Theme: 3.5. Architecture, Engineering and Construction: Architectural Design

Digital Fabrication and Bamboo

Analysis of Principles for Utilising Digital Fabrication Methods to Advance Bamboo for Construction.

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The research proposed in this paper aims to combine to craftsmanship, engineering and architectural design, investigating that the way in which architects, designers and craftsman conceptualise and realised bamboo structures. The research shows how computational design and digital fabrication coupled with traditional craftsmanship can contribute to the advancement of bamboo for construction.

The paper discusses the key principles of computational design and digital fabrication which lead to the field workshop carried in Colombia. A purpose made digital fabrication tool was developed to test alternative fabrication methods in the construction of a bamboo structure.

Background and Context

The construction industry today is separated between people who design buildings and people who construct them. This divide has evolved for various political, economic and cultural reasons, implying that those who conceptualise, design and propose; are not the same as those who materially engage in the making process. “Construction insight is wholly missing from the conceptualisation of the design, and design insight is applied only sparingly during its execution”. (Bernstein 2010)

Hand tools and tacit knowledge offer specific insights into our processes of making and conceptualising. The craftsman allows knowledge to grow from the crucible of our practical and observational engagements with the beings and things around us (Dormer 1994; Adamson

2007). With the advent of digital fabrication, new fields of architectural discourses are emerging; expanding on the intrinsic relationship between designing and making is forging new dialogues, with digital and physical technologies enhancing the mind and the hand, the tool and the material.

This research project focuses on the relationships between material properties, culture and technology, critically engaging in modes of practice which relate to innovative architectural conceptualisations. The terms Design Ecologies and Ecologies of Making becomes representative of these modes of practicing as thinking, making, material behaviour, tools and environments are interconnected in symbiotic relationships for the materialisation of form and space. Critically, this research focuses on material as the key driver in the ecology of making, bringing together digital and non digital methods as an exploratory mode of practice for material innovation.

This research is contextualised in current movements in architectural design research with a focus on materiality, digital fabrication and the designer as a maker (Carpo 2011; Menges 2016). The research is underpinned by the theories of morphogenesis where form develops through a symbiotic relationship of intrinsic qualities determined by material knowledge (Hensel 2004, 2008; Menges 2006; Oxman 2010; Ingold 2013).

The research framework broadens out from the technical domain of fabrication, to explore the meaning of 'craft' in current practices and this knowledge occurring in specific conditions and contexts. The research examines the particular social, cultural and environmental conditions of craft, design and fabrication in Colombia, where a specific species of bamboo (Guadua) is widely used for construction.

Bamboo offers incredible solutions to many of the environmental, technical, social and cultural issues present in our built environment. The high-quality bamboo has certain characteristics that exceed those of steel in terms of strength due to the strong fibres in the shoot; compressive strength is very high due to the hollow cylindrical shape of the culm.

Bamboo is also very good in seismic regions as the elasticity to weight ratio reduces inertial forces from the earthquake. It is clear that this natural material could replace certain uses of steel, timber and wood in buildings, yet bamboo is not established as a mainstream material. One possible reason for this is the intrinsic variability of the material which complicates performance analysis, construction methods and systems, and dimensional co-ordination amongst other factors. Many bamboo structures therefore have relatively high levels of redundancy with a consequent loss of efficiency and elegance, and sophisticated architectural uses of bamboo have compromised cost or performance advantages over equivalent structures produced using more established engineering materials.

Whilst construction applications are common, the technology is characterised by bespoke small-scale routes to delivery with low levels of systemisation or automation, and compares unfavourably with established supply roots for other materials in developed economies such as timber framing, light steel framing, fabricated steel frames and offsite concrete.

The research project investigates opportunities for the lateral translation, or technology transfer of modern production technology as already established in parallel fields, to the specific context of bamboo.

There are two dimensions to the problems which this research contributes to. The first is technical and focuses on bamboo as a material for construction, identifying possibilities and constraints; looking at existing tools and modes of constructing with bamboo. The second dimension is more cultural and pertains to both the mode of thinking of the designer and the use of mathematical computation to advance design methodologies through material performance. Achim Menges, director of the Institute of Computational Design at the University of Stuttgart explains this relationship to better understand the strategic methodological approach to this research project: “Computation enables architects to engage facets of the material world that previously lay outside the designer’s intuition and insight. (…) It has been recognised that material processes also obtain a computational capacity – the ability to physically compute form. When seen together, these two aspects suggest that we are now in a position to rethink the material in architecture through computation." (Menges 2016, p.78)

Bamboo has been used as the case study material to guide the research in enquiring the interaction between the mind (designers thinking, spatial and material-cultural experience), tools (digital, non-digital, drawings, etc) and matter (material behaviour and performance). The focus is on different architectural scales, analysing the detailed technical components, the human processes and the architecturally scaled bamboo built structures. In parallel the research looks at precedent studies of similar projects, as well as physically constructing and manipulating the material.

Digital technology is not intended to be the main topic of research but a vehicle for notating and instrumentalising the intricate relationship of form, material, structure and ultimately space (Menges 2006). Historically, there has been a disassociation of digital design with making which is now finding new means of dialoguing between conceptualisation and production. This has led to a new relationship between designing and making, exploring new ways of engaging in materiality and performance (Kolarevic, 2004; Menges, 2006a). Through investigating into digital fabrication with bamboo, the aim is to let the nature of the material determine the path of investigation, informing the conceptual development, the tool and the architectural form.

The fieldwork is based in Colombia as this is a country which traditionally uses Guadua for the construction of houses and other architectural structures and where cultural meanings are derived from the social and environmental context. There is a live inheritance of traditional knowledge in how to work with Guadua that is inherited from one craftsman to another, which carries important layers to the engagement with this material at an architectural, spatial and cultural scale.

