

## **BAMBOO RECIPROCAL GRID CANOPY 0386**

### **1 GENERAL**

#### **1.1 GENERAL**

This work section refers to the selection and on-site robotic manufacture of bamboo culms for their use in the reciprocal frame in this project. In the context of the project, the bamboo canopy is expected to be replaced every 3-5 years as the material naturally degrades.

As bamboo is not yet a recognised structural material under Australian Standard and NCC, International Standards are referenced to provide guidance on material properties and design of bamboo structures in this project.

#### **1.2 CROSS REFERENCE**

The following documents are to be read in conjunction with this section:

- ISO 22156:2021, Bamboo structures – Bamboo culms – Structural Design
- ISO 22157:2019-Bamboo structures – Determination of physical and mechanical properties of bamboo culms – Test methods
- ISO 19624:2018, Bamboo structures – Grading of bamboo culms – Basic principles and procedures

The following documents are referenced in this section:

- AS 4024.3301:2017, Safety of machinery, Part 3301: Robots and robotic devices – Safety requirements for industrial robots – Robots
- AS 1391:2020, Metallic materials – Tensile testing – Method of test at room temperature
- ASCE/SEI 19-10, Structural Applications of Steel Cables for Buildings
- AS 2550.5:2025, Cranes, hoists and winches – Safe use, Part 5: Mobile cranes

#### **1.3 DEFINITIONS**

For the purposes of this work section the definitions given below apply:

- Bamboo: The common name of a diverse group of members of the grass family that makes up the subfamily Bambusoideae.
- Rhizome: Part of the stem that is within the soil.
- Culm: A shoot of bamboo comprised of the entire unaltered cross section.
- Nodes: Transverse diaphragm along the length of a bamboo culm, observable as a ring on the surface.
- Internode: Segment of culm between two nodes.
- Outer diameter ( $\varnothing$ ): The largest distance between two opposite parallel tangents on the section of the bamboo.
- Wall thickness: The thickness of wall of the bamboo culm, measured near the centre of an internode, taken as the average of four measurements around the cross section.
- Ovality: Variation of culm cross section from a circle, reported as the ratio of the greatest to least diametric measurement near the centre of the internode.
- Bow: Variation of culm from straight condition, reported as the ratio of greatest transverse deviation to reference culm length

- Length (L): The distance of a culm from end to end.
- Reciprocal structure: A self-supporting structure made of a grid of beam members.
- Reciprocal unit: A module containing four pieces of bamboo members connected with notch and ropes.
- Notch: The Boolean concave surface on the bamboo member that functions as the receptacle of a connecting bamboo member.
- Milling: The subtractive design to robotic production (D2RP) process of manufacturing a precisely carved notch.
- Notch depth (d): The depth of the resulting Boolean concave surface from milling, measured from the tangent of the cross section parallel to the milling plane to the lowest point of the notch.
- Boolean notch: The resulting geometry of the subtracted member when two bamboo members partially intersect each other.
- Top member: The member that sits on top in the connection, which is milled.
- Bottom member: The member that sits on the bottom in the connection, cross section of which remains unaltered.
- Span (S): The distance between two connections on a beam member.
- Inclination angle ( $\theta$ ): The angle caused by the vertical rise in the out-of-plane connection in the reciprocal structure.
- Milling plane angle ( $\alpha$ ): The angle between the planes of the two notches to maintain the inclination angle.
- Lashing: Ropework to secure connecting bamboo members.
- Tension cable: Steel wire used to provide tensile bracing for the structure.

#### 1.4 SAMPLE

A selection of 10 bamboo culms harvested from the same plantation are gathered on site to inspect the range of deviation.

Confirm average diameter of selected batch prior to design finalisation to ensure the size of resulting reciprocal grid achieves desired geometry.

#### 1.5 TOLERANCES

Selected members for the construction of the canopy conform to the following tolerance allowances:

Measurement	Tolerance
Length*	$\pm 150$ mm
Diameter	$\pm 10$ mm
Ovality	<2%
Bow	<1%

**Table 1      Tolerance Table**

\*Due to the assembly geometry of the reciprocal grid, lengths of members are irrelevant, given it exceeds the length requirement defined by the distance between two connections made on the same member. Tolerance for member length is suggested to ensure overall aesthetic and form conformity.

