Relooking at bamboo: A journey into exploration of bamboo components for structural possibilities

Ar. Brinda k. Sonpal

School of Interior design, CEPT University, Ahmedabad, 380009, Gujarat, India.

brinda_sonpal@yahoo.com

Abstract:

Bamboo, a material which is renowned for its incredible versatility throughout history, has proven itself suitable for a great number of purposes, from housing to paper and from food to clothing. Its easy availability and workability facilitates the usage of bamboo across the Indian sub continent and also across the World.

In spite of all the succession in utilization of the material in various fields, the structural potential of the material is yet to be harnessed fully. Though bamboo has been used structurally in various applications, there are other structural possibilities, which can be explored. For that reason, experimentation[i] with bamboo, with a rationalized thought process, is a need of the hour.

In addition, majority of researches and investigations have been done, concerning the plant and material properties. But very few researchers have attempted experimental research with bamboo. Most of the experimental structures explored till now, utilize full bamboo sections. The explorations[ii] on split bamboo sections[iii] are yet to be instigated. Hence, the study focuses on structural potential of bamboo split sections and concerning that various practical experiments have been performed on real scale material. A variety of components[iv], modules[v] and systems[vi] have been generated following a certain methodology. A number of analytical studies have been done to study the structural behaviour of resulted modules/ systems. The study also involves testing of a selected system to evaluate the performance of that particular system under different loading conditions.

Keywords: bamboo split sections, structural potential, experimentation, components, modules and systems.

1. Introduction:

Bamboo forms an essential part of many human civilizations across the world since prehistoric times and till today it is in use, adapting to the changing requirements of human being. Bamboo is not only a useful material for everyday life, but it also has already been developed into a so called “bamboo culture”[vii] through the long time of cohabitation with people. Today bamboo is being hailed as a material for next generation, a super new material, a magical rod and etc.

According to Xiobing Yu (2007), “In spite of all the succession in material utilization, we are not able to utilize the structural potential of the material to the fullest. For example, India, being the second largest bamboo producing country, spends 60% of the bamboo crop in paper pulping. While china being the first largest bamboo producing country spends only 10% on paper pulping. However, the fact remains that, although India is the second largest bamboo producing country in the world, the material’s vast potential is yet to be harnessed fully. Instead of industrialization, modernization should be the real solution for the problem of utilizing bamboo in the industrial context. Modernization means the modernization of the relationship between the material bamboo and human needs, which was connected by craftsperson in the pre-industrial time, whereas this is achieved by a designer in an industrial context."

To achieve this change, experimentation and explorations are required with bamboo, focusing on its structural and cultural dimensions. It will essentially require a focused and rationalized dynamic thought process and methodology. A huge amount of research has already been done on physical, chemical, biological and mechanical properties of bamboo, bamboo culm, bamboo shoots, various bamboo species, bamboo composites, bamboo as an alternate raw material for wood, bamboo as sustainable and renewable building material, bamboo for large span structures and many more. Very few researchers have attempted experimental research in bamboo, which has been listed briefly in chapter 3.

M. P. Ranjan (1986) expresses his concern in 'Bamboo and Cane Crafts of India', "Despite the extent of use of bamboo by local crafts person, not much organized scientific research has been done to record the properties of different species. Neither has sufficient work been done on the study of the structural properties of the numerous sections that could be generated by splitting a bamboo culm."

The study here tries to address to this concern and focuses on structural potential[viii] of bamboo split sections. To identify various parameters on which the study can be rooted, different bamboo crafts are analysed, which form a component or a module or a system. The different identified parameters are then utilized to work out an appropriate methodology, for a systematic experimentation. Using the derived methodology various components, modules and systems have been generated, using real scale material. One of the systems has been tested to evaluate the performance under certain loading conditions. Digital tools like Rhinoceros and AutoCAD have been used to explore the endless propagation possibilities with each and every resulted component.

2. Bamboo - a versatile material:

Bamboos are plants with a special kind of structure which makes them different to any other plant in nature. Its special structure is the result of million years of natural evolution. On one hand, its unique structure has proved itself a very effective and efficient organism and on the other hand it also makes bamboo a very useful material for human beings. Its natural structure explains why bamboo is used by so many people and has such a long history in people's life – not only as a material, but also as a cultural being in the human society. From a plant to material, man has re-structured bamboo into numerous objects, products and elements to meet his needs in everyday life. Different roles, which bamboo plays in relationships to nature and human beings represent on one hand the way, bamboo's internal structure adapts itself to the outer environments and on the other hand how humans utilize bamboo's internal structure for their own needs (Xiobing Yu 2007).

