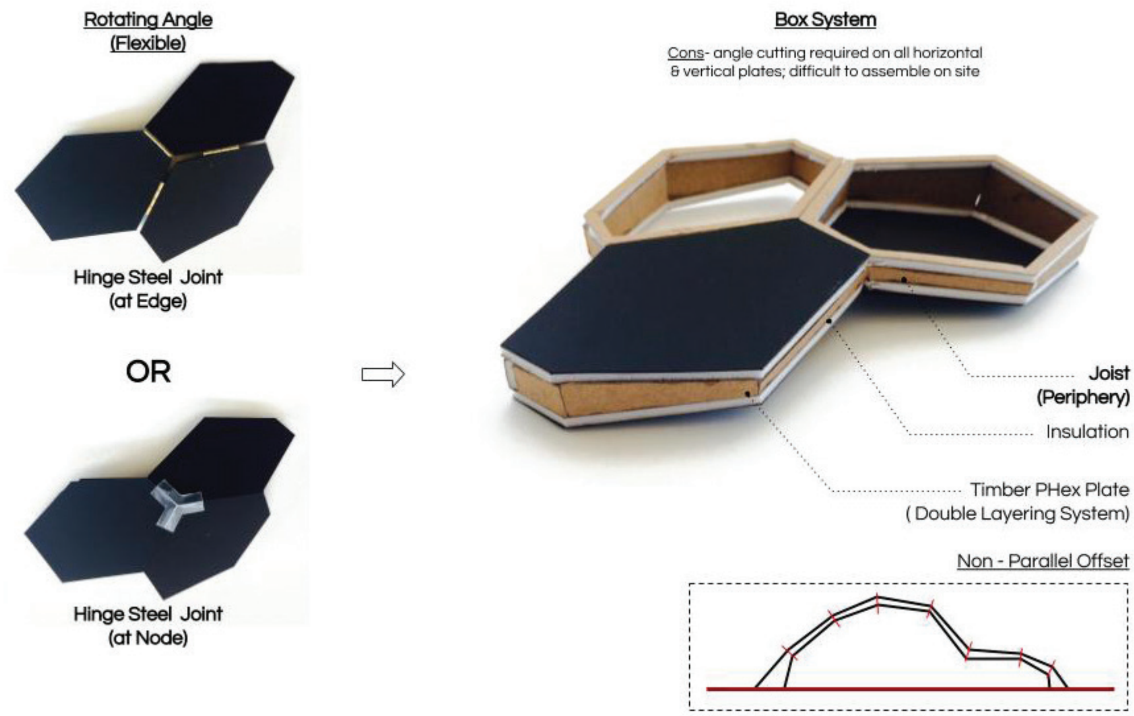


Figure 3.4.2.2: Option 02, double layering box system

Option 02- the boxes are formed individually with joist placed at periphery. The 3 individual boxes are then connected together by a hinge steel joint at the edge or at the node. This option gives the flexibility to create non-parallel offsets as it dimension of vertical joist plates are changeable.

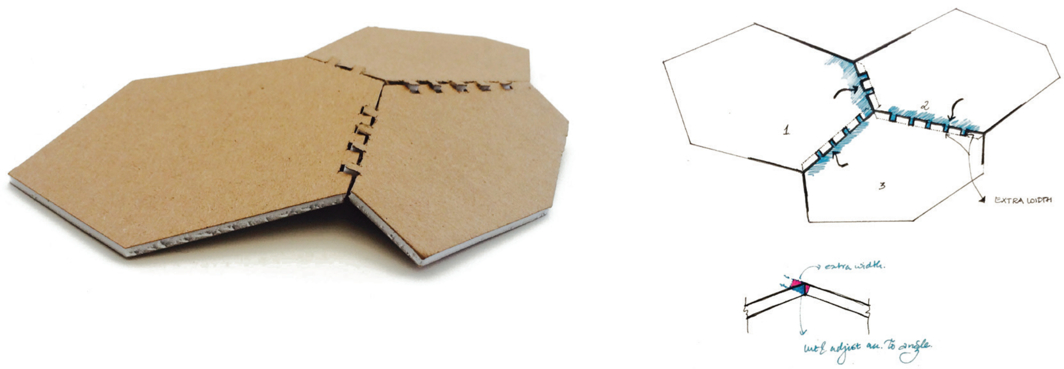


Figure 3.4.2.3: Option 03, single layering system

Option 03- plates can be joined together by finger joint in such a way that they achieve the desired angle required. But this option restricts this possibility because the 3 plates have to be flat first, then joined by finger joint and rotated to achieve the desired angle. It would be difficult to grow the plates when forming entire structure.

3.4.3 Steel Connections

To deal with the various angles of PHex form, it is important that the steel connection is flexible enough to be fixed at the desired angle. For example, in case of door hinges, the steel joint gives such flexibility to rotate the door. Similar concept can be applied to deal with changing angles of PHex form. The rotational stiffness and shear forces have to be kept in mind while dealing with steel connections.

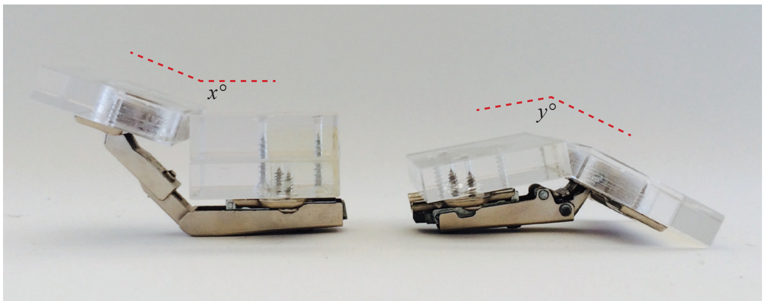


Figure 3.4.3.1: steel door hinges - obtuse & reflex angle

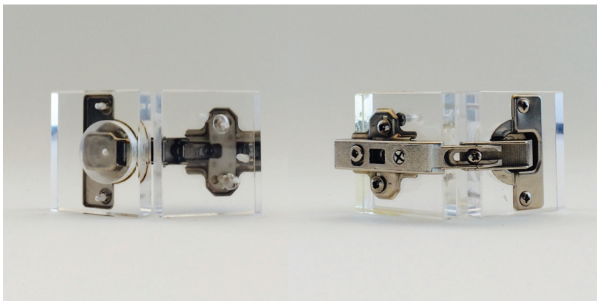


Figure 3.4.3.2: steel door hinges - front & back view

3.5 <u>Research Questions & answers for solving the appropriate connection</u>

Inference - while finding solutions for an appropriate joint, the process lead to develop further questions that needs to be answered in order to solve the connection.
Therefore, a double curvature is taken and then optimized into PHex surface digitally and then analyzed to understand the behavior of the connection detail and hence choosing the most optimized connection detail and applied on the entire structure. This will provide a new way to achieve a PHex Building Structure. This will be discovered in the further chapters.

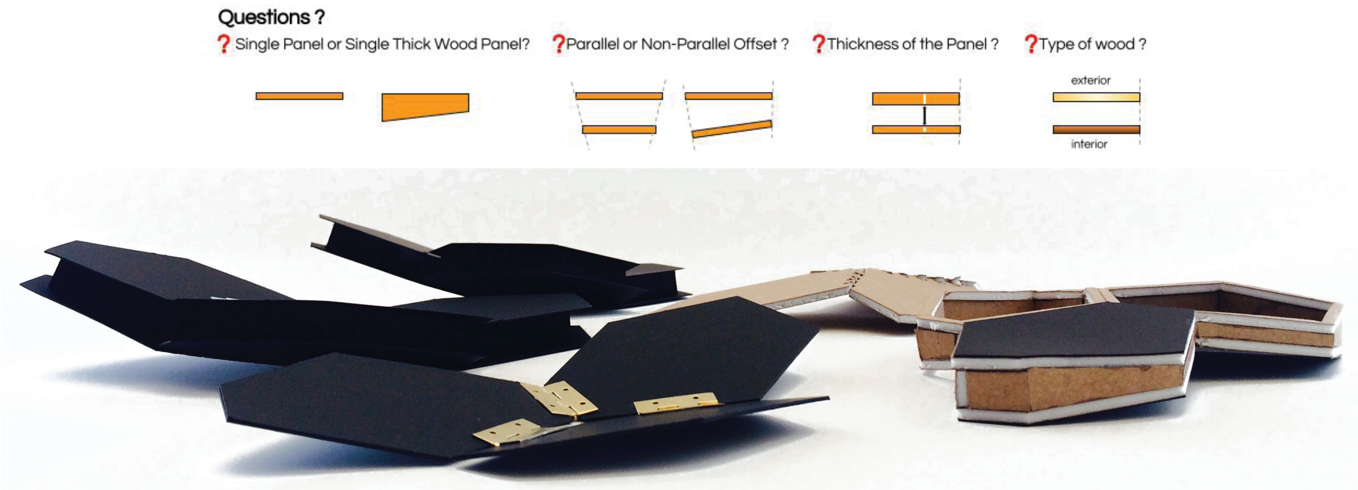


Figure 3.5.1: physical model view

4. FORM FINDING & OPTIMIZATION FOR PHEX SURFACE

4.1 Digital experimentation for a double curvature surface

The building form is a part of torus. Being a double curvature surface, the form shows synclastic and anticlastic properties. The opening sizes are - 8.0X3.0m and 4.5mX10m.

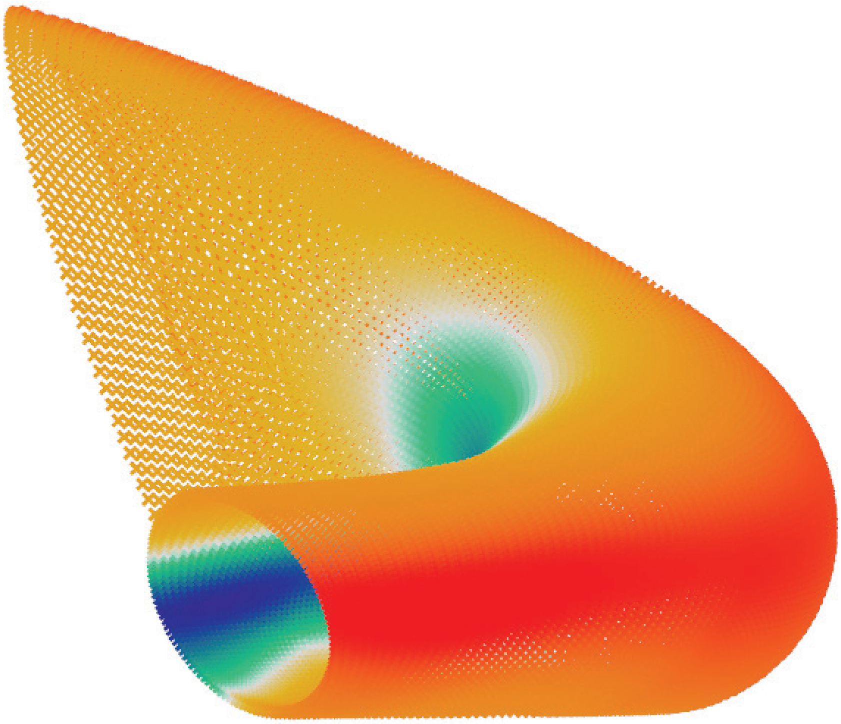


Figure 4.1.1: torus form showing synclastic & anticlastic properties

4.2 Planar Clustering (topology behavior)

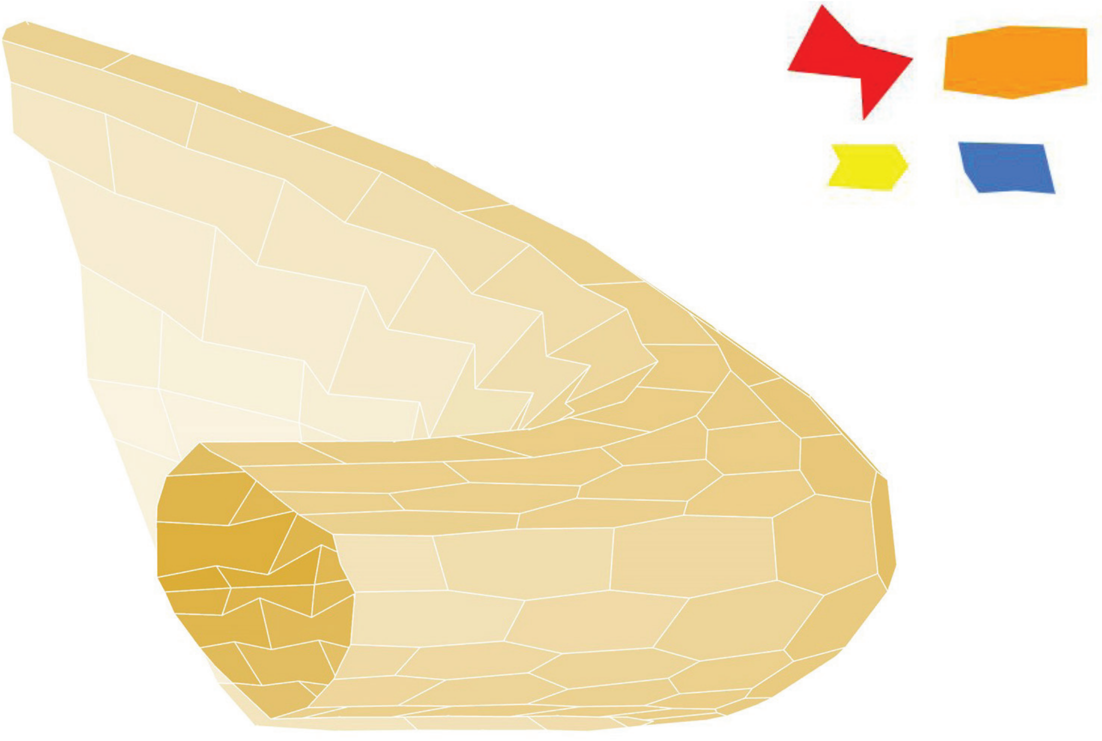


Figure 4.2.1: Phex Optimized torus form / Properties

The torus form is approximated into a PHex form by dynamic relaxation method. The only constraint to achieve this form is that the test for individual geometry/surface has to be true.