## 2 PRODUCTS

### 2.1 BAMBOOS SPECIES

Bamboo species selection to be considerate of propagation nature of species as a preventive measure to plant invasion. The clumping species, which have vertical rhizomes, are generally considered non-invasive, and are suitable for plantations.

The following are examples of clumping bamboo genus and species sufficiently recorded in construction and structural applications:

- Bambusa: B. blumeana, B. stenostachya, B. oldhami
- Dendrocalamus: D. giganteus, D. asper, D. strictus, D. barbatus
- Guadua: G. angusofolia Kunth, G. aculeata
- Gigantochloa: G. apus, G. atter, G. atrovioleacea
- Phyllostachys: P. edulis, P. meyeri, P. nigra, P. bambusoides

Australia has one native clumping bamboo species, *Bambusa arnhemica*, with culms up to 120 mm in diameter and grows to 12 m in height.

Selection of bamboo species is based on geographical availability and soil conditions. In this project, bamboo species with culms of diameter 70-100 mm and heights over 5 m with a uniform cross section would be appropriate.

### 2.2 ROPES

Natural fibre ropes made of cotton (cotton rope) or hemp (manila rope) are preferred for lashing connections. (3.6) The ratio of the diameter of rope to the diameter of bamboo is about 1:8-10.

### 2.3 STEEL WIRES

3mm stainless steel wires are used. The cable is secured in the lashing. (3.6)

Products are to be chosen in accordance with AS 1391.