Contemporary architectural practices in Colombia include cultural-material layers in their design and specification processes that are aimed at working specifically with Guadua. Aspects of the research enquire into the importance of the role of the designer in the specificity of material knowledge, craftsmanship and cultural subtleties inherent in the weaknesses and strengths of a specific technique, in relation to broader theoretical discourses in architectural productions.

The methodology traditionally used by designers and fabricators has limitations when viewed from the perspective of digital computational fabrication methodologies. “While in most architectural design approaches a scheme is conceived and drawn, modelled or even digitally generated as a construct of geometrically described, inert parts, in computational design material elements can be defined by behaviour rather than shape.” (Menges 2012, p.45). This research promotes an approach that can enable architects to exploit the resources of computational design and manufacturing through an unfolding of performative capacities and spatial qualities inherent in the material systems.

Here the research’s objective is to broaden the definition of material beyond bamboo as we perceive it, to engage in a holistic study of parameters covering biological properties, environmental performance, spatial resolution, social-cultural and technical perception.

An essential characteristic in the joining of bamboo elements is the craftsmanship, skill and knowledge to cut precisely the individual elements to make the node. The hammer and chisel carving and the circular saw-cup are the most successful techniques in managing precision variability and control. The challenge posed by these techniques are the level of skill and experienced required by the carpenter. This is one of the limiting factors for the wider use of bamboo in construction as skilled carpenters are difficult to come by. This research project is trying to address this issue by bringing forward innovative and alternative technologies to successfully deliver fabricated components.

Through the lens of digital fabrication, contemporary research typically uses a multi axis robotic arm. Essentially this means that however complex and varied are the geometrical components from digital to physical, the connection is direct, without needing to be drawn to scale and interpreted by a maker. In the case of bamboo construction, the joint design and the geometrical configuration of the bamboo parts traditionally are rationalised down to two to three connection typologies where the carpenter can, to his workmanship skills, control the variability of variables and minimise the complexity of the construction system (Pye, 1968). In the case of digital fabrication and with the methodology proposed in this research project, the complexity of the geometry and the multiple variability of the joint connection typologies do not pose any challenges to the workmanship of the multi axis robotic arm (Carpo, 2011).

Critical reflections on the process of design and fabrication can be analysed through the relationships between the designer and the material. The methods of analysis determine critical conceptual and practical paths through the design process. These analyses relate to the comparative working methodologies of more traditional methods of craftsmanship and determine critical points between methods for the development of new knowledge in the fabrication of bamboo through computational methods.

Bamboo is an unappreciated material and is seen, in its native environment, as the poor man's material. Generally, developing societies aspire to newer construction materials abandoning the traditional knowledge of bamboo farming and building techniques, not investing in new developments and applications. Bamboo is popular with crafts and furniture making and in these fields there is a continual heritage. Historically, bamboo was widely used as a building material throughout South East Asia, Japan and Central America offering these peoples a material which is naturally more resistant to earthquakes has a low purchase cost, being also flexible and easy to replace, maintain, adapt and to dispose of.

Internationally, on the other hand, bamboo is also seen as a solution to the environmental crisis as a key material replacement in the construction industry providing solutions to mass deforestation of timber and poverty eradication through the development of farming economies, low cost housing, building skills and general craftsmanship.

It is a clear fact that natural resources are becoming scarce and human needs are intensifying. Bamboo is greatly available with species which can grow up to 30 meters high with an internal diameter of 200mm in one year with no special cultivation technology. The tensile capacity is claimed to be higher than that of steel and other great properties, providing powerful reasons to undertake research into this material.

The lack of acceptance in the construction field is another reason for the social neglect of bamboo. Architects and engineers prefer to work with standardised, graded materials which are more stable and reliable for construction specification. But some architect and designers are promoting bamboo through modern designs of houses, public buildings and bridges as a way to uplift the profile of bamboo from a cultural perspective, encouraging social and political acceptance.

Bamboo not only contributes to the physical buildings but also plays a significant role in that it carries traditional meanings, techniques and styles; contributing to vernacular characterisation of buildings. From this perspective, bamboo has been a material that continuously readapted to the changing conditions and requirements of societies and communities, to adapt to different housing typologies and cultural artefacts. The continuity of bamboo in building traditions demonstrates a process of physical, social and cultural tradition. The nature of vernacular as argued by Marcel Vellinga "creates new manifestations of tradition or localized hybrid forms that better suit current circumstances and requirements; (…) adopting a more dynamic interpretation that more explicitly recognizes the ways in which old and new building traditions merge, adapt, combine and, in the process, become vernacularized"(Vellinga 2006, p.88).

Computational Design

Through the rational of geometry, architects and designers have historically been able to advance the possible ways of describing complex form. “Geometry looks for generalities and, once established, offers them up for use; architecture employs these general relationships constructively to underpin and create specific spatial relationships” (Burry 2012, p.9). Digital computation since the last two decades is offering new possibilities of spatial and temporal engagement beyond the limitations of Euclidean geometry and Cartesian planes. Through parametric algorithms, the design is a topological system capable to define a range of geometrical possibilities. This intelligence is a mathematically based system of geometrical hierarchies and relationships defined to describe topological possibilities through algorithms that enable the emergence of forms resulting from principles established in the design of the topology rather than the (visual) geometrical form itself. As described by Jane Burry, solid modelling programs place no demand on the modeller to engage closely with the abstract symbolic geometrical descriptions of surface. In this way designers can move conceptually to the more general geometrical world of topology, foregrounding connectivity and continuity, a familiar starting point for space planning but not a traditional metaphorical starting point on design of form (Burry 2007, p.613). Designers are generally intensely concerned with the formal (shape) output and not with a more genuine topological space concealed within the design of mathematical algorithms and spatial relationships of these geometrical objects.