The PHex form has been cut at the base in order to form a building structure. This building Phex form will be used for analysis and for solving connection details.
The PHex surface comprises 134 hexagon plates. The opening sizes are - 8.0X3.0m and 4.5mX10m. The plate edge size ranges from minimum of 200mm to maximum of 3300mm length.

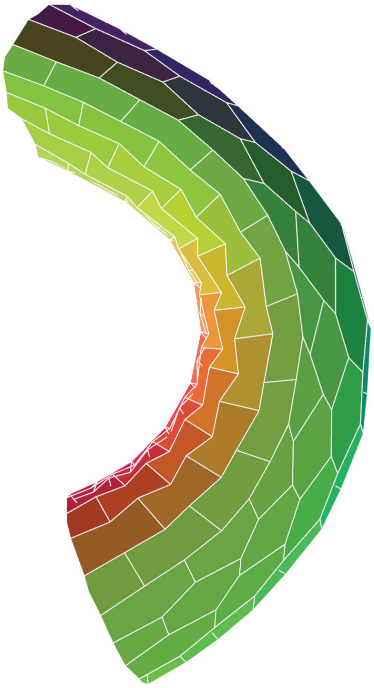


Figure 4.2.2: Phex surface, top view

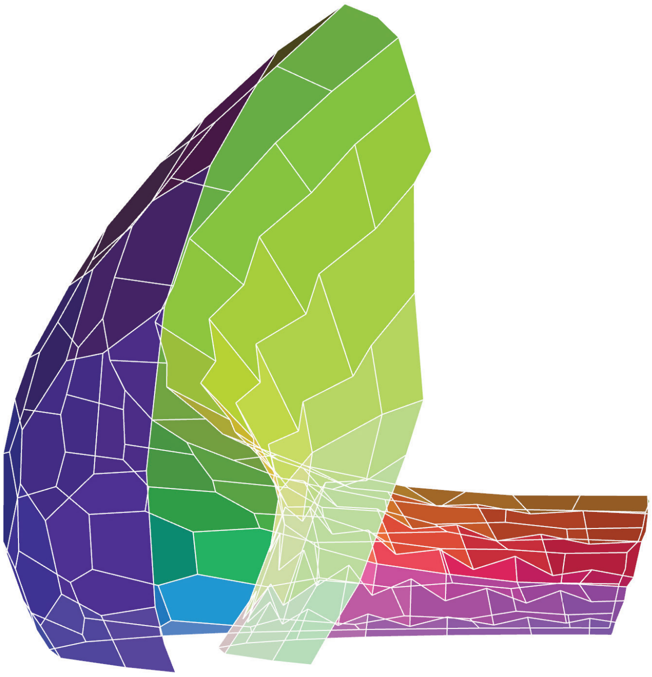


Figure 4.2.3: Phex surface, perspective view

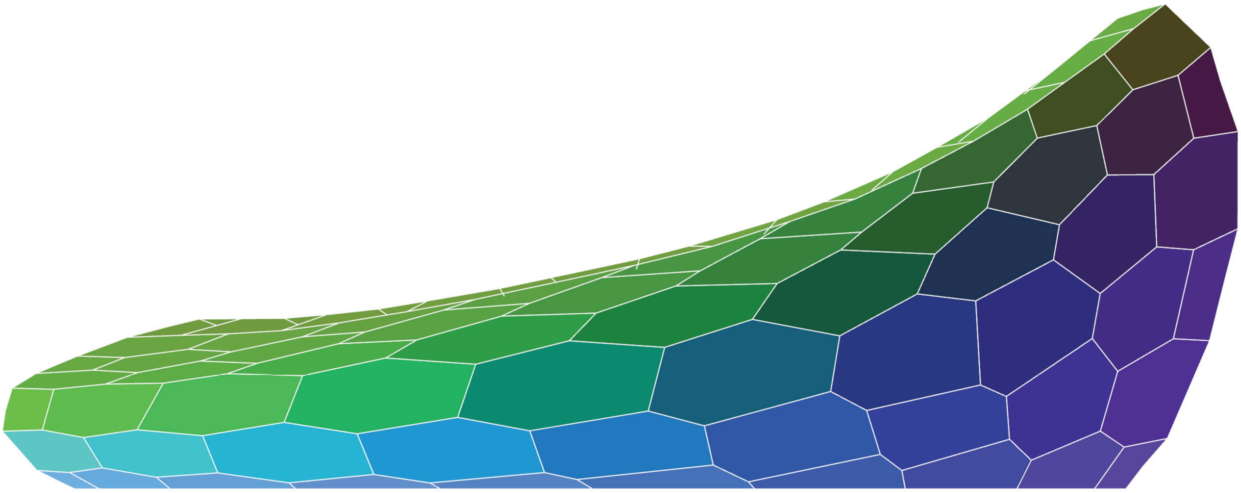


Figure 4.2.4: Phex surface, side view

4.3 Structural Analysis

4.3.1 Experiments conducted for different cross-sections and thickness - option 01/ option 02

Option 01 - shell 3cm thickness,
Option 02 - shell 30cm thickness.

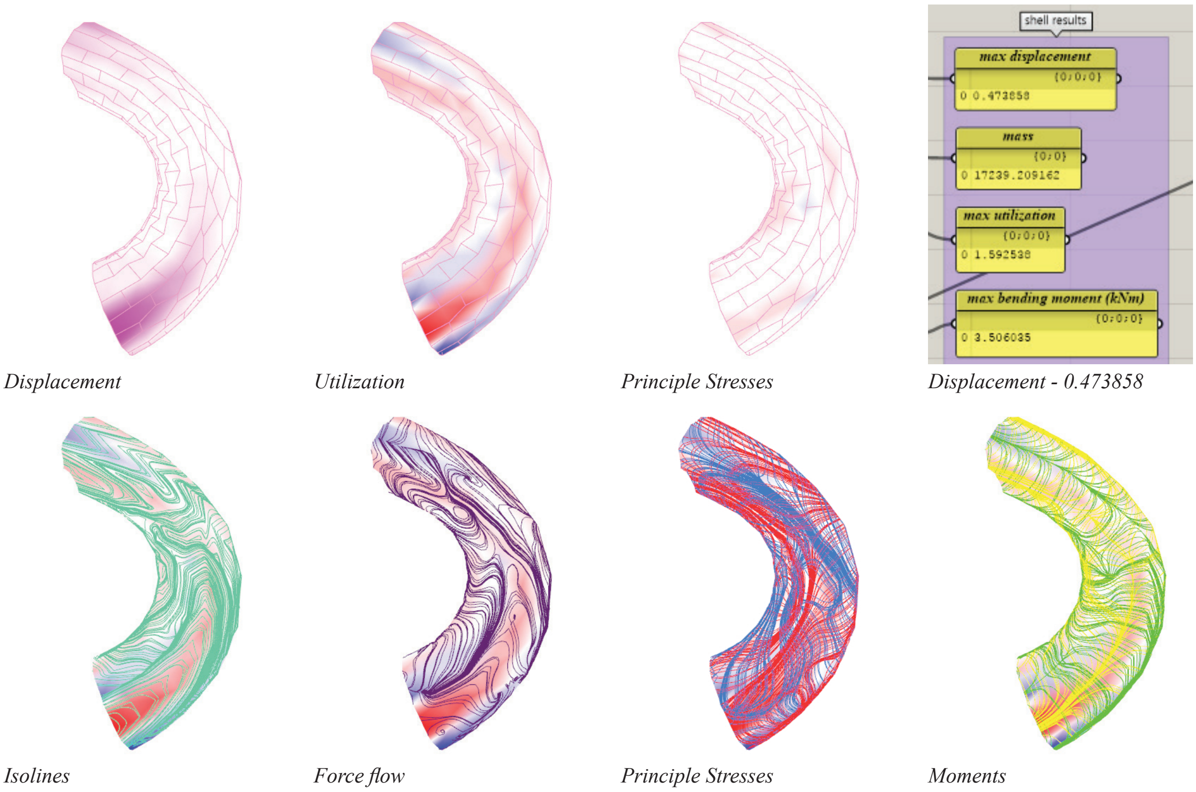


Figure 4.3.1.1: Analysis for option 01

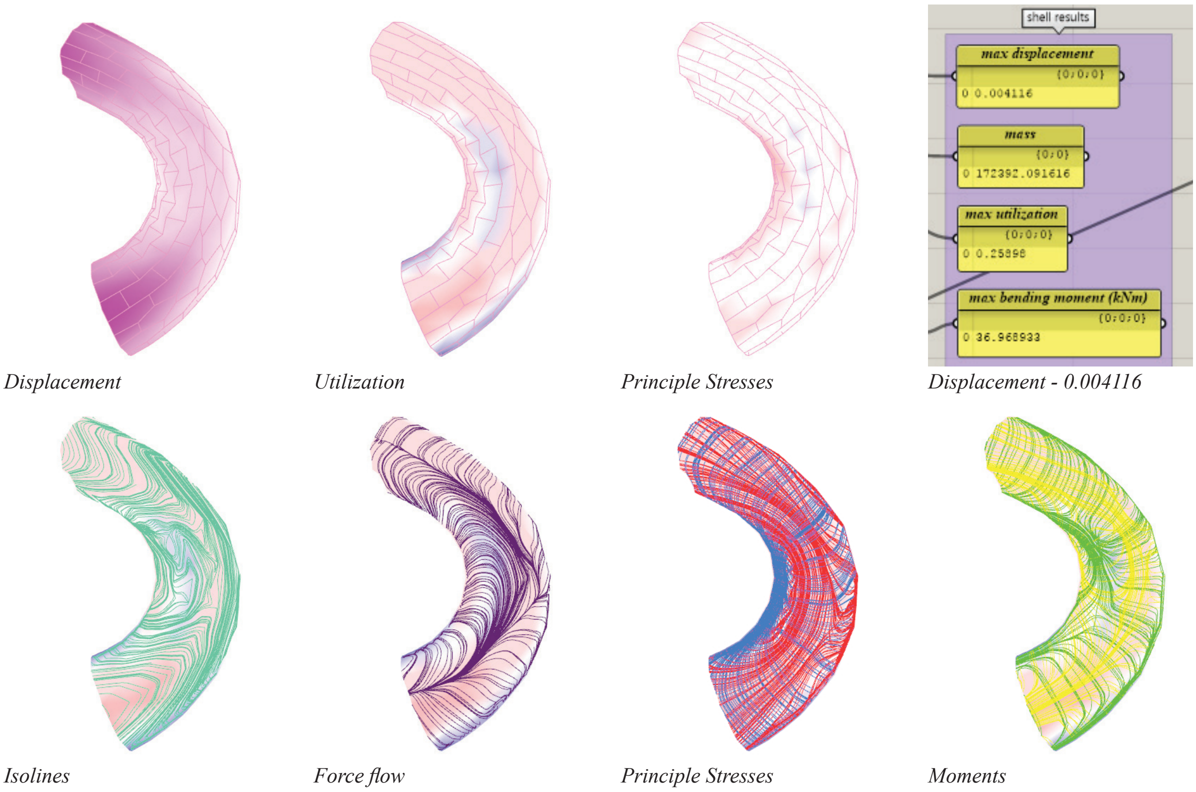


Figure 4.3.1.2: Analysis for option 02

4.3.2 Analysis results

The 3 plate edges always meet together at just 1 point (NODE), a principle which enables the transmission of normal and shear forces. Plate Structures transfers internal forces across edges not only through axial forces but also through in plane shear forces. Therefore, either the node has to be solved or edge or both for load transfer.