2.1 Notion of bamboo construction:

According to Nilay Oza (1995), two different notions for bamboo construction are as follows:

2.1.1 Rural bamboo:

Bamboo lends itself easily to the image of a tropical, humid, rural and pastoral setting. It is an image that has come to load the word itself with a rural, low tech overtone. The image considers the fact that technologies of building with bamboo have remained simple extensions of what they were in past.

2.1.2. Urban bamboo:

There is another contemporary setting for bamboo which makes for a drastically different image, where bamboo is looked at, with an image of a material with inherent innovation potential which can be utilized in various sectors of design, economy, sustainability, etc.

3. Research done on bamboo:

Researches and investigations done, till now on bamboo, can be categorized mainly under two divisions:

3.1. Scientific research:

The researches done in this field are related to physical, mechanical, chemical and biological properties of bamboo. The research is focused on using bamboo, as raw material for wood-based composites such as particleboard (PB), medium density fibreboard (MDF), hard fibreboard (HB), plywood, oriented strand board (OSB), zephyr board, laminated bamboo lumber, parallel strand lumber (PSL) and oriented strand lumber (OSL), inorganic-bonded board (i.e., cement), wood plastic composites (WPC).

Bamboo is not a new field for researchers. In China, in Jin Dynasty (265-420 A.C) there has been monograph which observed and recorded the botanic properties of diverse bamboo species. Notable contributions of Von R. Bauman-1912, Sioti Uno-1932, David Farrelly-1938, H.E. Glenn-1944, Liese-1961, 1985 & 2003, Mcclure-1966, Dunkelberg-1978, J. Janssen-1981, Frei Otto-1985, M.P.Ranjan-1986, G.K. Ghosh-1998, Zhang -2001, Bess – 2001, Oscar Hidalgo-2001, Vinoo kaley-2006, Valentijn de Vos-2010, can be listed here.

3.2. Experimental research:

The researches done in this field are all about experiments and explorations done, using the material - bamboo in architectural practices.

For example, a dome by Yona Friedman-1930 (figure 1), a geodesic dome by Buckminster Fuller-1977, many experimental constructions by IL, Germany-1985 and Aachen University, Germany-1986 (figure 2). Modern bamboo joinery explorations by Renzo Piano and Shoei Yoh-1989 -1997 (figure 3) can also be included in this category. Designers have explored bamboo for large span structures also. For example, *"truss me"* collection by Sandeep Sangaru-1997 (figure 4), different large span structures by Vaibhav Kaley-2009, Green school by Anna Heringer-2010, ZERI pavilion by Simon Velez -2010 (figure 5), Wind and Water cafe by Vo Trong Nghia Architects-2011 (figure 6), Bamboo symphony by Manasaram architects-2011 and etc.

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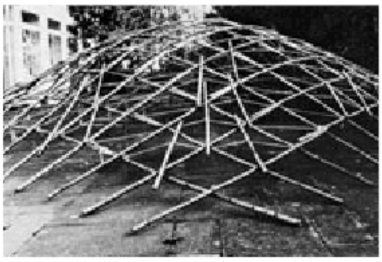

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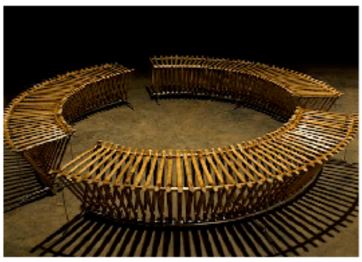

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Looking at the time-line of researches done on bamboo, it is noticeable that, experimental researches have been explored comparatively lesser than scientific researches. In most of the experiments and explorations, bamboo is utilized as full bamboo section. In most of the cases, bamboo has been amalgamated with other conventional materials like steel and concrete. Potential of bamboo split sections is less explored through research so far and hence this research here focuses on the structural utilization of bamboo split sections more than full bamboo sections.

4. Need for experimental research on bamboo:

Bamboo plays an important role not only in everyday life but also in art, literature and philosophy due to its structural and material properties, elegant shape and finish, practical utilizations and symbolic meanings, in most of the countries across the world. But in the automated industrial context today, this excellent natural material could not be utilized as in past because of its irregular form, inhomogeneous structure and variation of the material properties. It is difficult to be processed by standardized machines and to be assembled with standardized industrial components and sophisticated automation programmes.