To summarise, the design space is multiple, a) composed of the Euclidean descriptive and projective geometry, b) topological space of the relationships between geometrical objects and c) a space of infinite possible spatial variations or iterations.

“It is necessary to think of geometry as a biological system or computational form not only as the description of the fully developed form, but as the set of boundary constraints that act as a local organising principle for self-organisation during morphogenesis”. (Weinstock in Hensel 2004, p.14)

The genetic algorithm principles to be established in this design project have to do with the already mentioned characteristics of bamboo's inherent anatomical morphology. Under the principle of continuous fibre, 1) segments of bamboo fibres (culms) are to be connected to other linear fibres (culms) in a continuous way so as to provide for a morphological change in geometry rather than a mechanical one. Whilst the scale of application is much larger than originally observed, at a microscopic and macroscopic scale, the topological principle maintains. 2) The longitudinal direction of forces should prevail through the connectivity of bamboo culms where members meet at oblique angles distributing forces along each segment rather than at right angles, where too much force is imposed on individual elements (culms). 3) The typology of nodes throughout the form is variable dependent on the geometrical composition of the form in its locality and the stresses imposed. The Finite Element Analysis (computational prediction of real world forces) and the Computational Optimisation (methodology for finding optimum solutions – structural and material arrangement) tools generate the form and resulting component anatomy. In this way, the geometry cannot be described at the outset of the project but only a set of rules and relationships. The computational system can offer models for analysis to determine the physical, spatial and material conditions for a possible form and further technical realisation.

Computational design material elements can be defined by behaviour rather than shape. Thus larger assemblies can be explored and derived from the interaction of such behavioural elements and external data, and understood as contributing to the overall performance capacity." (Menges 2012, p.45)

Geometrical principles

To develop the overall form typology through computation, the principles established are the result of the research into bamboo and inquire into a method of computationally developing a model, which follows the design criteria from the joint method to the node typology and to the overall form morphology.

The joint method is further described in the proceeding section. The key principle is that an end piece of bamboo meets the side of another avoiding node intersection with more than two elements of bamboo.

The geometrical principles are based on the hypothesis that the joining of the bamboo components should be staggered and that no end piece of bamboo should meet another. This is a variation from the current typical typology where nodes are formed with a mechanical connector, as it is not possible to manage the physical and technical union of the parts. (see image below)

Figure 1 - Examples of joint connections of multiple end pieces

To create a more fluid continuity between members, staggering the joints implies one end piece meeting the side section of a culm. In geometrical terms, this raises an interesting problem because most three-dimensional forms are described through a network of lines and grids. Multiple edges meet at points forming clusters of multiple end pieces. The image below describes 3 types of grids: an irregular triangulated surface with varying numbers of nodes; a regular hexagonal grid with constant dimensions, angles and numbers of edges per vertices and; the found solution to the geometrical problem: an hexagonal reciprocal shifted pattern where each node is made of one end piece meeting the side of an edge.

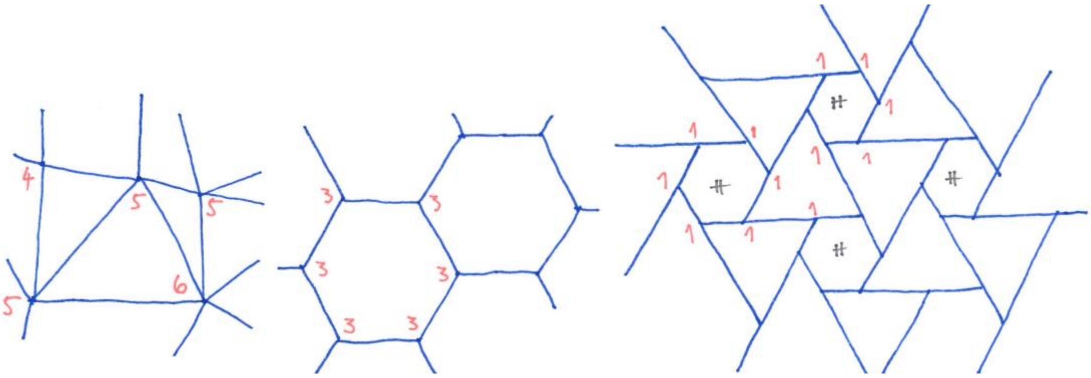

Figure 2 - Different grid patterns

The design process to find this solution was based on a regular hexagonal pattern as shown in the image below. These principles were taken from a set of algorithmic parameters from a multiple authored community forum. The algorithm essentially instructs a parallel offset from the edges of the hexagonal. Each edge is given a number based on a rotation of 1 from the original object. The lines are then extended 1-1 prime; 2-2 prime, etc. Because of the regularity of the geometrical grid, if the offset is equal to all hexagonals, the extended lines will meet the neighbouring hexagonal and the overall geometry will function.