## 3 EXECUTION

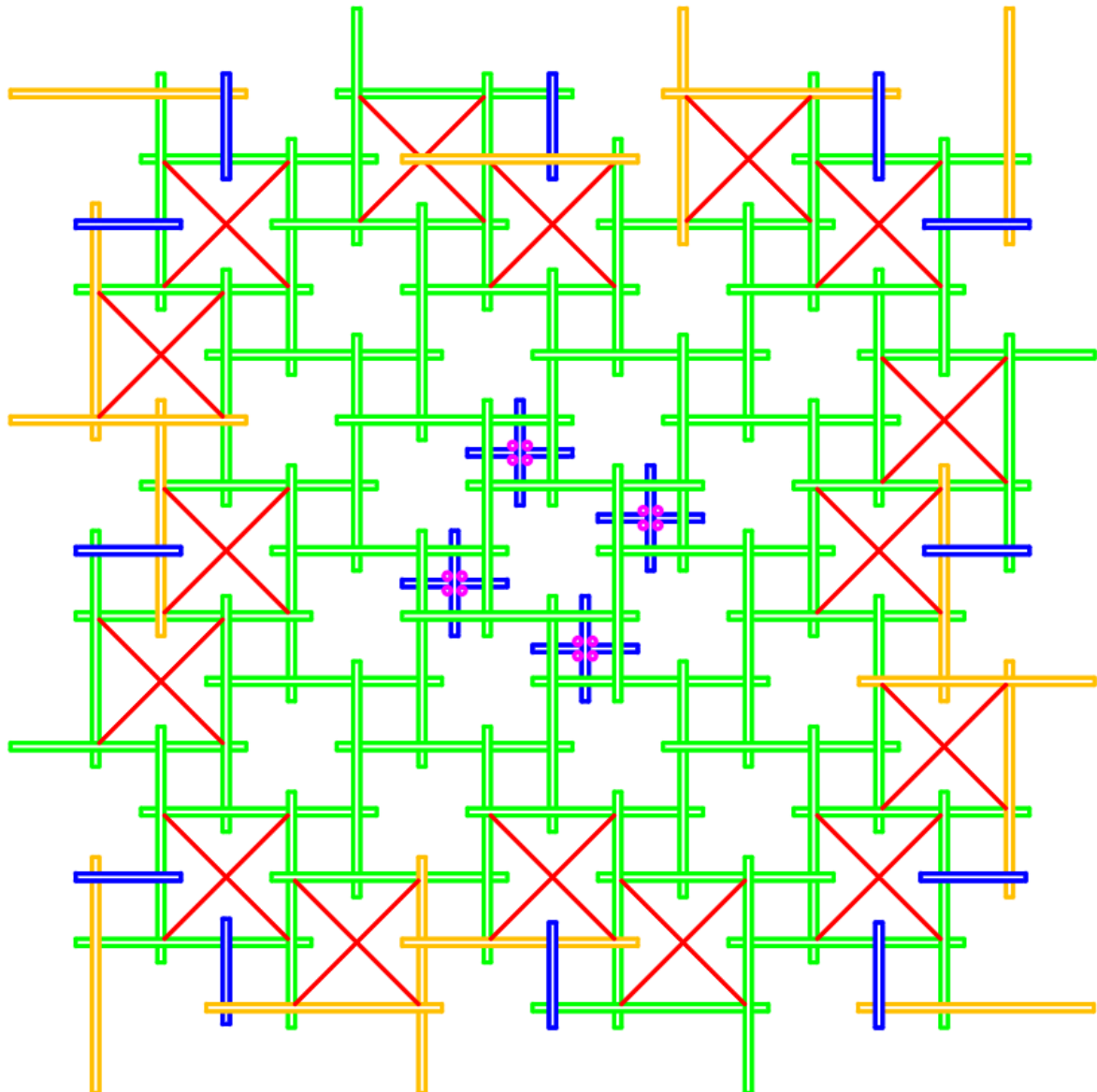
### 3.1 HARVESTING AND TREATMENT

Bamboos are harvested after 3-5 years of growth. Bamboos used are dried and unseasoned. A visual evaluation in accordance with ISO 19624:2018 [6, 8.2.1] is conducted to determine the suitability of members.

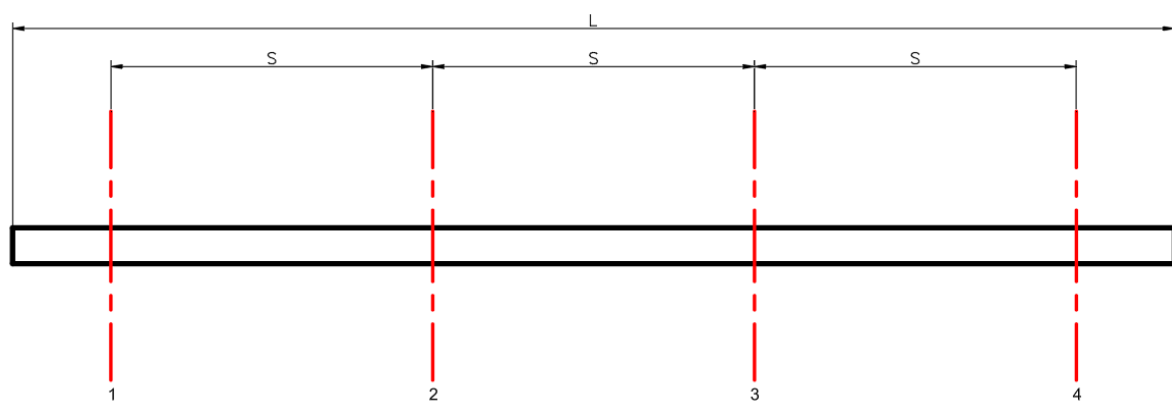
Members are sawed to appropriate length, and selected according to conformity in diameter, ovality, and bow, in accordance with accepted tolerances detailed in **Table 1**.

### 3.2 SORTING

Harvest members of acceptable ovality and bow variances are sawed and sorted by length. This section details the length and amount of bamboo members required to construct one canopy structure.



**Figure 1**      **Structural plan of canopy**



**Figure 2**      **A full length member**

The span (distance between two connections),  $S$ , is determined:

$$S = \varnothing \cdot 9$$

The length of the longest member, L, required is determined:

$$L = S \cdot 3 + 400\text{mm}$$

Colour	Description	Length	Count
Green	1 reciprocal unit; consisting of 4 members of length L	L	17
Orange	1 member of length L	L	16
Blue	1 short member	S + 400 mm	20
Magenta	Column	4000 mm	16

**Table 2 Key to Plan of canopy**

Length sorting and count:

Length	Count
L (long beam)	84
S + 400 mm (short beam)	20
4000 mm	16

**Table 3 Length sorting and count of members.**

### 3.3 MEASUREMENT AND DOCUMENTATION

The selected pieces (and spares) are grouped in fours and labelled accordingly. The following parameters are recorded in preparation for the milling process:

- Diameter ( $\varnothing$ )
- Length (L)
- Position of nodes

### 3.4 MILLING

The following section involves the usage and operation of robots. All operations should be conducted with safety precautions in accordance with AS 4024.3301.