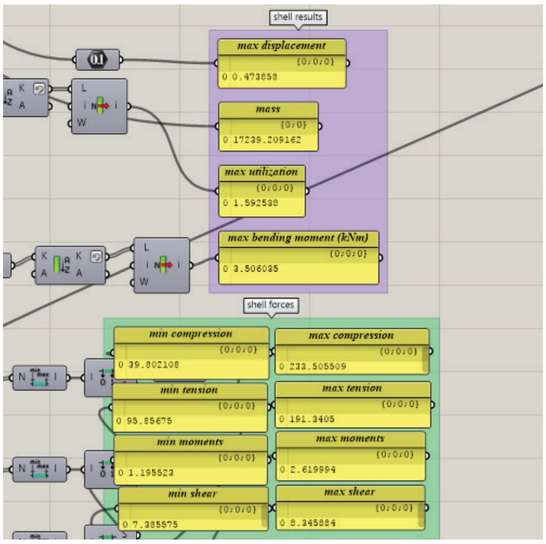


Figure 4.3.2.1: Analysis result for option 01

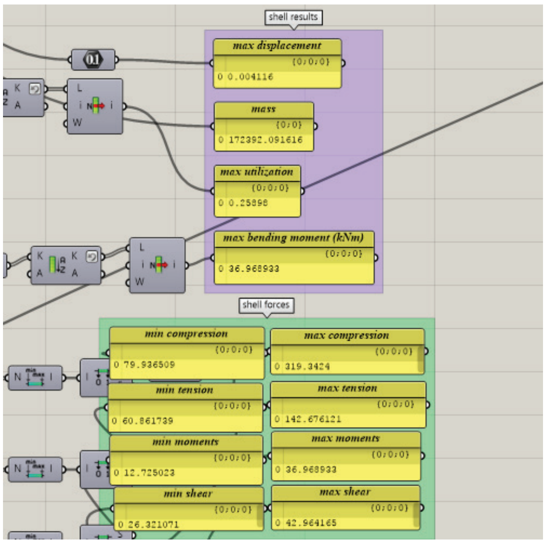


Figure 4.3.2.2: Analysis result for option 02

Option 02 gives minimum displacement, minimum stresses, minimum bending moment. Therefore, maximum height of the structure can be achieved.

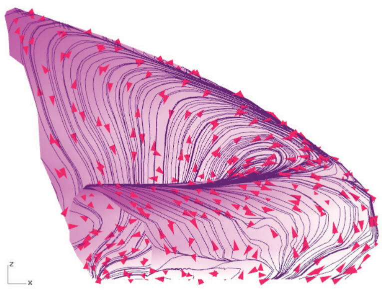


Figure 4.3.2.3: force flow lines to understand load distribution

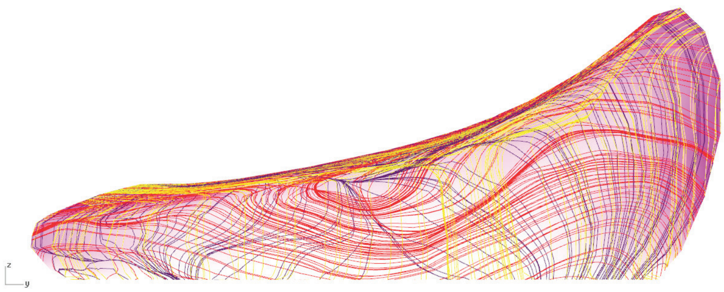
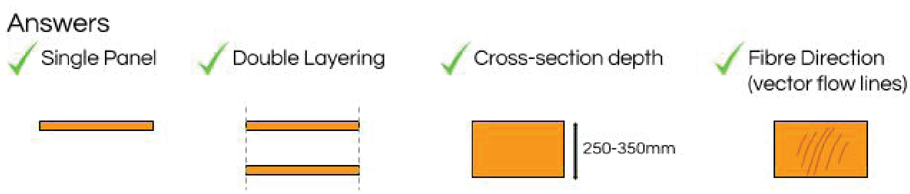


Figure 4.3.2.4: force, displacement, moments, stress combined

Inferences -

- Ground Anchoring (more supports means less displacement) can be done to resist wind loads
- Double Layering of 250-350 mm with insulation would be a viable option
- Fibre direction (align with force flow lines to get most effective layout and pattern)



4.4 Permutation & Combination for choosing the optimum connection for fabrication

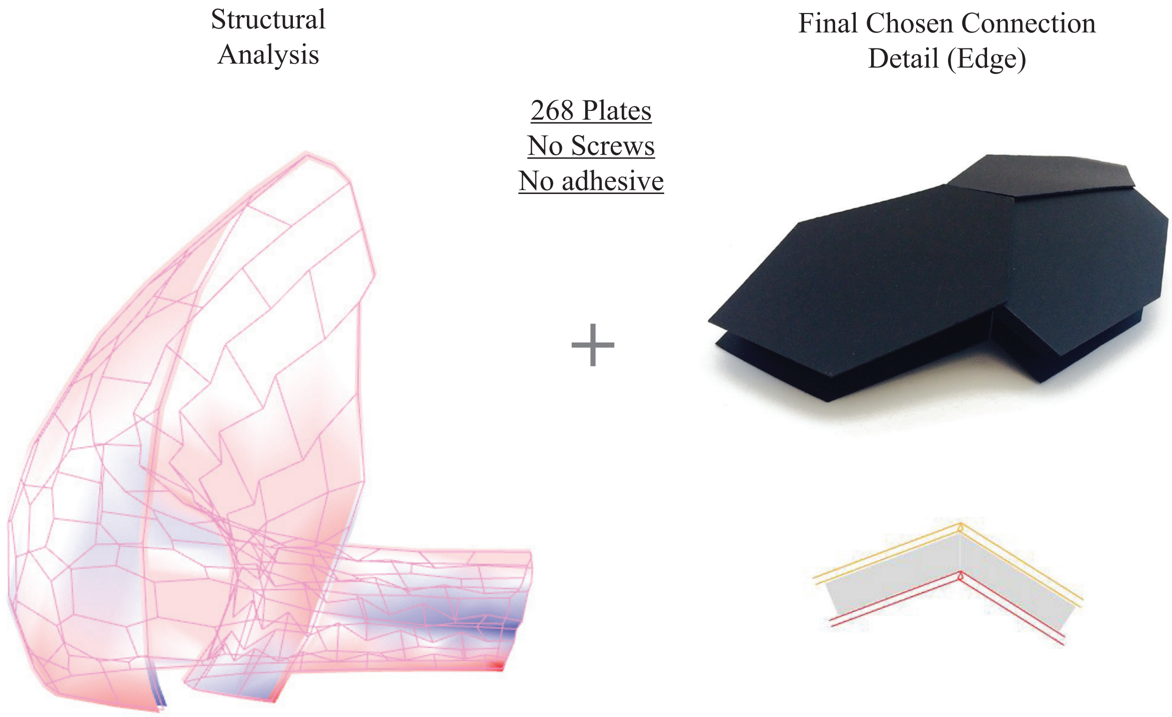


Figure 4.5.1: final form and connection detail

• Combining experimentation results from structural Analysis & connections, hence implementing on the PHex building form
• Choosing the most optimum joint for fabrication & finding the answers...

5. FABRICATION OF TIMBER PLATE STRUCTUREs

5.1 Digital experimentation for the PHex surface - Testing on 3 adjacent plates

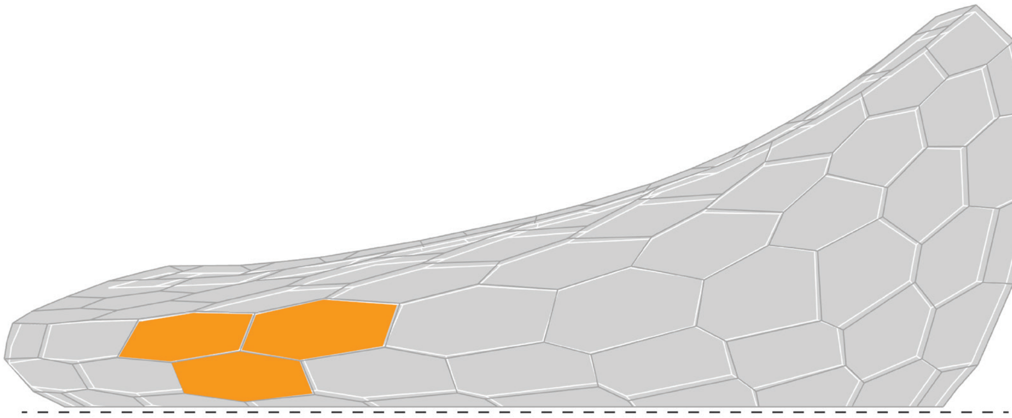


Figure 5.1.1: 3 adjacent plates selected for further study, both interior & exterior sides

For further research, 3 adjacent plates of interconnected interior & exterior sides are selected. These plates shows synclastic properties with convex curvature where K>0.

5.2 Solving Connection Detail - Prototype Production for 3 adjacent plates

For prototype production, the 3 adjacent plates are studied on the basis of the following 5 pointers :
1) Joint Geometry Generation
2) Connection Generation
3) Fabrication process
4) 3 plate Assembly
5) 3 Plate Finished prototype
For solving the connection detail, the 3 materials that are studied are as follows ;
A) Timber
B) Steel
C) Insulation
These pointers will help in achieving a double layered box system timber plate prototype, which can be applied to any plate to build the entire PHex structure.

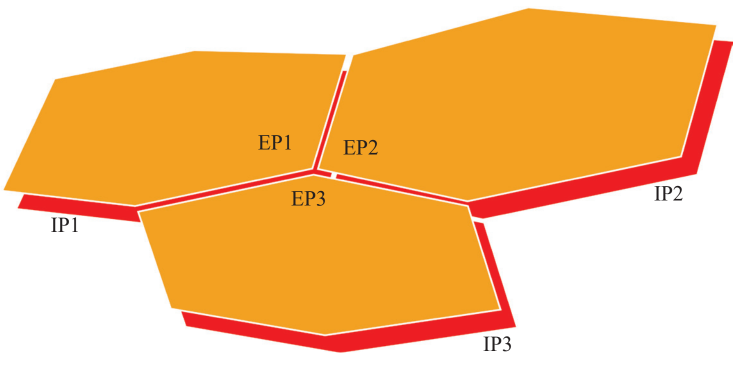


Figure 5.2.1: 6 plates; EP = exterior timber plate; IP = Interior timber plate

5.2.1 <u>Joint Geometry Generation - timber; steel; insulation</u>

5.2.1.A Timber - Material, Size, Thickness, Fibre Direction

Type of wood : **Timber structural plywood**
Thickness : 21 mm
Board Size : 3000 X 1200 mm
Grade : CD

Figure 5.2.1.A.1: timber plywood

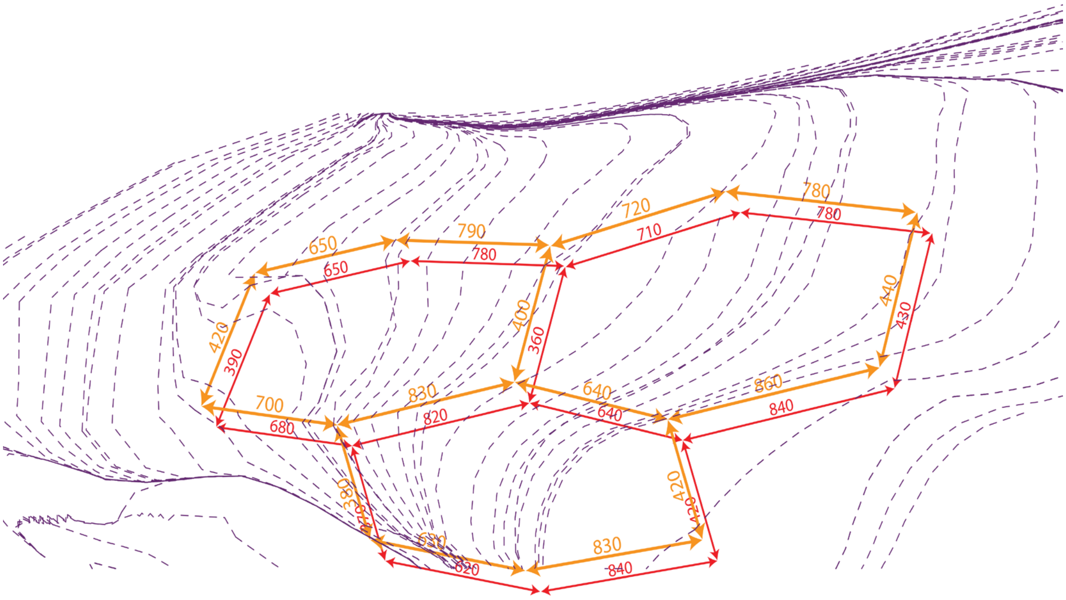


Figure 5.2.1.A.2: plate size and fibre direction of plates

The exterior plates edge length varies from 400mm to 860mm and the interior plates edge length varies from 360mm to 840mm. This size of hexagon can be cut from 21mm thick, 3000 X 1200mm timber structural plywood. The fibre direction will decide the Grain Direction for Orientation of timber plate.