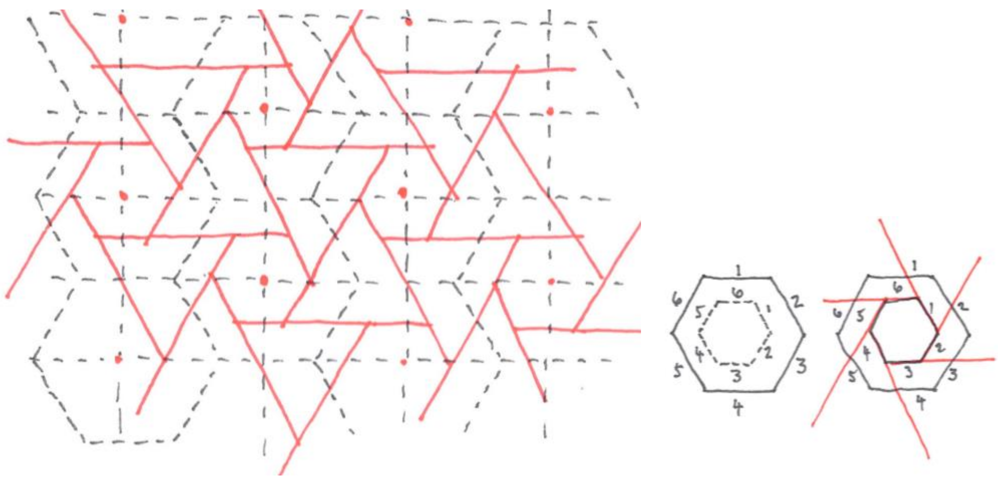

Figure 3

This same mathematical equation can be applied to other geometrical grids as shown in the computational image below. This is a triangulated surface where we would have observed the each edge meets at a node of 6 which would not satisfy our bamboo design application. Applying the same algorithm we can create a condition where, based on a computational 3 dimensional surface, the end pieces of bamboo meet the side of another culm (edge).

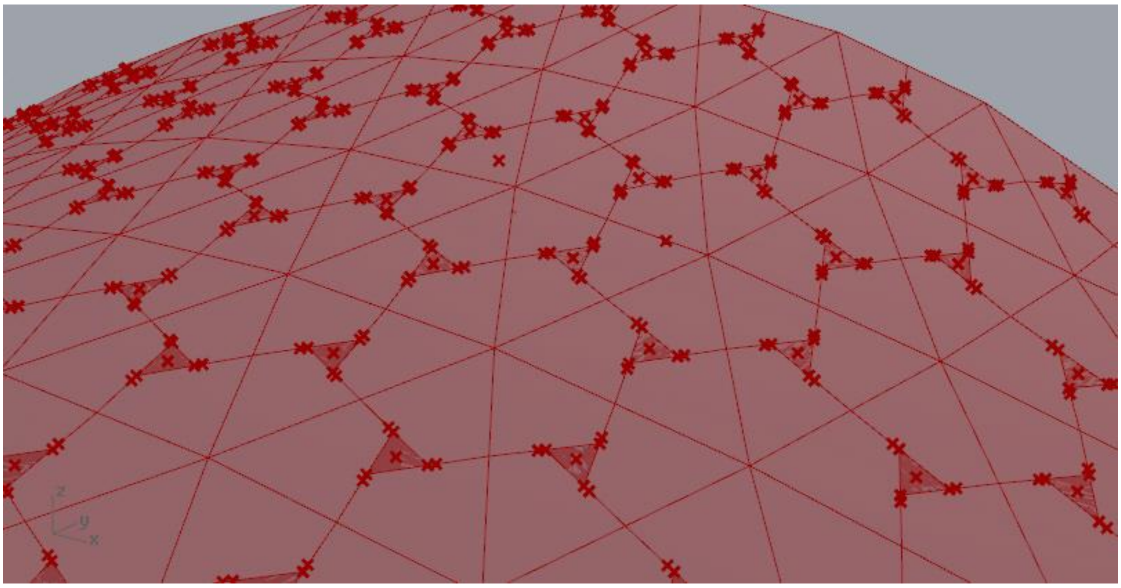

Figure 4

The potential design limitation here would be the requirement of the geometry to be regular throughout. This would imply regularity to each node and to each intersection, resulting in an overall regular and symmetrical shape, like a dome or a vault. Subtle variations are possible but this design research project aims to find a wider scope in form finding, surely not pre-imposed by geometrical limitations.

This demonstrates the possibility of constructing an irregular geometrical form bases on points located in space as an input, providing therefore a specific logic in form finding based on: typology and morphology of bamboo, site specific data which can be both physical (heights, contours) and environmental (solar exposure, wind direction, water management). The creation of form becomes interrelated with multiple data criteria developed from the material conditions, environmental and technical abilities specific to each project.

The form optimisation developed (figure 5) utilising the principles of the research by triangulating elements to optimise the angular bamboo intersections, minimising multiple nodes at one point.