After the industrial revolution[ix], many new materials were invented and the traditional material like bamboo and bamboo goods lose their place in the modern industrial world. The industrialization of the material bamboo was supposed to solve the problem of utilizing bamboo in the industrial context, which has been considered an important strategy for local economic development, in many developing countries where bamboo sources are abundant. But in this process of industrialization[x], there are threats about bamboo losing its structural advantages and at the same time about losing the connection to its traditional bamboo culture. In the industrial working process, bamboo has following disadvantages in two dimensions, compared to industrially standardized materials,

4.1 From the material perspective:

Its irregular and tube-shape structure has varying dimensions from one culm to another and its strong longitudinally arranged fibre is difficult to be joined with other materials by common means like nail or screw.

4.2 From the designer perspective:

The designers have been educated to use standard materials, which are easy to integrate into the industrial production process. Even if they find that bamboo is an excellent material they would have to give up working with this material because of the difficulty of handling it. The mass production and standardization are the key factors behind industrial production environments.

Without fitting into this production system, it is difficult for bamboo as a material to get into the industrial world. This process can be seen in two ways:
a. First, the mechanization, in which the powered machines are used to replace manual power in the bamboo working process. Mechanization saves manpower in the production and offers a wider range of products.
b. Secondly, the standardization, which here in its narrow sense means to turn the bamboo tubes into certain standard forms to fit the whole industrial working environments (XiobingYu 2007).

To make this possible, Experimentation with bamboo will be the first step. The experimentation with bamboo is not like a totally new thing from the outer world, but more like one step of a continued process. With more and more new bamboo components, modules or systems having been explored with appropriate consideration of its structural dimensions, bamboo as material can build its new structural identity in the industrial society. It is possible to create an identity with multiple modern meanings which represent a harmony of its internal structural dimension and the outer industrial context.

5. Derivation of methodology:

This study prefers to choose bamboo, as an issue from the perspective of design research only and shall not be another bamboo encyclopaedia. A methodology is specifically structured to support and suffice the pace of research. Each of the objectives is followed by several stages, which aims to accomplish the particular objective. The methodology, adopted is explained here in brief,

Objective 1: Understanding different parameters[xi], which form components of bamboo split sections, in various bamboo craft.

Using available literature on bamboo, such as technical reports, magazines, books and websites related to various fields (architecture, civil engineering, structural engineering and product design) the data to accomplish this objective has been put together. The considered objective is followed by the stages, listed below;

Stage 1: A study to find out various bamboo components formed out of bamboo split sections, in various bamboo crafts, prevailing in traditional and contemporary architectural practices, till now.

Stage 2: Analyzing and organizing the collected data, to extract various parameters which form the bamboo components and which can be used to derive a systematic methodology for experimentation.

The results of the literature study can be categorized into four, which in turn are considered as various parameters which form the bamboo components/ modules/ systems in architectural practices. The categorization of different parameters is as follows;

[Note: The results can be categorized into a huge number of categories, but considering the aim of the study, they are restricted to only four categories.]

For example,

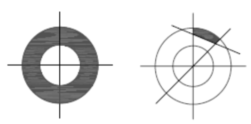
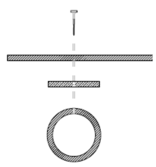
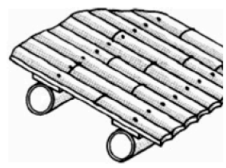
Technique: Nailing		
Application: Floor deck		
Components:	Module:	System:
		

Table 01: Segregation of parameters.

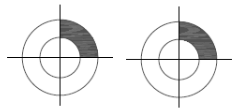
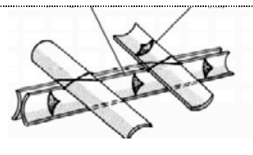
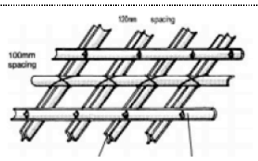
Technique: Tying		
Application: Bamboo reinforcement		
Components:	Module:	System:
		

Table 02: Segregation of parameters.

As shown in the table 01 and 02 above, many examples have been categorized into all four categories. As a result of this study, different parameters which form bamboo components can be listed as below:

a. Techniques used.
b. The predetermined form.
c. Connections between the split sections.
d. Scale and proportion of different split sections and their composition.

[Note: Some other parameters such as tools and etc. are not considered here. The considered parameters are further distributed into sub parameters and are framed, considering time limitation. For example, the long list of techniques is restricted to only tying, cutting, bending and splitting. Similarly, other parameters are also restricted, as explained below.]

a. Techniques used:

Tying, cutting, nailing, bending, splitting, twisting, weaving, flattening

↓

Tying, cutting, bending and splitting

b. The predetermined form:

In most of the cases, the form of the end product is predetermined at the initial stage only. But for an experimental research, forms cannot be predetermined, as it might limit the potential of outcome and also diminish the possibilities for propagation[xii]. But it is very necessary to limit the propagation possibilities, as it is possible in each and every direction.