Timber - Angles for Interior Plates

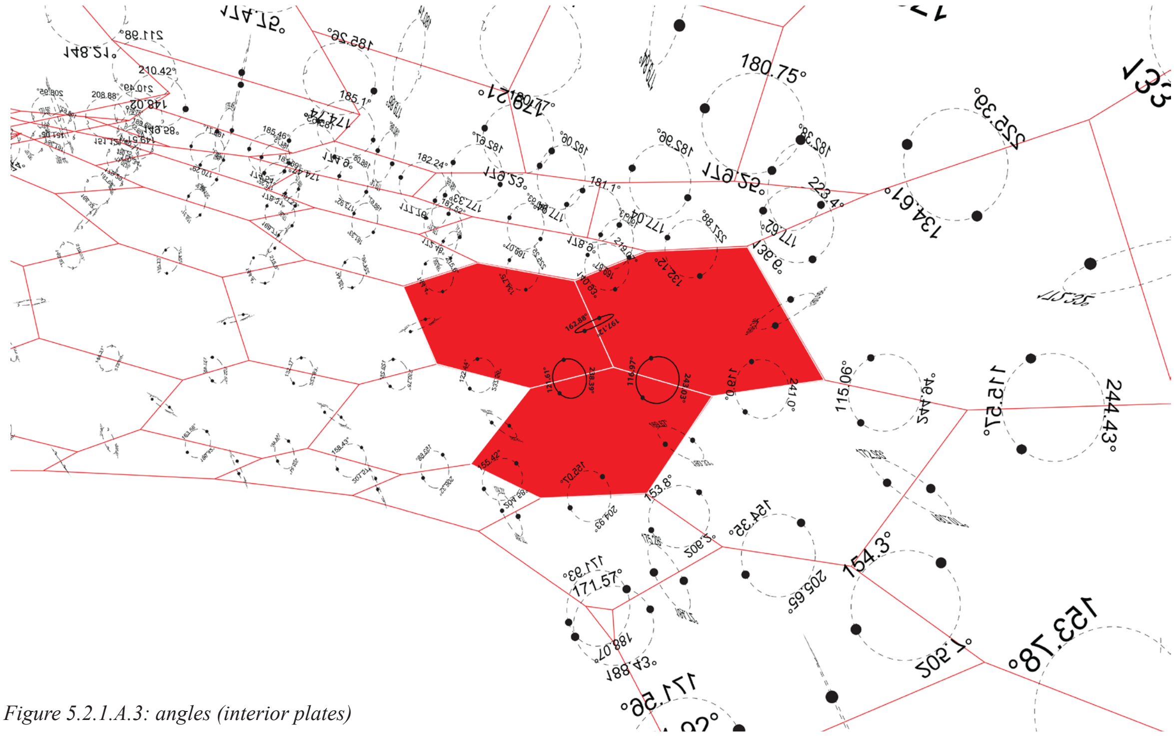


Figure 5.2.1.A.3: angles (interior plates)

The plates have 353 interior angles. The Minimum Interior Angle is 113.96° and Maximum Interior Angle is 186.72°. The interior obtuse angle between IP1 and IP2 is 162.88°, between IP1 and IP3 is 116.97° and between IP2 and IP3 is 121.61°. The exterior reflex angle between IP1 and IP2 is 197.12°, between IP1 and IP3 is 243.03° and between IP2 and IP3 is 238.39°.

Timber - Angles for Exterior Plates

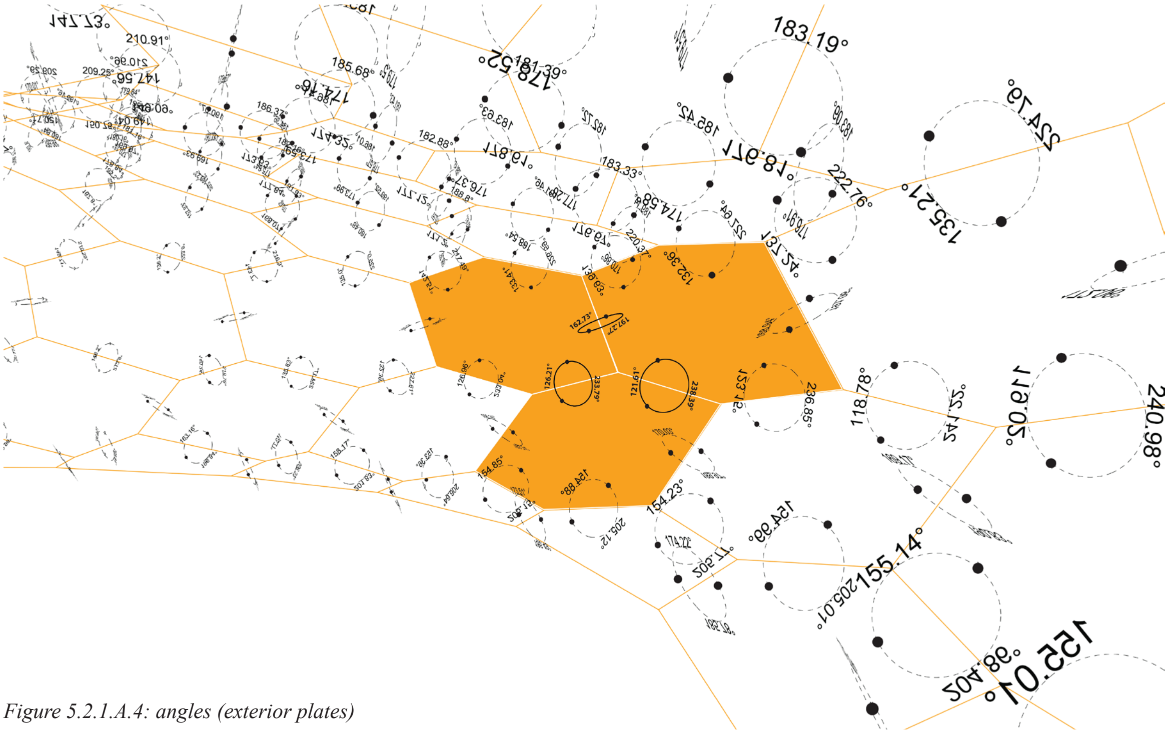


Figure 5.2.1.A.4: angles (exterior plates)

The plates have 346 interior angles. The Minimum Interior Angle is 122.66° and Maximum Interior Angle is 186.60°. The interior obtuse angle between EP1 and EP2 is 162.73°, between EP1 and EP3 is 121.61° and between EP2 and EP3 is 126.21°. The exterior reflex angle between EP1 and EP2 is 197.27°, between EP1 and EP3 is 238.39° and between EP2 and EP3 is 233.79°.

5.2.1.B   Steel Plate - Material, Size, Thickness, Angle

Angle L-Bracket

Fixed
Bends at the required angle

Angle Hinge Brack-

Flexible
Rotates at the required angle

The material will be stainless steel, with custom size and angle according to the design requirement and with minimum sheet thickness of 4mm. The steel plate can either be an angle L-Bracket which is bent at the required angle and then joined to the timber plate or an angle Hinge bracket which can be rotated at the desired angle. In this case a single plate will need to be designed which can be rotated to the maximum angle of 186.72°.

5.2.1.C Insulation - Material, Size, Thickness, Angle

Type of insulation : **Flexible Wood Fibre Insulation board**
Available Thickness(mm) :
40 50 60 80 100 120 140 160 180 200 220 **240**
Sawing & Milling : boards cut to size and edges milled
(custom size)
Standard Size : 1350 X 575 mm
Dry Process Installation in single course

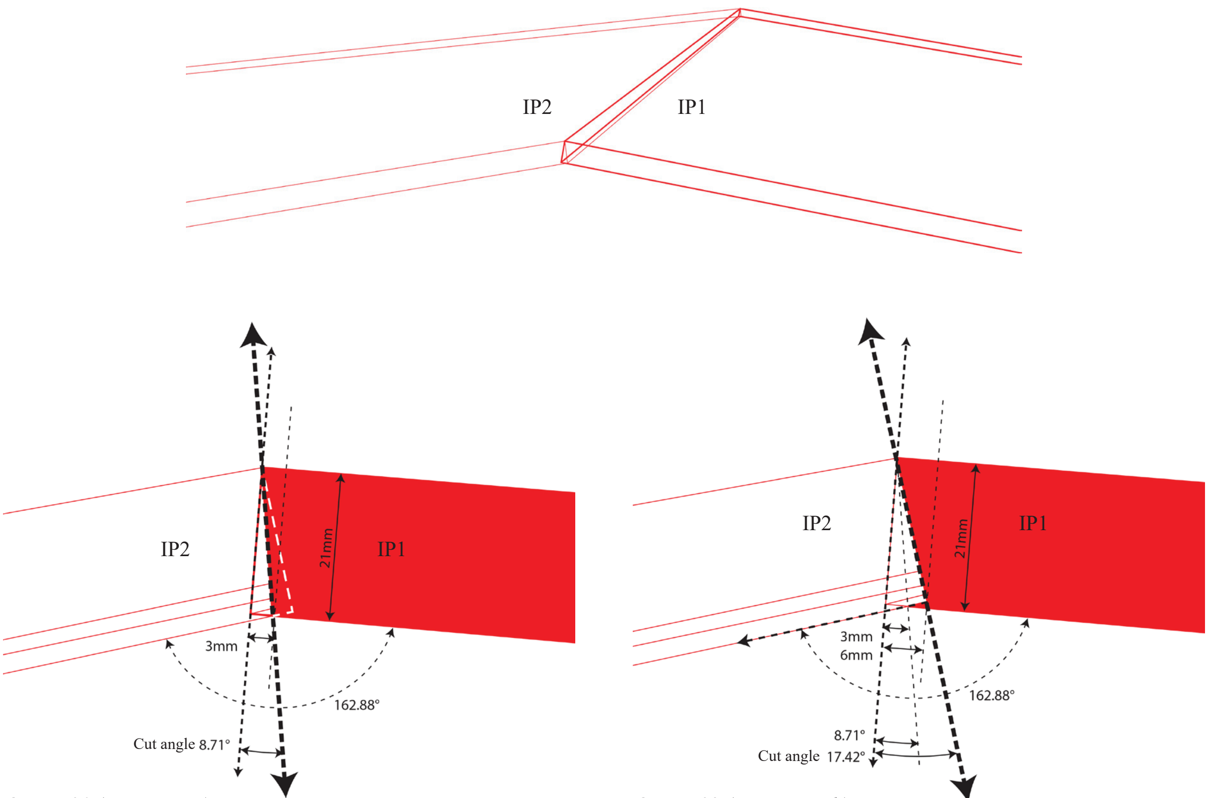
Figure 5.2.1.C.1: wood fibre insulation board Gutex)

The insulation is lightweight, therefore the weight of the structure is less. It helps in following protections : Humidity Under Control; Durable Weather Protection; Fire protection and Acoustic Insulation.

5.2.2 <u>Connection Generation - timber; steel</u>

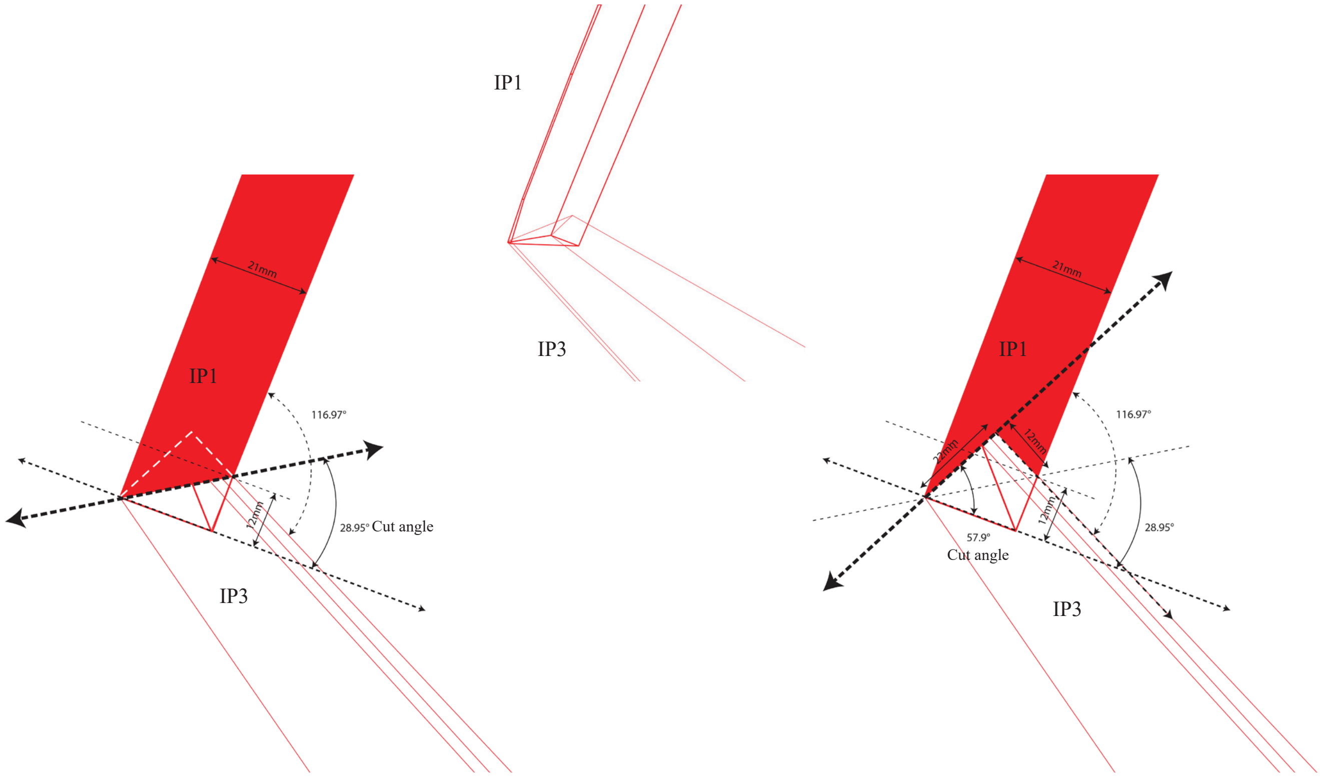
5.2.2.A Timber - Solving intersections for interior plates