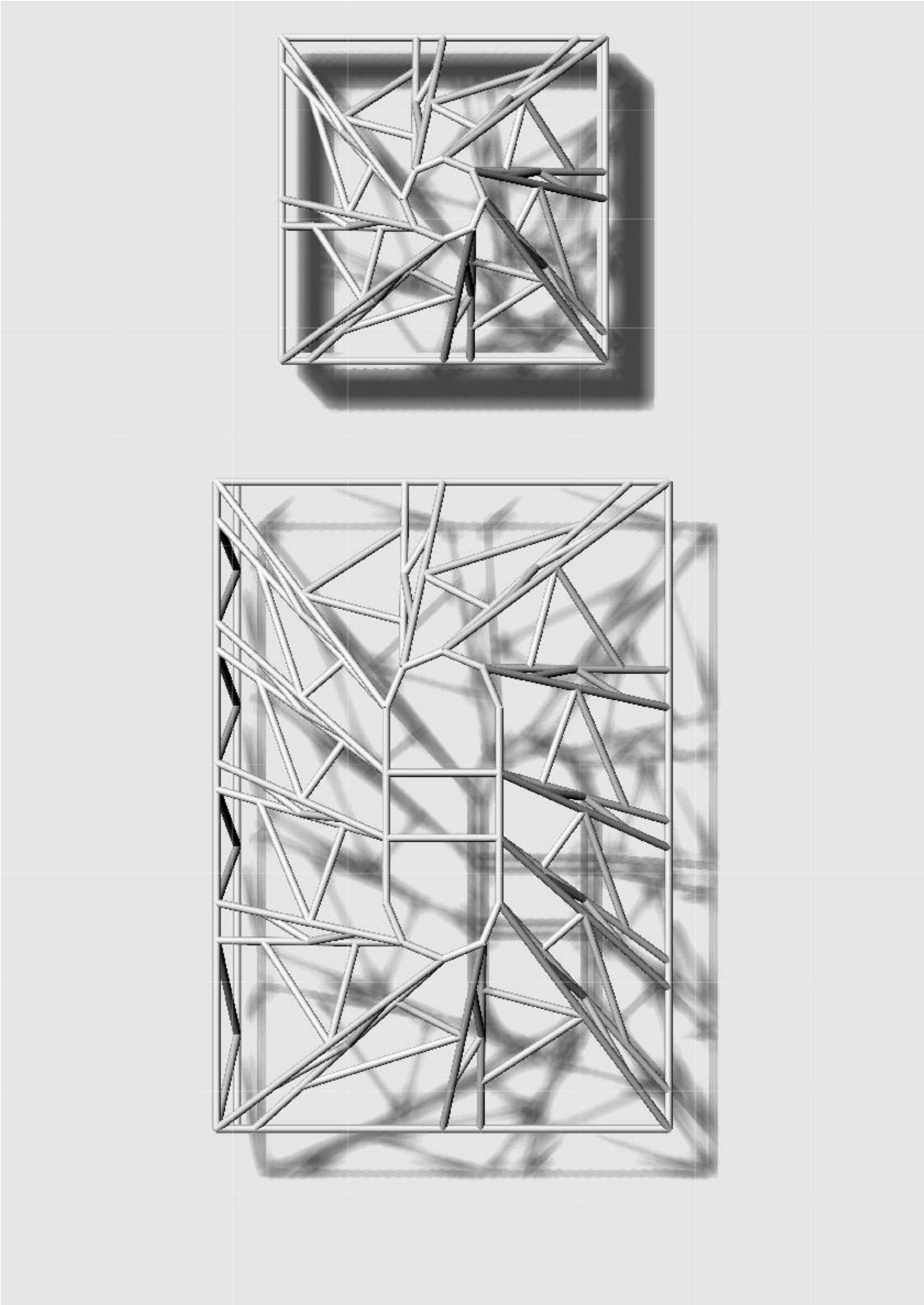

Figure 5 – Form design proposition based on triangulations optimising strength and node connections.

Design Influences – Joint Technology

The most important aspect of bamboo construction is the formation of joints that transfer forces from one element to another. This is favourable by complete contact between the bamboo elements in intersection. The most common of these connections is called a 'fish mouth' and is perpendicular to receiving bamboo section. If the cut is inclined, it is called a 'flute tip' (Minke 2012, p.41). The flute tip is the specific joint type, which this thesis will try to develop and apply as a joint typology. As the Flute Tip deals with the multiple angles to the centre line (see image below) it also includes the Fish Mouth which is one on the possible angles within the range. It is the moment in which the bamboo is symmetrical to the centre line.

Generally Flute Tips are more difficult to fabricate because of the difficulty in knowing how to cut the angles. The typical system employed in cutting fish mouth ends is to symmetrically cut diagonal lines from the centre line of the culm. This is easier to control and determine during construction rather than working with asymmetrical angles. This is one of the reasons that flute tip cuts are not more used in the construction process.

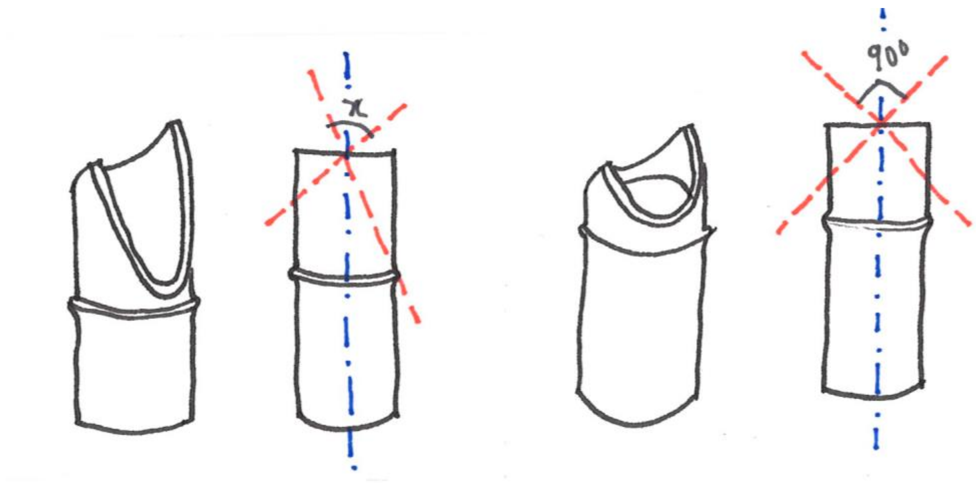

Figure 7 - Cut lines for Flute Tip (left) – asymmetrical to centre line and Fish Mouth (right) – symmetrical to centre line.

With the proposed fabrication methodology, the cnc machining can cope with any angle and variation making these joints more applicable in the design process. The fundamental reason why this research focuses on these joints is to develop a system where the ‘wall end of the mouth’ of the cut is precisely for a perfect ‘coupling’ onto its receiving bamboo. When constructing on site, the carpenters cut the bamboo with rough dimensions, generally ‘eyeing’ out the components for a near about precision (estimated tolerance of +/- 10mm). This is generally acceptable because the joint does not rely on the perfect bonding of the bamboo pieces as it relies on mechanical fixing.