Therefore, to limit this study, the axis of propagation is restricted to,
a. Horizontal,
b. Vertical,
c. Inclined and
d. Curvilinear.

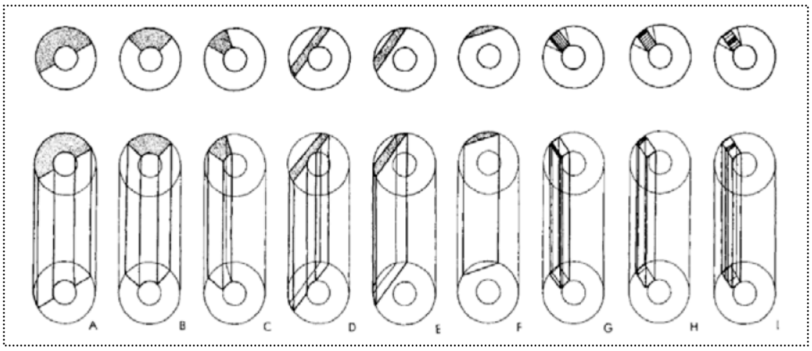
c. Connections between the split sections:

Rivets, nuts & bolts are used for assembling components of split sections. Jute twine and aluminium wire has been used for tying based experimentation.

d. Scale and proportion of different split sections and their composition:

The craftspersons of India exhibit diverse variety in utilization of different bamboo split sections, for various applications. For example, the strips from the upper part of the bamboo are used for making bamboo cable, as they are good in tension. While half bamboo sections are interlocked, to be used as roof tiles. Different bamboo split sections, used by the craftspersons till now, are illustrated in figure 07.

After reviewing various bamboo sections, the sections which can be utilized in architectural practices, are classified into six categories, as shown in figure 08. Further considering the time limitations, the selected split sections for the study are marked by dotted boundaries in figure 08. Using the above classified six type of split sections, iterations can be achieved by plotting the split sections on the x and y axis of a graph, as shown in the figure 09. This gives a general idea of various types of permutations-combinations [xiii] possible with bamboo split sections, which offers wide range of possibilities to explore different components.



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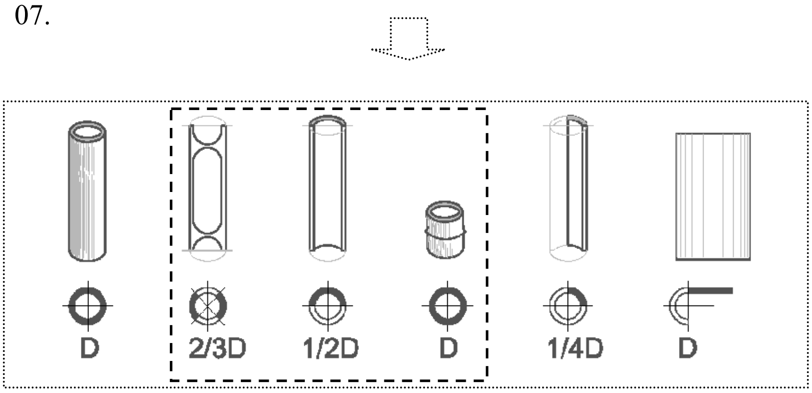

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Objective 2: Exploring different components/ systems, using the derived methodology.

As the study has been confined to particular split sections only, various iterations - marked with dotted boundary (figure 08), are taken into consideration.

Stage 4: Listed techniques are applied over various iterations, classified in figure 09 below, which result into components. The procedure will be repeated, for all considered iterations. The procedure leads to a wider range of bamboo components which can be utilized for different structural and non structural elements.

Stage 5: Propagation of resulted components.

Most of the components are propagated till module level. After this level, only few selected modules are propagated to system. Rest of the modules have been propagated, using Rhinoceros and AutoCAD as digital tools. These digital tools open up a wider range of possibilities for form explorations.
[Note: Each of these components can be propagated as modules and in turn to system. Though, it is not mandatory that a component must be propagated as a module, it can rather propagate itself as a system.]

Stage 6: The achieved components/modules/systems are analyzed considering the framework of analysis as below;

a. Intentions:
What were the intentions of making the particular component/ module/ system?

b. Making process:
Picture presentation of each step of the making process.

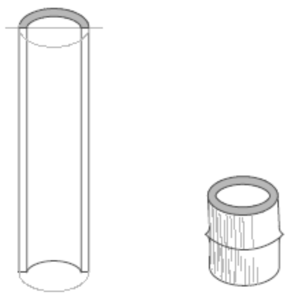
c. Structural virtuosity:
Structural behaviour of the Joint:
Whether the joinery allows rotation along any axis?