Intersections has been solved for the 3 interconnected edges. Option 01 solves intersection at the point where the two edges of the plates intersects each other, i.e. the common sharing edge between two plates. Option 02 solves intersection at the point where one plate meets the other plate, i.e., one plate has a square notch which combines with a non-cut plate. Option 01 is more feasible because of minimum splintering in the plates. This method has been used to avoid screws and adhesives in the plate structure. The 3 intersections solved for interior plates between IP1 and IP2 ; IP1 and IP3; IP2 and IP3 respectively are as follows :



Option 01 (intersection) *Option 02 (square notch)*

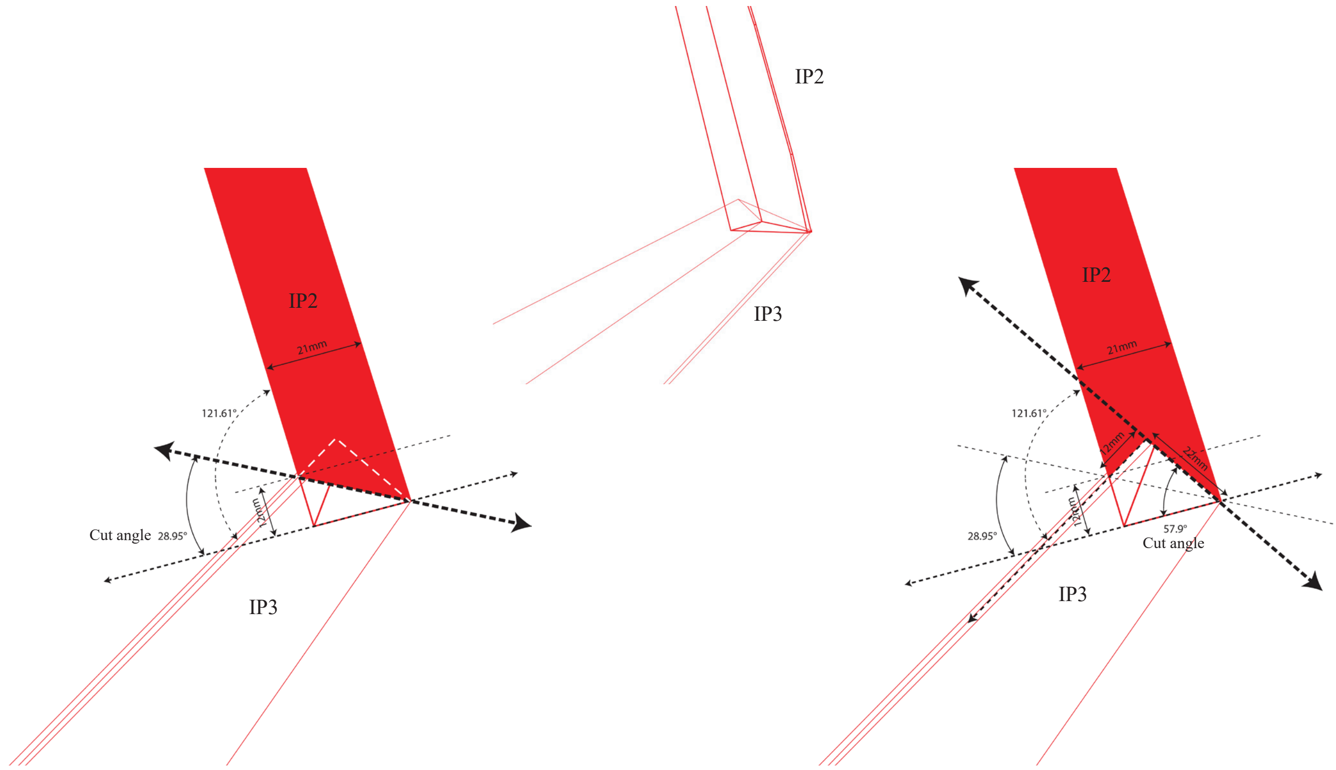
Figure 5.2.2.A.1: solving intersection between plate IP1 and IP2; cut angle = 8.71°



Option 01 (intersection)

Option 02 (square notch)

Figure 5.2.2.A.2: solving intersection between plate IP1 and IP3; cut angle = 28.95°



Option 01 (intersection)

Option 02 (square notch)

Figure 5.2.2.A.3: solving intersection between plate IP2 and IP3; cut angle = 28.95°

Timber - Solving intersections for exterior plates

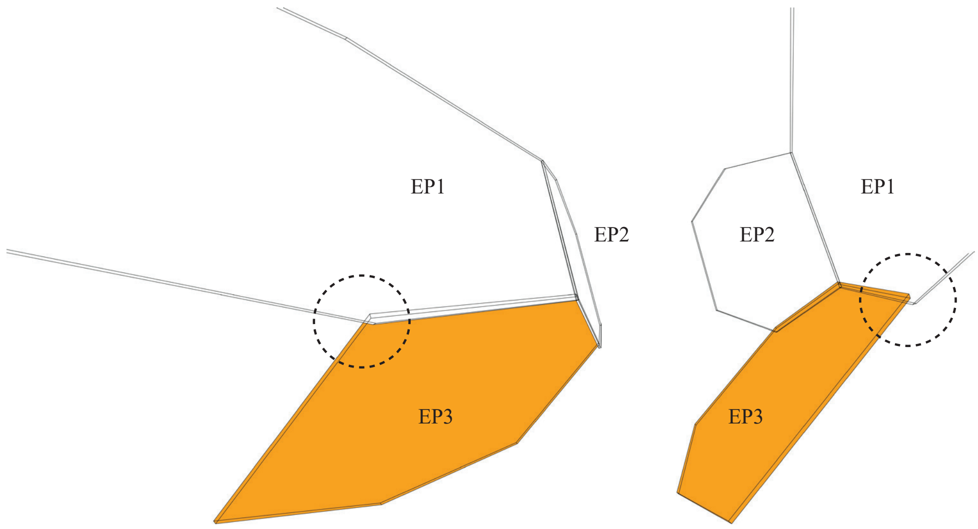


Figure 5.2.2.A.4: solving intersection between plate EP1,EP2,EP3

Intersections has been solved for the 3 interconnected edges. The upper plate is extended by 20mm over the timber plate below for waterproofing purposes. This overlap has been used for proper drainage across the entire structure. The 2 intersections solved for exterior plates between EP1,EP2 with EP3 is shown above.

5.2.2.B Steel Hinge / Bracket location

The connection location for the steel plate can either be at the center of the plates edges or placed at a distance from the center. The 2 options are as follows :

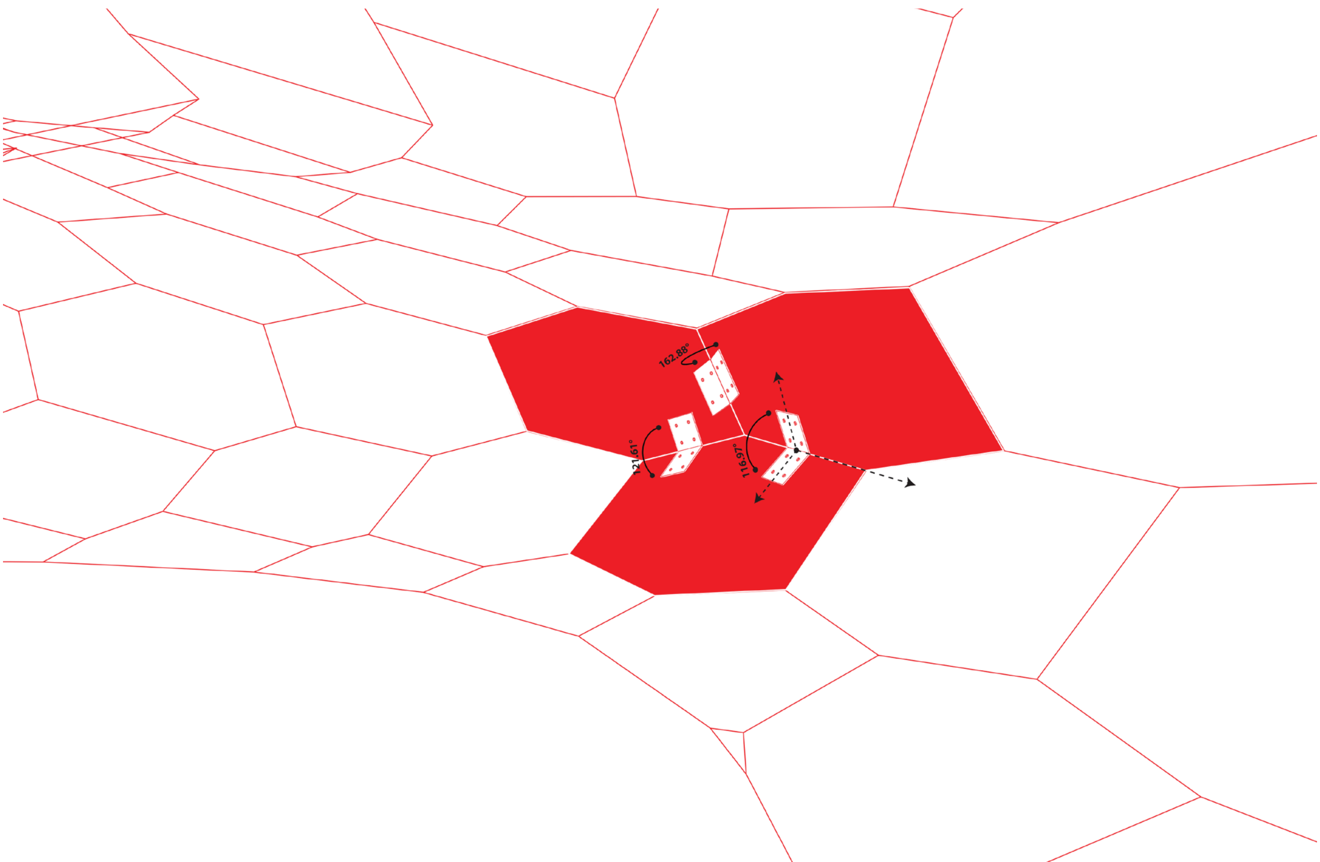


Figure 5.2.2.B.1: option 01; steel plate located at center

The connection location for the steel plate is at the center of the plate edge.
Plate size = 240X180X4 mm; Minimum Angle = 113.96°; Maximum Angle = 186.72°