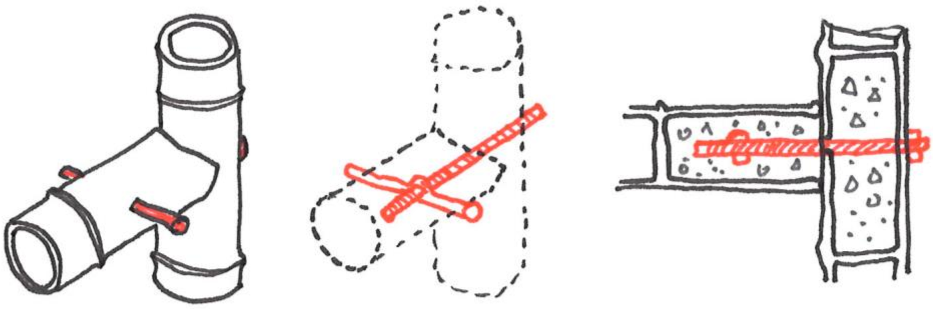

Figure 11 - Typical example of a mechanical joint using concrete

In practice, the common system is to use metal threads, rods or pins to connect the elements by filling the internodes adjacent to the joint with concrete (see image above). This helps to bond the mechanical fixings.

Conceptually, the aim is to express the natural properties and qualities of bamboo, working with the inherent nature of the bamboo for a larger architectural scale. With a richer variability of possible intersecting elements, the scope of design widens significantly. The current applicable architectural designs are limited to the technological constraints as explained above. With the system proposed, the architectural form can take on new geometrical morphologies and open the potential application of bamboo for architecture.

Design Influences - Fabrication

The fabricability of the proposition is fundamental in determining the validity of the hypothesis. One of the key issues is the ability to deal with the complexity and variability inherent in the computational design model. Traditional craftsmanship is unable to deal with this potential complexity. This is a significantly changing attribute in the existing modes of working with bamboo and is one of the key contributions to existing knowledge, providing a new way of working with bamboo. Traditional craftsmanship and workmanship rely of managing risk and controlling the quality of the work being produced. In a typical design to fabrication process, information is transferred to the maker through annotated drawings, indicating dimensions, positions and other specifications that the maker follows. The quality of the workmanship is judged by reference to the designer’s intentions (Pye 1968, p.13). In this mode of operating, to minimise complexity and risk, the simpler the design the easier it is to make. If the design is complex with multitudes of variations, complex angles and subtle variations in dimensions, the likelihood of risk is higher.

Figure 8 - Images showing typical bad workmanship in cutting the bamboo to couple with the receiving bamboo – Source: Building With Bamboo – Gernot Minke

In the existing uses of bamboo for architecturally scaled constructions, workmanship is done with hand tools not using accurate jigs or precise measurements. The level of inaccuracy in the construction is approximately 10mm and this is due to the level of precision and control of the design, the fabrication and the variability of the material itself.

Figure 9 - Types of tooling used in the fabrication of joints. Note the lack of precision in the jigs and the reliance of the user to ‘eye’ out the accuracies. Image source Gernot Minke

CNC Fabrication

The CNC tool has been developed from identifying the limitations of working with the material and the inability to digitally fabricate with bamboo without a multi axis robotic arm. Typically, multi axis robotic arms cost over 50,000 USD and are not available in regions where bamboo is native. For this reason, this research project developed a 3 axis prototype Computer controlled Milling Tool for under 1,500 USD.

Figure 10 – Image of the3 axis digital fabrication CNC tool with mounted bamboo.

The principles of the CNC tool are quite simple, constructed using 3 stepper motors, a desktop computer, a spindle router, sheets of plywood, chains, sprockets, bolts and screws. The jig setup has been developed to enable control over the angle of milling around the elliptical circumference of the intended bamboo flute tip cut. This specific cut (figure 15) has a varying angle throughout the path of the cut, specific to the angle of intersection and to the receiving bamboo's circumference. Whilst the cut is quite complex, especially when considering the multitude of angles in which the bamboo elements will meet, the receiving intersecting solid (the bamboo) is always (approximately) a cylinder.

The fabrication tool was developed through a range of prototypes to mechanically coordinate a range of cutting angles within a set scope of possible geometrical configurations. Both the digital and the physical characteristics of the system evolved in parallel to coordinate the local joint configurations (genotype) with the overall geometrical architectural form (phenotype).