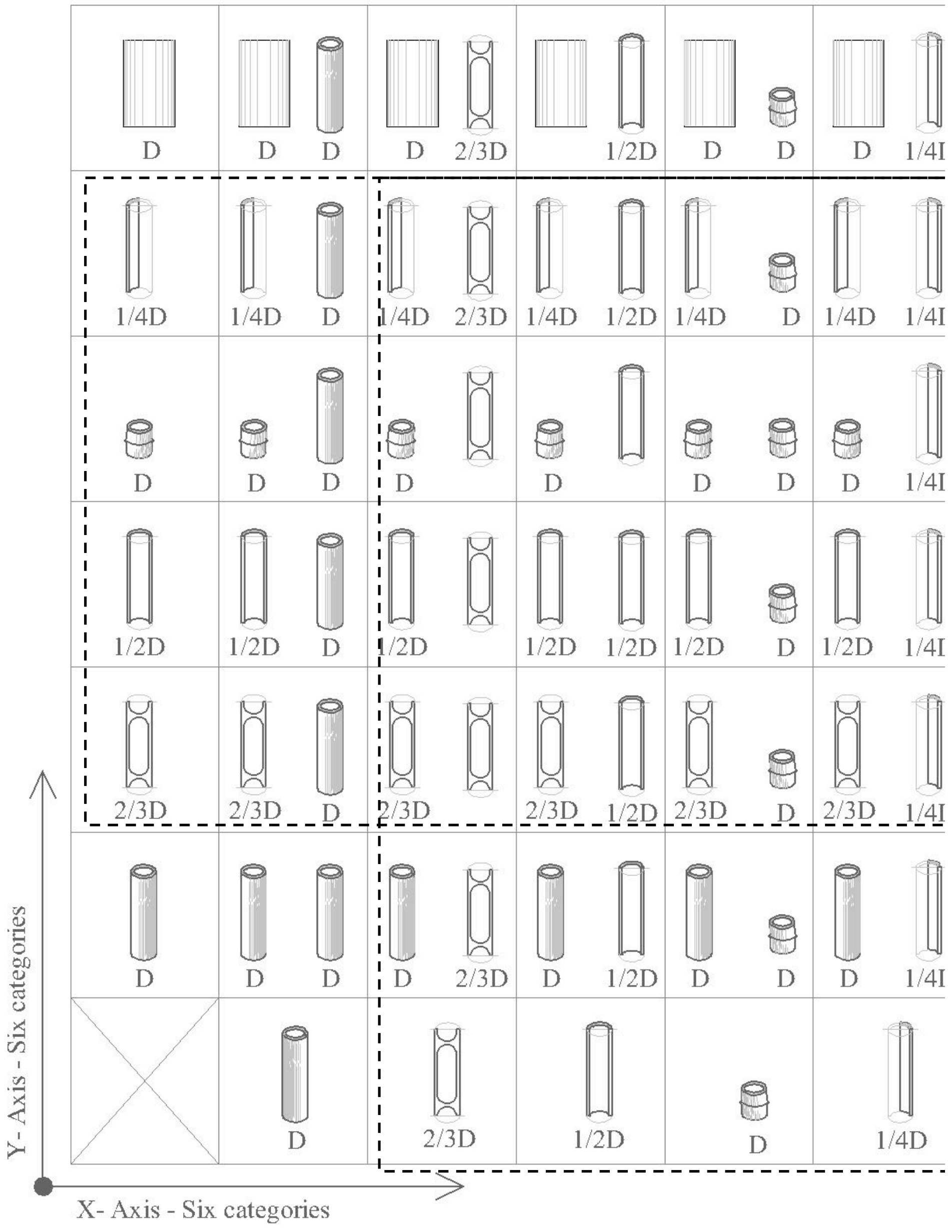
d. Behavioural pattern:
How a particular component/ module/ system behaves under compression and tension loading conditions?
What are the strengths and weaknesses of the derived component/ module/ system?
How does the load transfer?

e. Further scope of the research:
What are the future possibilities / scope of the same research?
What are the possible ways to modify the component/ module/ system?

f. Possible direction of propagation:
Vertical, Horizontal, Inclined, curvilinear (2d or 3d drawings for all the possible propagation possible)

g. Probable application:
What can be the future applications of the resulted components/ Modules/ systems?





Stage 7: Directions for further research - One of the combinations, from figure 09 and one of the techniques, from the listed techniques, are selected for a detailed study, based on area of interest.