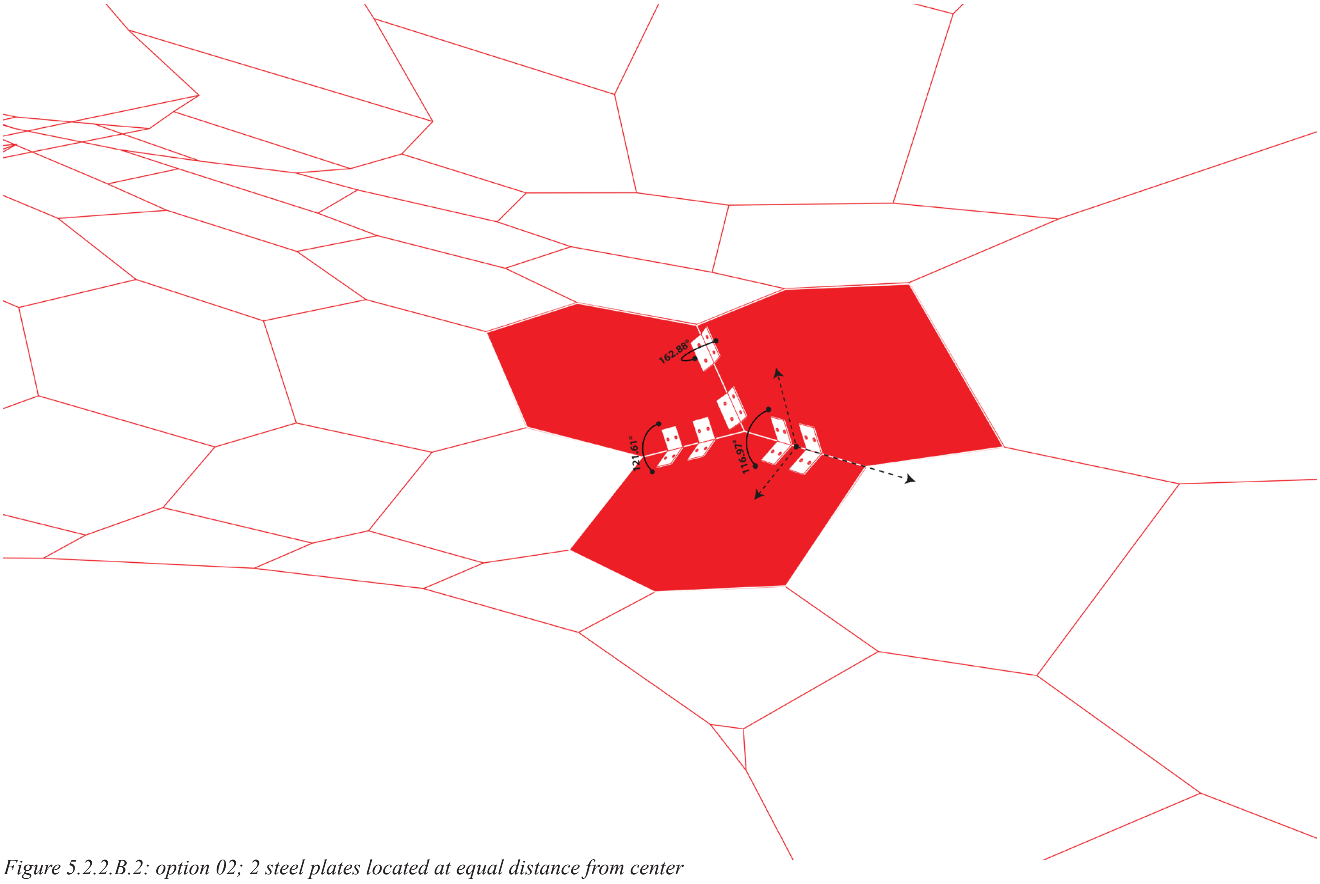


Figure 5.2.2.B.2: option 02; 2 steel plates located at equal distance from center

The connection location for the steel plate is at equal distance from center of the plate edge.
Plate size = 160X120X4 mm; Minimum Angle = 113.96°; Maximum Angle = 186.72°

5.2.3 Fabrication process - timber; steel

5.2.3.A Timber -

The aim is to find a solution to fabricate timber plates using low-cost/practical machines & technology. First step is to cut the hexagon timber plate from the plywood board. Then, the edges of timber plate are cut at the desired angles. Therefore, it is important to look for technology or machines that can either cut the plywood board or can angle cut the edges or do both.

Plywood Milling Technique

Using a 3 Axis CNC Wood Router (Manual/Semi-Automatic/Automatic)
Specifications :
Router table; XYZ working area = 1300 X 2500 X 200mm; Command = G-Code; Milling tool=Flat mill 10mm dia

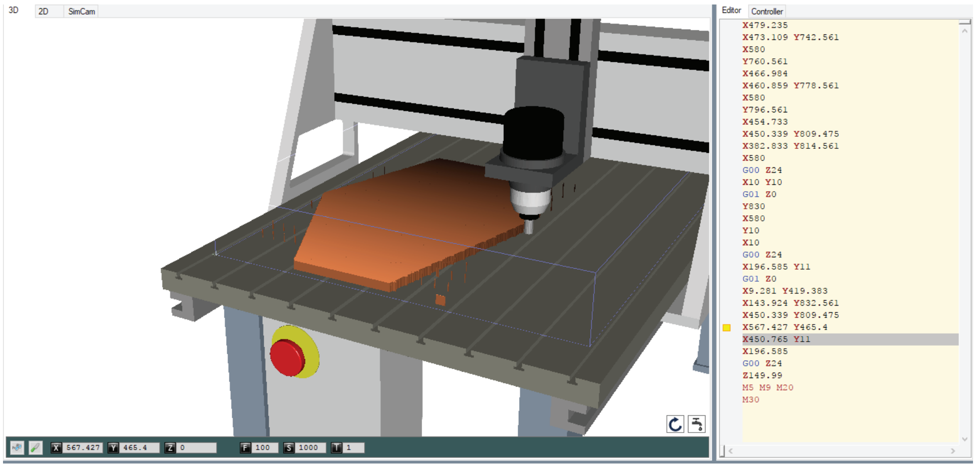


Figure 5.2.3.A.1: Router table for cutting plywood

Edge Angle Cutting Technique

Mechanically Powered Saw
(Manual/Semi-Automatic/Automatic)

Circular Blade Saw | Table Saw | Circular Blade Saw

Figure 5.2.3.A.2: Bosch GCM12SD 120 volt 12" DB Glide Saw / DEWALT 12" Slide Miter Saw DWS780

Figure 5.2.3.A.3: table saw

Figure 5.2.3.A.4: saw blade

Specifications :
Blade dia = 12.0
Blade size = 12"
Bevel Angle Range = 47° left and 47° right
Category=

Specifications :
Blade dia = 10.0
Blade size = 10"
Cut angle is controlled by adjusting angle of blade
Blade height-7.5cm

Plywood Cutting & Edge Angle Cutting Technique

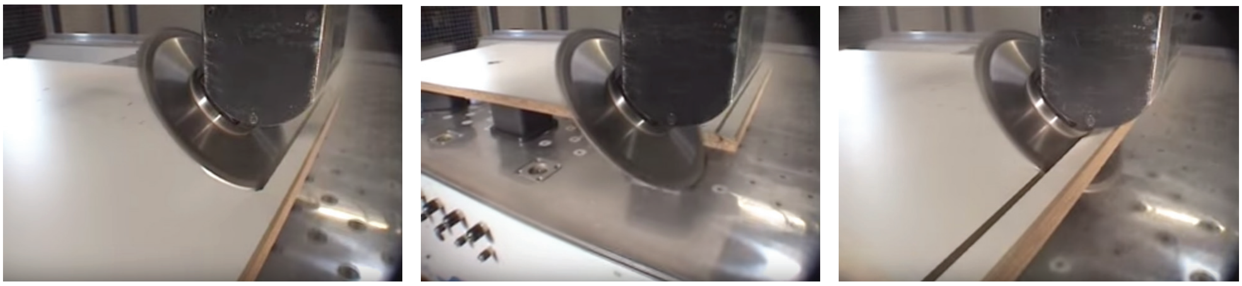


Figure 5.2.3.A.5: 3/4/5 Axis CNC Wood Router with Saw Blade (Combined machine)

The angle of the tool outlet can be adjusted manually from -100° to +100°
(Benz woodworking aggregate - type Flex)
(tipped saw blade)

Plywood Cutting & Edge Angle Milling Technique

5.2.3.B Steel -

The fabrication of steel plate requires bending of plate at the desired angle. Therefore, research is done to find a way to bend steel plate, to understand the bending geometry and what bending machines can be used?

Bending Technique

Press Brake V - Bending Machine

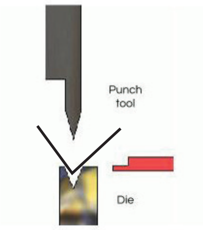


Figure 5.2.3.B.1 : air bending

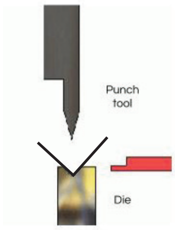


Figure 5.2.3.B.2 : bottoming

Swivel Bending Machine

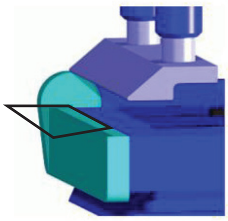
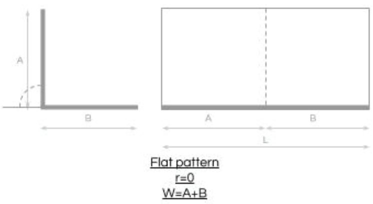


Figure 5.2.3.B.3 :

Bending Geometry



Design Rules

Bend Location
(Min W=4t + r)

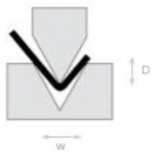
Die Ratio
D α punch force
(w = 6 to 18 X t)
□ die ratio = w/t

Bend Angle

Bend Radius
(Min r α t)

Bend Direction
(□ to rolling direction)

Bolt Holes Position
d = 3t + r
□ d = 30mm(min)



W=width of flange
t=thickness of steel plate
r=bending radius
D=depth
w=width of die opening
d=distance b/w holes

Bending Machines

CNC Press Brakes
TRUMPF TruBend Machines

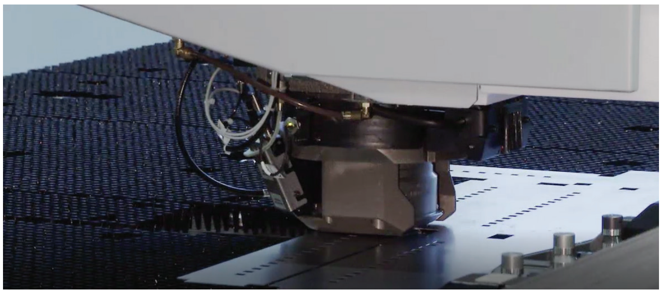


Figure 5.2.3.B.4 : CNC Cutting & Punching

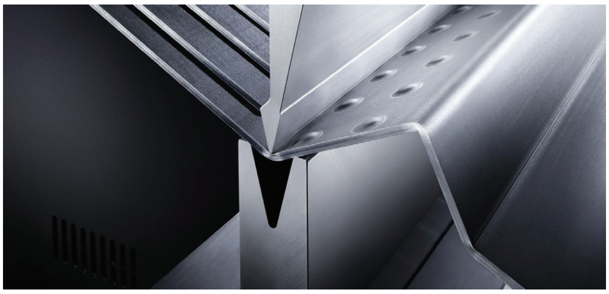


Figure 5.2.3.B.5 : V-Bending (Semi-Automatic)

CNC Press Brakes
ACB Wireless/Laser Angle Measuring system

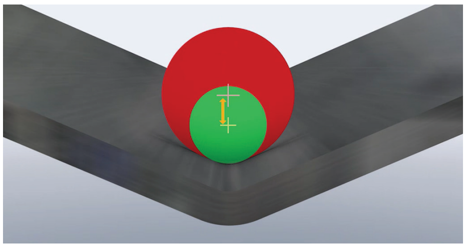


Figure 5.2.3.B.6 : bending angle determined by relative disc movement

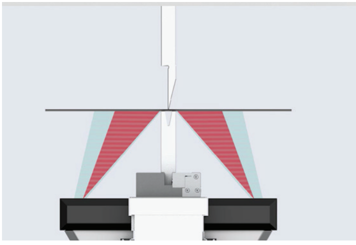


Figure 5.2.3.B.7 : laser projects a line on the workpiece surface; camera system detects this line

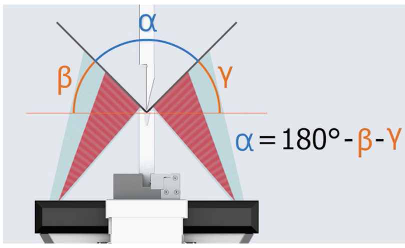


Figure 5.2.3.B.8 : exact bending angle achieved due to measuring units

• Allows accurate bend line positioning
• Achieve different bend lengths and angles
• The distance that the programmable V blade enters into the V block will define the angle achieved of the final bend

Therefore, steel plates can be bended at the desired angle by using bending machines with proper angle measurement system.

5.2.4 3 plate assembly

In the exterior, the 3 plates are assembled in a way that the upper plates EP1, EP2 are overlapped and interlocked over the lower layer EP3 and then steel plates are bolted to get the desired angle. In the interior, the 3 plates IP1, IP2, IP3 are assembled together at the intersection point and connected by steel plate to get the desired angle. These plates, both exterior and interior, rest on the lower most layer of timber plates which are anchored to the ground for the support.