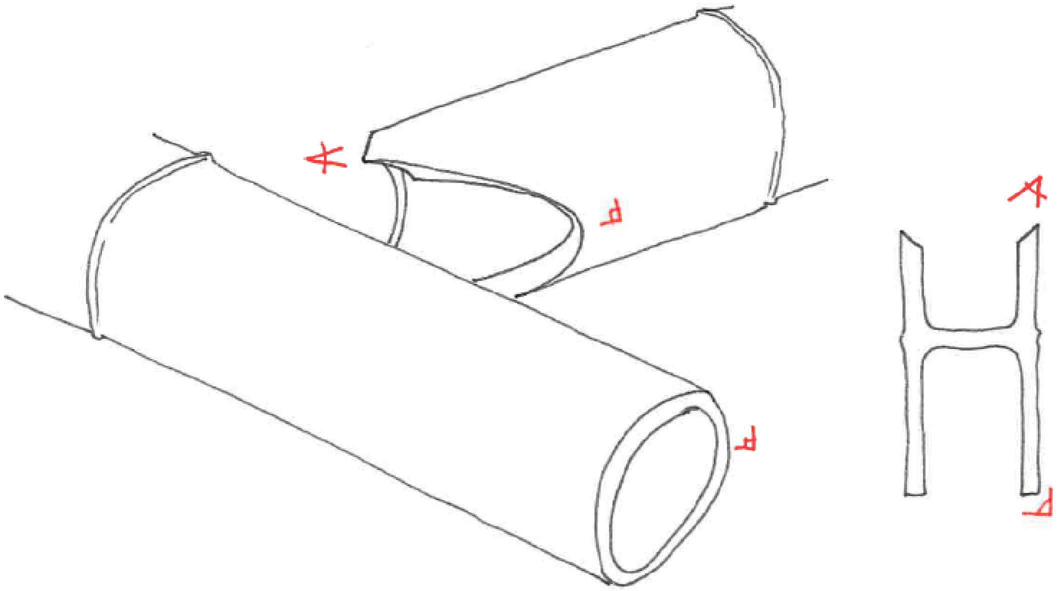

Figure 11 - Diagram showing the variability of angles in a Fish Mouth or Flute Tip joint

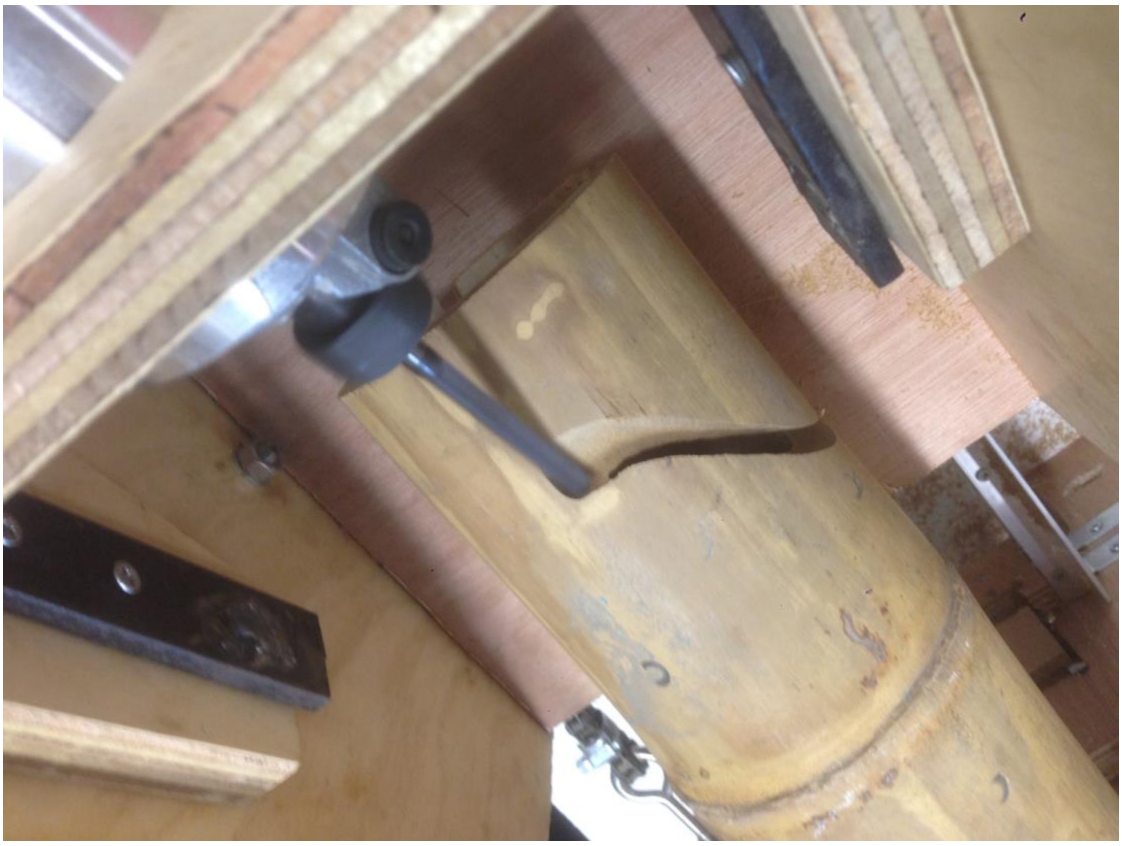

Figure 12 – Image of the digital fabrication too milling a 'fish mouth' joint

Figure 13 – Image of a digitally fabricated reciprocal triangulated connection.

In field research workshops in Colombia, we worked with bamboo carpenters to determine the workability of the digital system. We wanted to determine the relationship between of our digital system and current methods typically used for the creation of architectural structures. The outcomes of the research workshops revealed insight into required levels of craftsmanship; precision and types of tools; design thinking; fabrication methodologies and overall efficiency in fabrication.

By working with experienced bamboo carpenters, we were able to identify the key relationships between the design of the form and the actual fabrication. We worked in parallel with hand tools namely the traditional hammer and chisel approach as well as with the electric circular cup-saw to determine efficiency, accuracy and quality.