Constants:
1. Combination of half bamboo with one node.
2. Bending technique.

Variables:
1. Angle of bending and
2. Number of the strips - from half bamboo section. (Two or three)

Stage 8: Further explorations are done, using the selected combination (figure 10), till component level.

Stage 9: The resulted components, from stage 8, are propagated as modules or systems.

Stage 10: Resulted modules/ systems are analyzed, on similar framework of analysis, as mentioned in stage 6.

Objective 3: Testing of the explored module/system.

Stage 11: Compression testing of a selected system has been performed.
Compression testing on a vertical system is preferred to be explored, based on time constraints. Test results suggest a brief summary about the performance of the particular system under compression. The results also suggest some modifications in the tested system, which will help to improvise the performance of the considered system under compression loading conditions.

6. Resulted components/modules/systems:

Considering the technique explored, the resulted modules/systems are majorly distributed into three groups, as shown in figure 11. Using tying as a technique - five modules (figure 12 – 16), and using cutting and splitting as the techniques; another five modules (figure 17 - 21) have been generated. Using bending as a technique and half bamboo having three splits, three modules (figure 22 – 24); similarly, with half bamboo having two splits, another three modules (figure 25 – 27) have been generated. To explore the propagation possibilities with real scale material, four systems have been generated, using 90 degree component (figure 28 – 31). For further exploration, five platonic solids have been developed, using various components (figure 32 – 35).

6.1 Tech

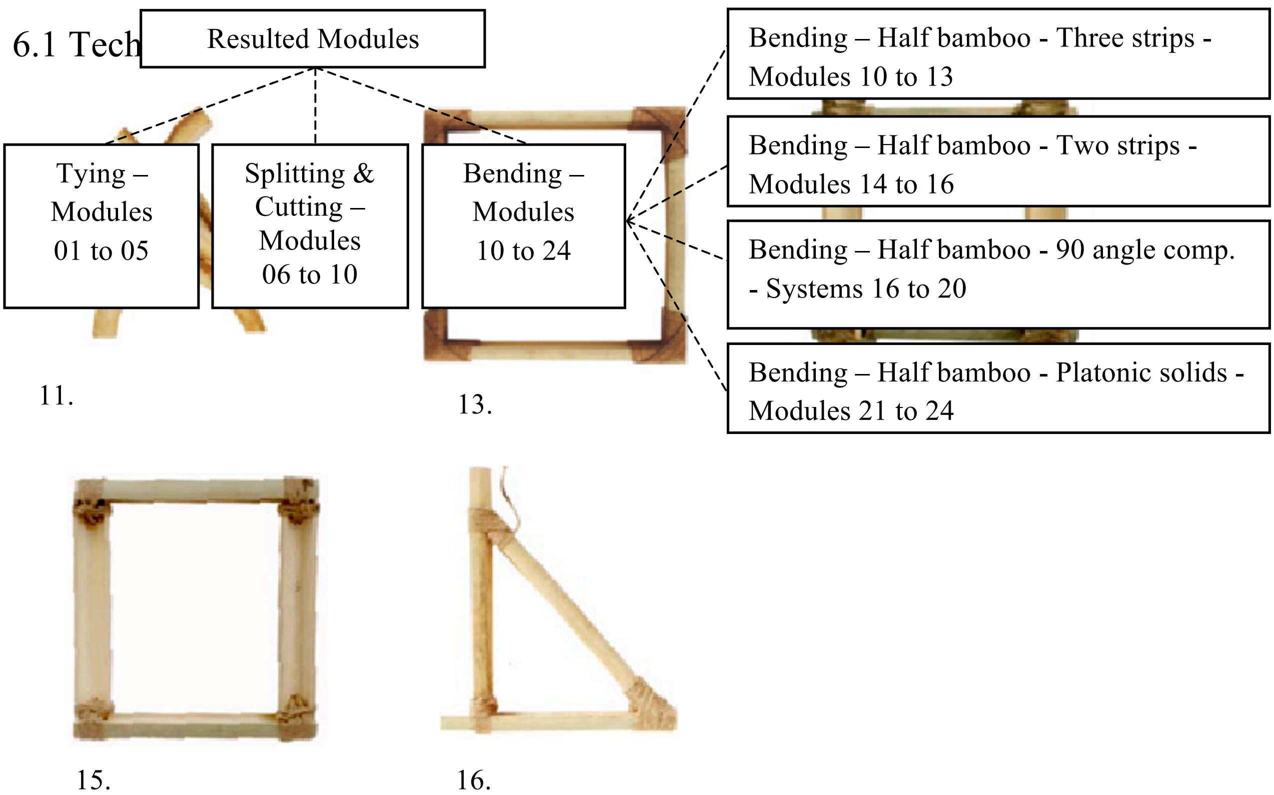


Figure 6.1

6.2 Technique - Cutting and splitting: -

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6.3 Technique - Bending (three strips):-