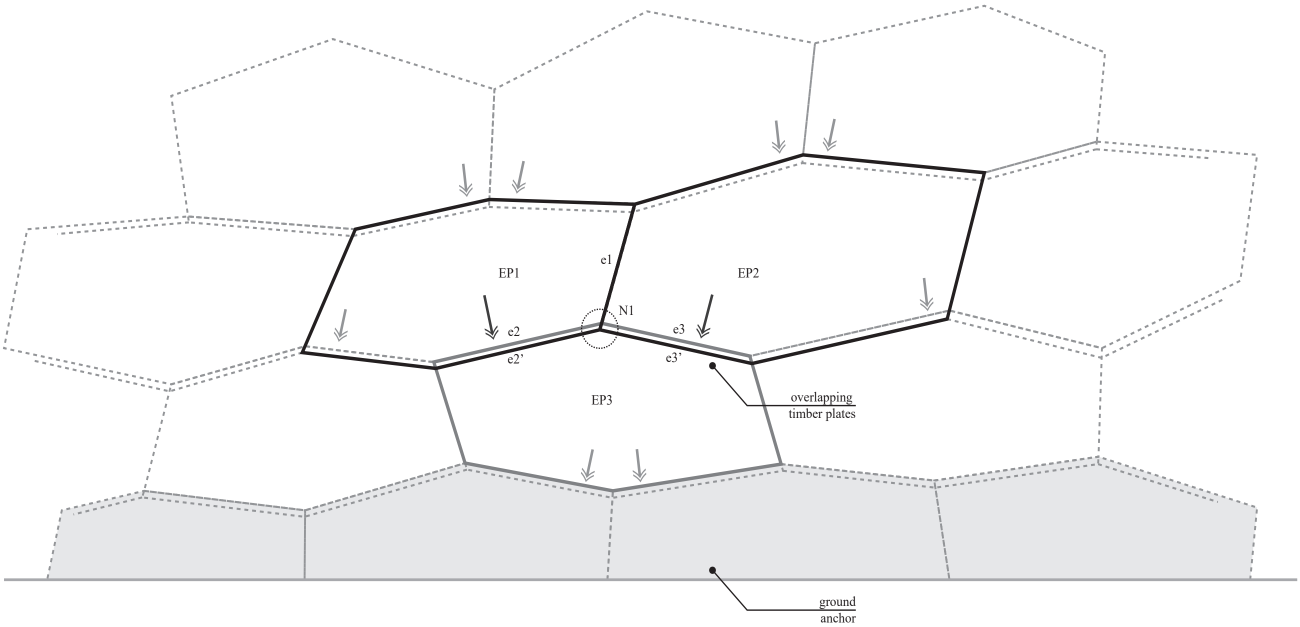


Figure 5.2.4.1 : 3 plate assembly for exterior plates

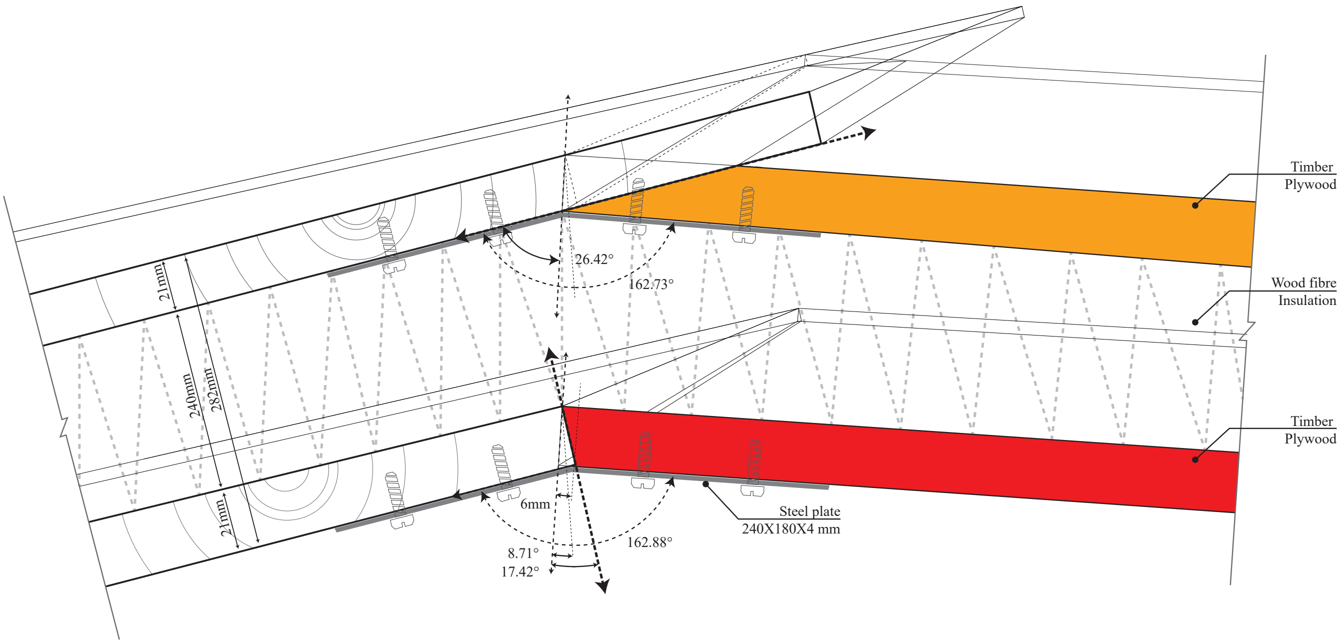


Figure 5.2.4.2 : 3 plate connection detail

This double layered connection detail is independent of each other. The thickness of insulation is flexible, and can range from 75mm to 300mm depending on where the structure is built, in what climate and type of insulation available.

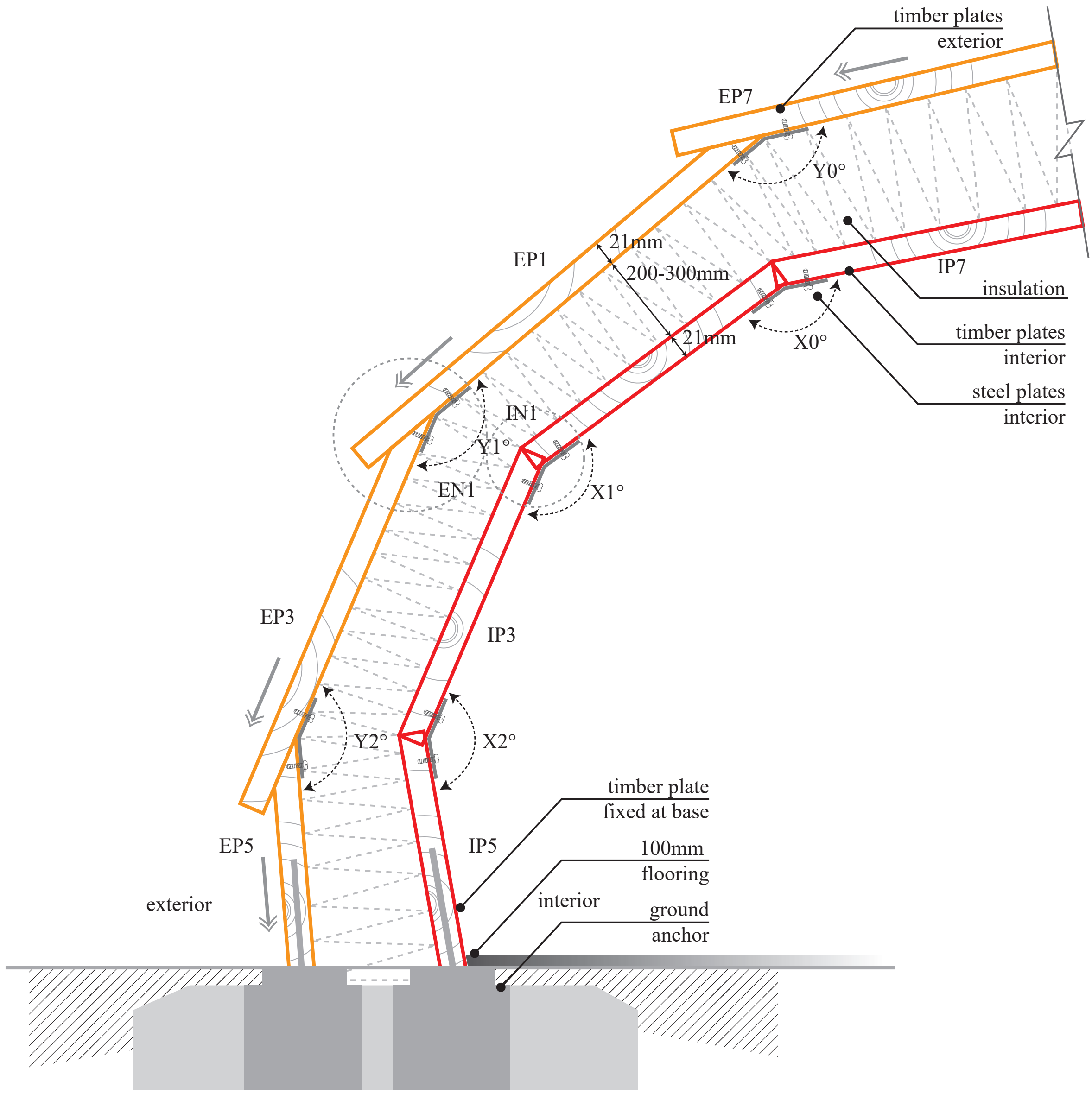


Figure 5.2.4.3 : section detail

Step by step sequence must be planned for interlocking plates together such that the completed structure can be disassembled plate by plate in the reverse order of assembly. Therefore, the whole structure is supported by the base layer of timber plates anchored to the ground at the desired angle. Then step by step layering is done till it closes on the top. First the exterior layering is done, then insulation is added either by gluing or bolting, and then the structure is closed with the interior layer. At the ends, capping is done to close the double layers.
As the exterior and the interior layers are not connected directly, it gives the flexibility to transfer the load, plate to plate and joint to joint. Because both the interior and the exterior layers are connected at the base, this double layering system helps in load transfer as a whole structure and at the same time gives the flexibility to increase or decrease the gap for insulation as required during actual construction on site.
This adjustable connection detail with the simultaneous assembly of plates layer by layer might be a feasible solution for building planar hex timber plate structures.

5.2.5 3 Plate Finished prototype

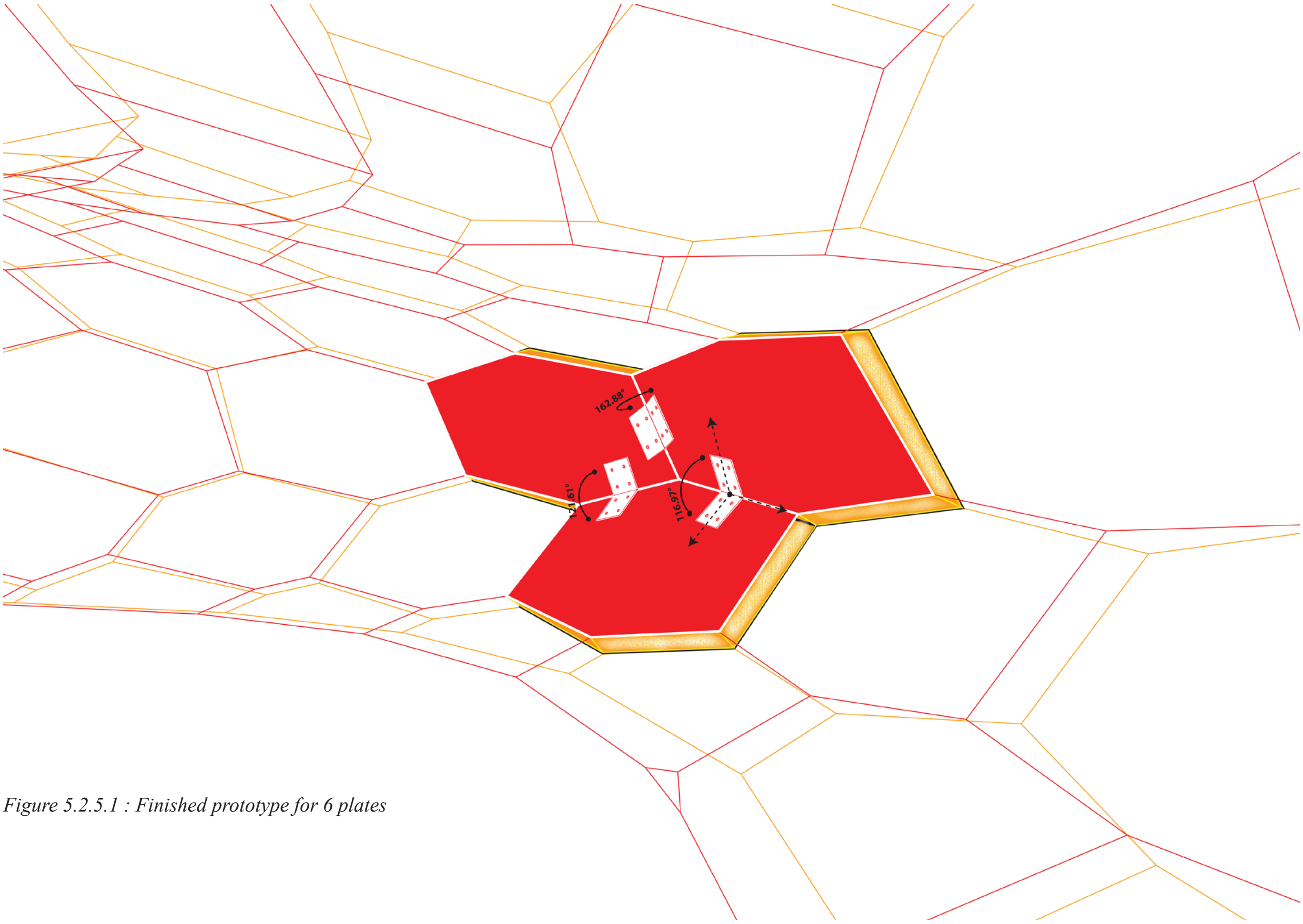


Figure 5.2.5.1 : Finished prototype for 6 plates

3 Plates
3 Edges
1 Node
for interior & exterior layer

21mm Timber Structural Plywood;
Double layered with 160°,115° & 120° fold
Adjustable Steel Plate connection;
Located At center
Insulation;
282mm