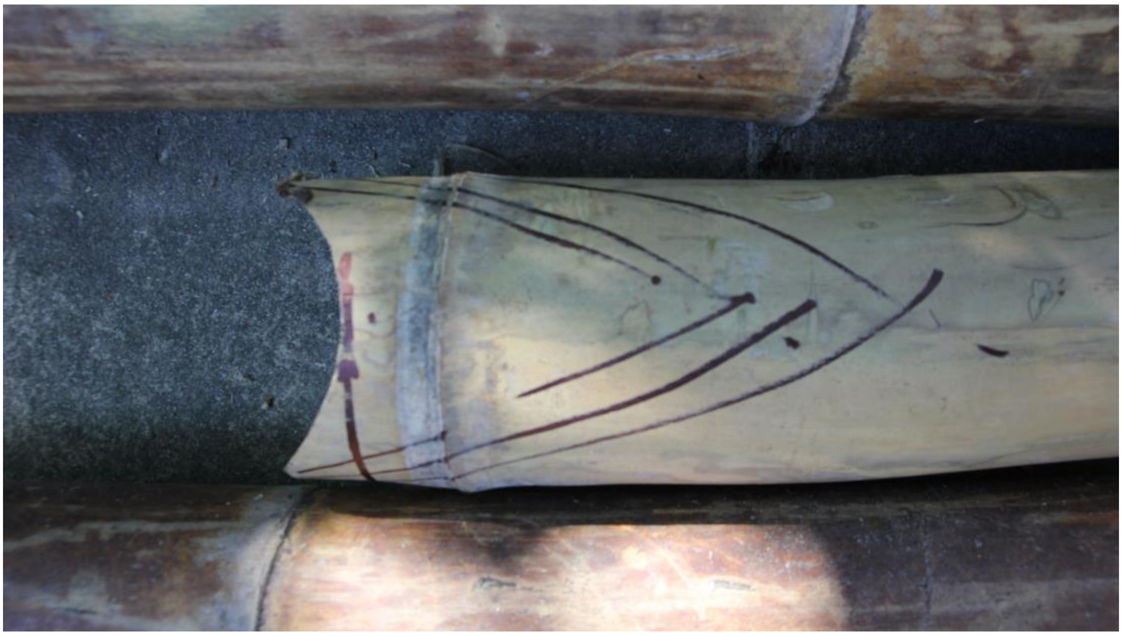

Figure 14 – Markings and adjustments made by the traditional craftsmen – levels of accuracy and geometrical control.

Figure 15 – Chisel and hammer crafting technique.

Conclusion

As an initial prototype, the digital fabrication system performed quite well overall. The cutting accuracy was quite high, offering a high digital 3D form to physical form ratio. The set-up of the machine on site has been designed to maximise on portability and flexibility but this will never be more efficient than the traditional hand tooling of the hammer and chisel. The skilled craftsman moves across the site and adjust themselves to the bamboo to cut the parts required. Their flexibility is a significant attribute to the way in which the components are fabricated. The craftsmen make little references to the scaled drawings and utilise the 1:1 scale as the measurement and guide for new elements. Progressively, the team of makers measure the 3D object using the actual pieces of bamboo, marking cut guidelines; laying the bamboo on the floor, between their legs to cut the required joint and its angle. This is then tested and corrected until the right piece is made. The digital tool operated differently. Each bamboo component is loaded onto the jig and accurately measured. Data is fed into the computational model which calculates the angle of intersection with the digital 3D form and its subsequent and previous bamboo element. The components produced were accurate but a certain range of physical corrections were needed to make the components suit. As the 3D form evolved, higher levels of inaccuracy occurred between the digital and physical realities. The variability of the bamboo was significantly contributing to the distortion. The craftsmen were more able to adapt to these variabilities because they didn’t have a predetermined 3D form to measure up against. The actual 3D making was both the design prototype and the final object.

We specifically worked on a complex geometrical form so that the challenges were not only in the complexity of each angle but in the overall form creation too. We wanted to establish the relationship between the designer and the maker. The role of the scaled drawing as a design instruction had to be played down to more of a guideline instruction. The maker became the designer because of the need to adapt to the variability of the material and technology.

The digital fabrication system was generally very well received. The concept of such a tool offers up new possibilities in bamboo fabrication. The reoccurring comments on bamboo construction is the lack of skilled craftsmen who can fabricate the joints. This relies on hand tooling skills and experience which is difficult to obtain. It is common to hear that architects and designers have their own teams of craftsmen who travel internationally to the projects because there are no local workers who have the skills.

The digital fabrication tool was viewed as offering a new range of fabrication solutions because the skills required to achieve the same type of flute tip cuts is very different. The operator of the digital tool is more computer and mechanically skilled and this requires a different type of individual and training. The digital fabrication tool is viewed with great potential in light industrial areas where it could be fabricating components for architectural elements. The further advantages of this digital system can enable a higher level of control over the variability of material and offer more consistency over quality and strength.

The research at this stage is still establishing key areas for further development and is building new possibilities for collaborative research to advance the use of bamboo in main stream construction.

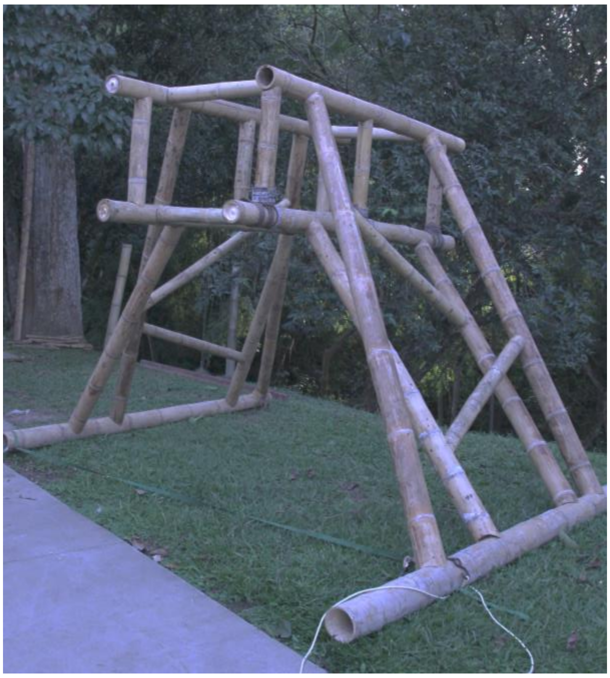

Figure 16 – Image of the bamboo structure and different tools utilised. (James Palmer, Ricardo Assis Rosa, Roger Martinez)

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