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6.4 Technique - Bending (two strips):-

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6.5 Technique - Bending (90 angle component):-

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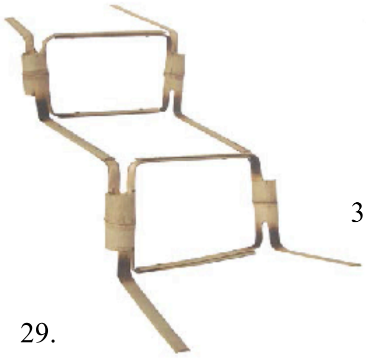

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6.6 Technique - Bending (platonic solids):-

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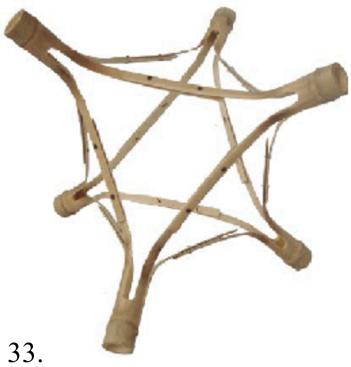

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All the resulted modules and systems have been analysed, using the framework of analysis – as described earlier.

Inferences have been drawn out for all the three categories (tying, cutting and splitting and bending) considering the following factors;
a. Advantages and disadvantages of the technique,
b. Types of structural joints it offers,
c. Possibilities of standardization and mechanization,
d. Degree of craftsmanship required,
e. Tools and technologies required and
f. Future scope of research.

7. Testing

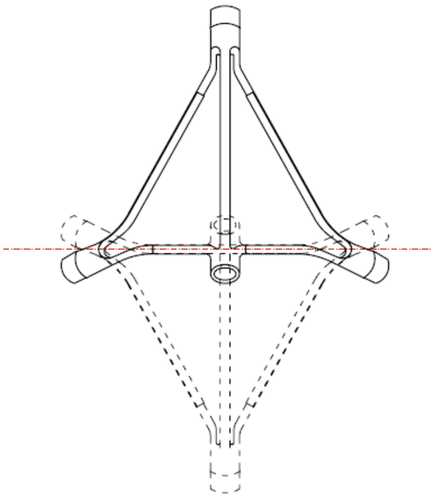
For an experimental research, it is very important to evaluate the derived results by some or the other means, which certifies the proposed methodology. Testing of a particular system has been chosen as a part of the evaluation procedure.

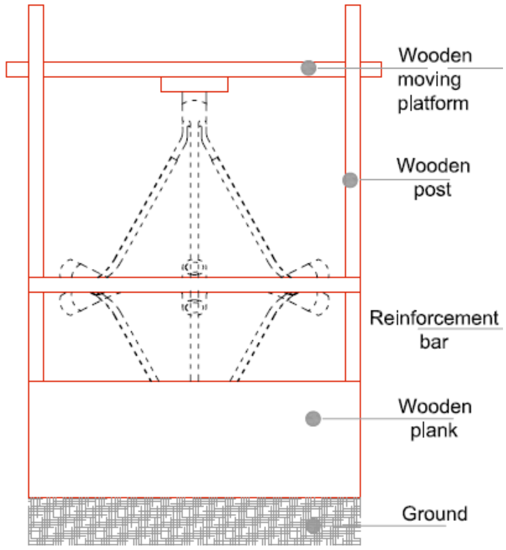
7.1 Methodology for testing:

Using available literature on bamboo testing, like technical reports, books and websites; the data has been put together, to have a brief idea about the testing done, till now, on bamboo. For example, Oscar Hidalgo has mentioned about various testing like compression, tension, bending and shear, on bamboo species, in his book - Bamboo: gifts of gods in 2001. As mentioned in IL-31: Bambus, the deflection test was carried out by Frei Otto - Institute of light weight structures in 1985. The Wondergrass team had carried out compression testing of bamboo beam in 2010, using Geo Tech appliances. The students of IIT, Delhi have also done high strength testing on bamboo in 2012.

To evaluate the performance of any module or system, it is important to test the module or system under five loading conditions as; Tension, Compression, Shear, Torsion and Bending. But it is clearly visible from the literature study that it is not possible to perform the testing for Tension, Shear, Torsion and Bending, without advanced laboratories. Hence, compression testing has been performed on a derived system.