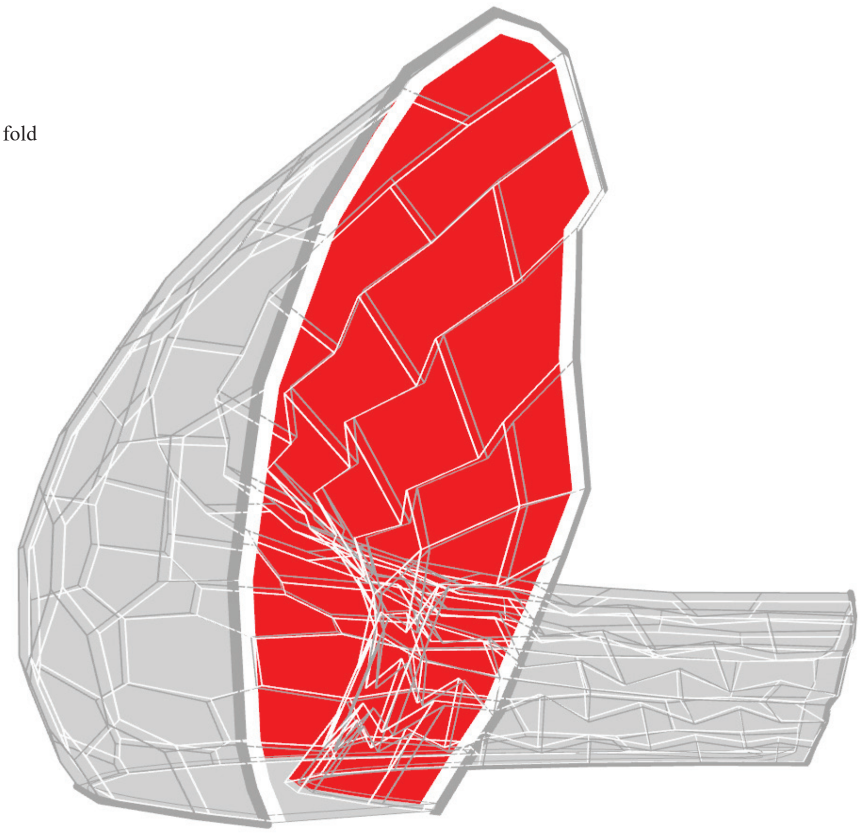
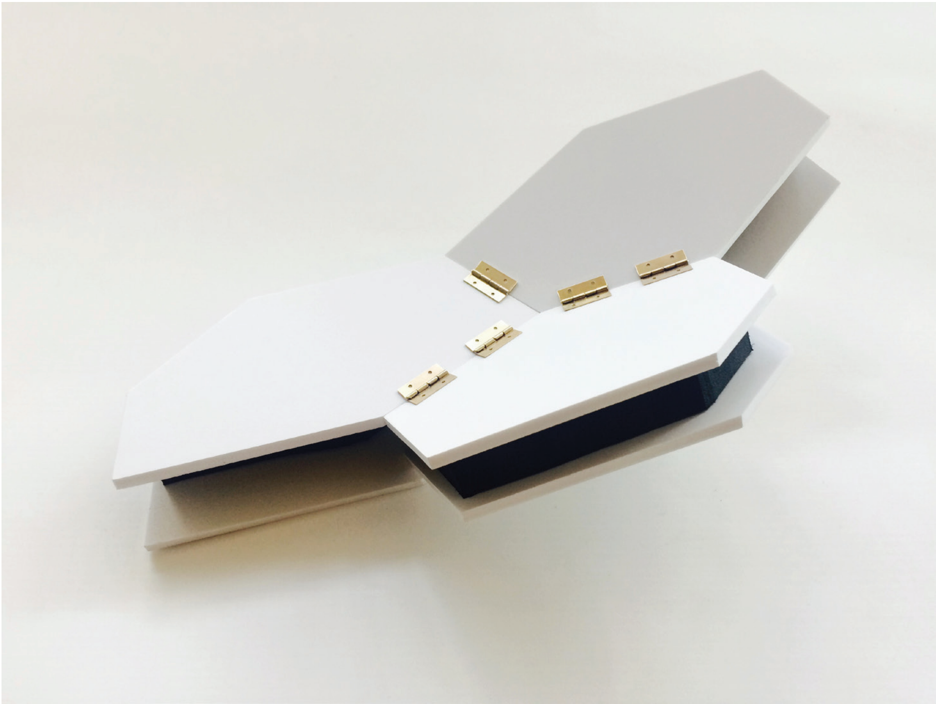
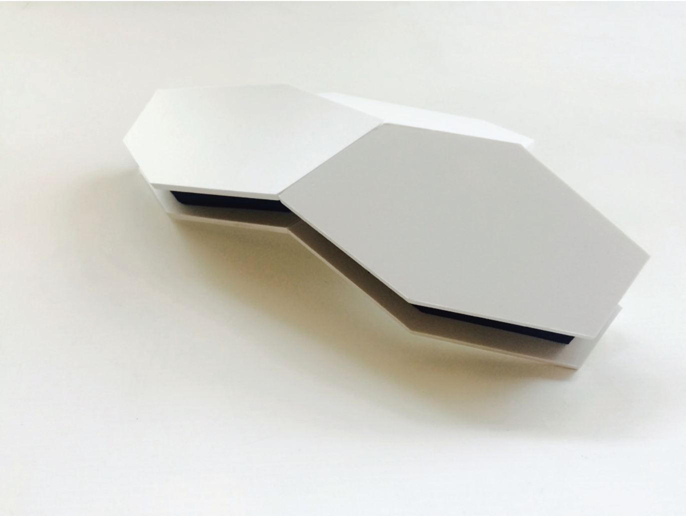
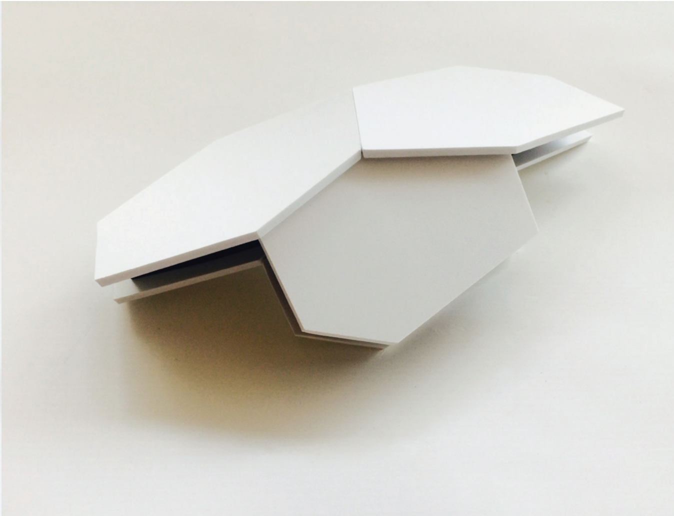
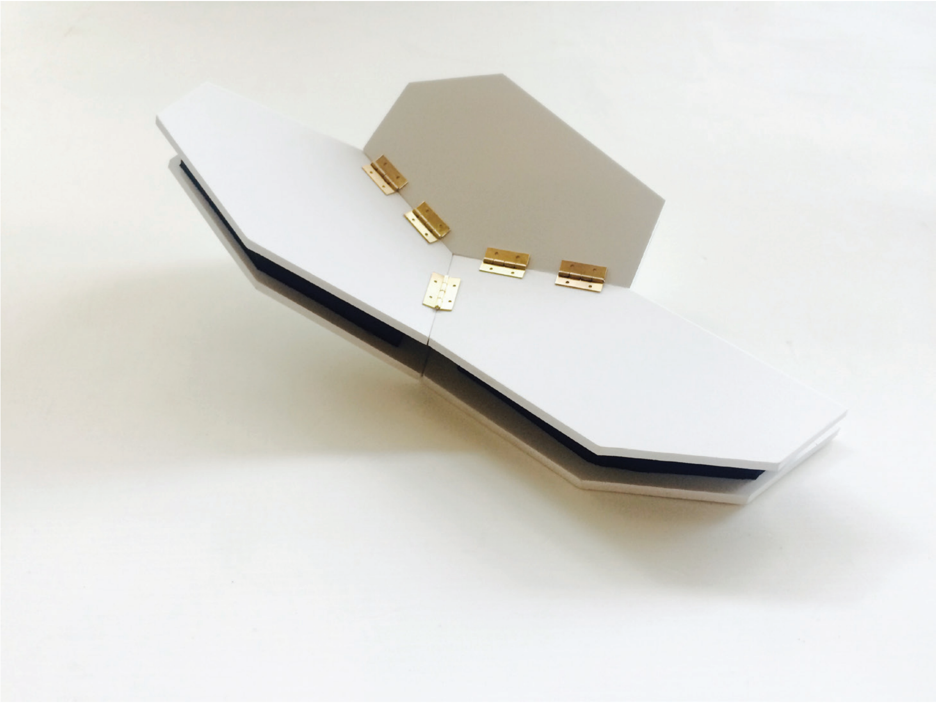


Figure 5.2.5.2 : Finished prototype



6 CONCLUSION

6.1 Inferences : Advantages of fabricating the PHex structure with the chosen connection

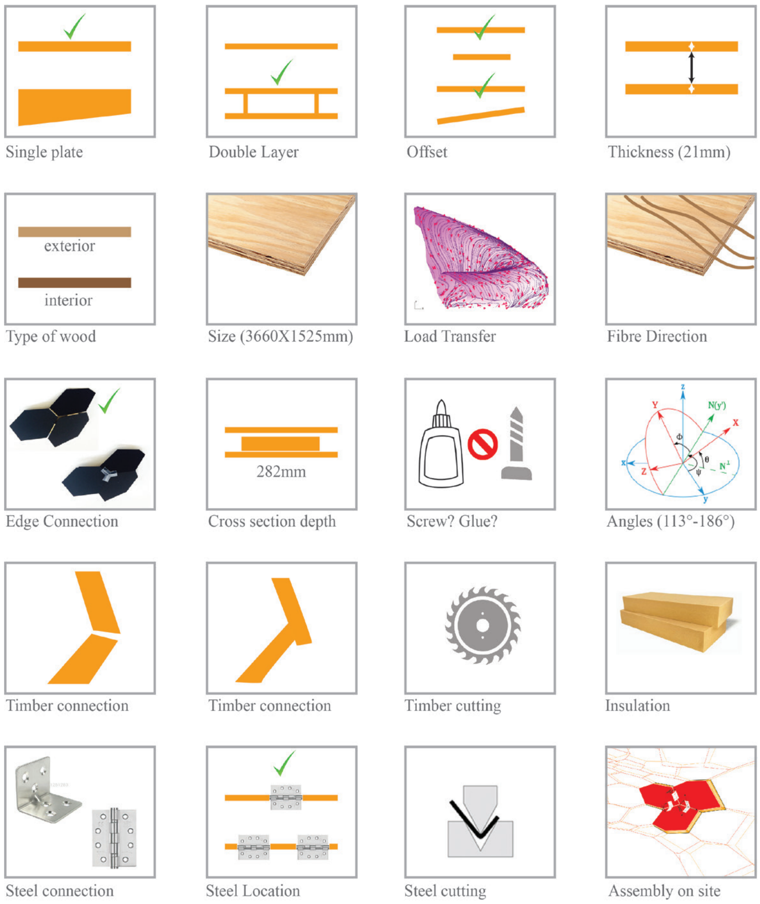


Figure 6.1.1 : conclusion

The connection detail discussed in this research paper is easy to cut fabricate and assemble on site anywhere and anytime. Therefore, it increases the flexibility to grow it on a larger scale.
This strategy of solving connections and assembly on site, is one of the ways to synthesize timber plate structures with planar hex, such that the strategy could be applied to any double curvature surface efficiently, to built a self stable structure.

6.2 Further Research

The further research can be done on finding an efficient way to sandwich insulation between exterior and interior plates for double layering system. Another research can be done to find out another strategy on how timber plate can be cut using 3 axis CNC or any other technology available. Further wind and load tests can be done to see if the building sustains itself or not. Structure analysis can be done to check the durability, strength, moisture content, tests under different loads to prove that planar hex timber plate structures are growing to be the new paradigm of parametric architecture.

7 REFERENCES

- Herzog,T., Natterer, J., Schweitzer, R., Volz, Michael. and Winter,W. 2008 : Timber construction manual. Germany : Birkhauser.
- Weinand,Y. (2017) “Folded plates made from timber panels”. In: Advance timber structures. Architectural designs and digital dimensioning. Germany: 14-32.
- Weinand,Y., Stitic,A. (2017) “Structural optimization of timber folded-plate structures”. In: Advance timber structures. Architectural designs and digital dimensioning. Germany: 32-40.
- Helmut Pottman, Architectural Geometry, Bentley Institute Press, 2007
- Wenping Yang,Ynag Lio, a note on planar hexagon meshes, technical report, 2007