#### 3.4.1 PAIRING

Nodes may be milled (**Figure 4**), depending on the geometry and diameter deviation of the connecting members, however, that the connection avoids the node. A larger contact surface between the two members is preferred.



**Figure 3 Example of members pairing and labelling**



**Figure 4** Example of bamboo member milled at node

### 3.4.2 MEASUREMENT AND SET UP

Parameters are accurately measured with respective tools to be input to Grasshopper script to produce a model:

- Height of the bamboo top from the bottom of the jig
- Notch position
- Width of notch (Diameter of pairing bamboo)
- Length of bamboo (L) (not essential but modelled to visually identify the position of notch is at the right place)

Adjust the milling template accordingly to generate a script that manufactures a notch that achieves the following:

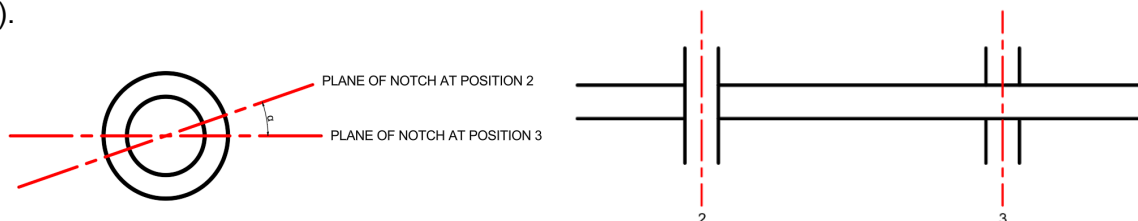
- Notch depth,  $d$ , is determined:

$$d = \varnothing \cdot 3 / 8, \leq \text{maximum depth allowed for drilled bit}$$

### 3.4.3 GEOMETRY

Each member is notched at two positions, position 2 and position 3 (**Figure 2**).

Members are inclined at an angle to produce the three-dimensionality in the reciprocal grid structure. The milling planes on the same member are out-of-plane with each other (**Figure 3**).



**Figure 5** Plane of notch geometry in cross-section and plan of milled culm

The inclination angle,  $\theta$ , is determined:

$$\tan \theta = (\varnothing - d) / (2 \cdot S)$$

The angle between the two milling planes reconciles the vertical rises of two connections on the same member, 1 span apart. The angle between the two milling planes,  $\alpha$ , is thus determined:

$$\alpha = 2 \cdot \theta$$

### 3.6 TENSIONING AND LASHING

Units on the outer ring are tensioned with a pair of cross bracing cables. (**Figure 1**; tension cables indicated in red.)

A non-invasive method of securing the tension cable to the bamboo connection is used. The cables are fitted with swaging. Installation of the tension cable should be conducted in accordance with ASCE/SEI 19-10 using the swage method [3.3.2, 5.3.3, 8].

Cross lashing wraps and secure the tension cable and connecting bamboo members. The connection should be tested in accordance with ISO 22156:2021 [10.9.3]. The lashing connections secure a self-supporting structure, where the geometry of the members is augmented to hold members in place.

The lashing should be overlapping at least three times. The rope is wetted in water before lashing, so that it shrinks to tighten the knot as it dries. It is imperative that the rope is of natural fi-bres for this practice to be effective.

The process of tensioning and lashing is outlined below:

- 1 Wrapping the cable around the connection.
- 2 Swaging the cables to permanently.
- 3 Using a spring lock for one end of the tension chord to allow removal or reconfiguration of parts. Cross lashing follows.
- 4 Tightening the chords by hand to make them taut after the form of the reciprocal unit is secured by lashing.



1



2





3



4

**Figure 6 Tensioning and lashing a reciprocal unit**

### 3.7 ASSEMBLY

The reciprocal units are assembled on the ground into a large reciprocal grid.

The finished canopy is then craned to the top of the four groups of bamboo columns. (**Figure 1**; columns indicated in magenta.) The operation should be conducted in accordance with AS 2550.5 [6].

### 4 References

All images in this document are produced by authors.

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