[Note: Vertically propagated -testing specimen (figure 38) and testing apparatus (figure 39) have been decided, based time limitation.]





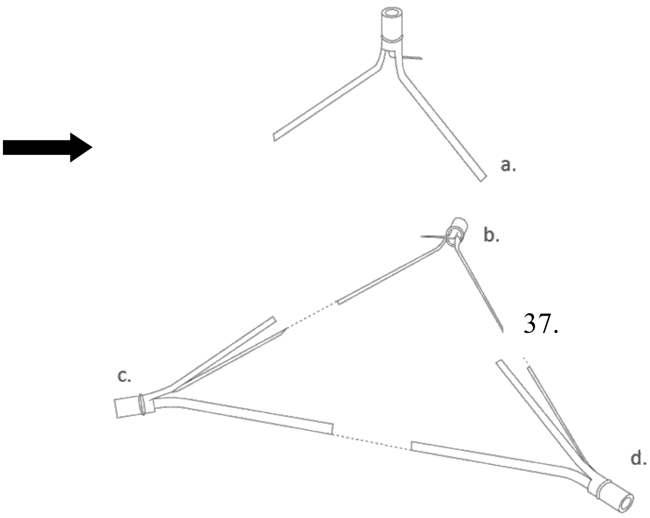
7.2 Description of testing specimen and apparatus:

7.2.1 Testing specimen:

As a result of the experimentation, many components/ modules/ systems were derived, using various tools, techniques and approaches. But as a result of an analytical study, it was proved that the tetrahedron performs better under different loading conditions. Therefore tetrahedron was selected as a module and various options were tried for a system – testing specimen. Considering time constraints, one of the options was decided, as shown in the figure 38.

a. Making process for the testing specimen:
A full bamboo section having a node and an intranode is considered here. The section will be split into three equal parts by means of a tapered knife. Each of these strips will be bent at 60 degree along a plane, perpendicular to the convex curve of their outer face. Hence a full bamboo section, having three splits (bent at 60 degree) is considered as a component, as shown in figure 36(a). The width of the strip is considered approximately around 30mm and the thickness of the strip is approximately around 7mm for each of the components. Four such components were joined together by means of metal rivets, as shown in figure 36(a, b, c and d), which resulted into a module – tetrahedron as shown in figure 37. Therefore the particular module – tetrahedron has six sides and four nodes.

For a testing specimen here, two such tetrahedrons were joined, as shown in the figure 38, by means of aluminium wire. The modules are not finished by peeling off the outer skin, as it might affect the strength of the modules.



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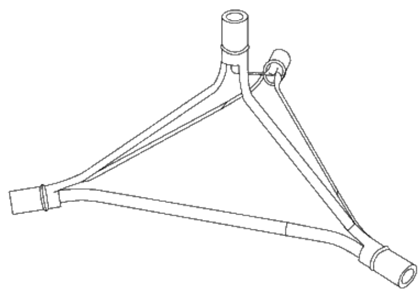

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7.2.2 Testing apparatus:

As the testing is done without a … pparatus for testing was designed manually. Many opti… sidering time and material constraints, a setup has been pr… rd platforms are joined by four wooden posts, as shown in figure 39. The platform at upper part is kept movable so that when it is subjected to load, it can slide along these four posts. The idea was to prepare a set up where load will be uniformly distributed[xiv] to the testing specimen along vertical axis.
[Note: Only metal nails are used to join wooden members.]

7.3 Procedure:

The considered system is supported by a node at top and another node at bottom. To avoid possible wobble of system during the process, additional lateral supports are provided. As compression testing has been considered here, the system should be loaded from top. Hence, the system is subjected to axial load from the top. The whole testing procedure is recorded by adding 7to 8 kg each time, as shown in figure 40-45. The behaviour of the system is observed throughout the process.

7.3.1 Process of testing:

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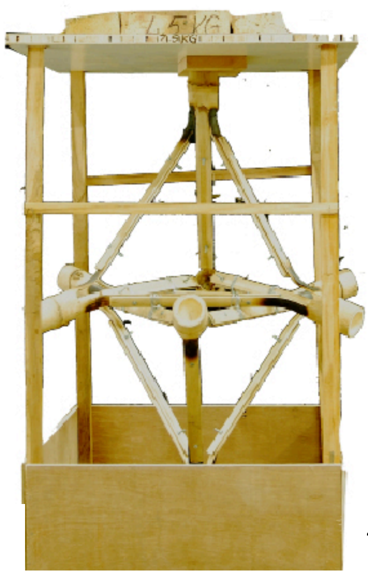

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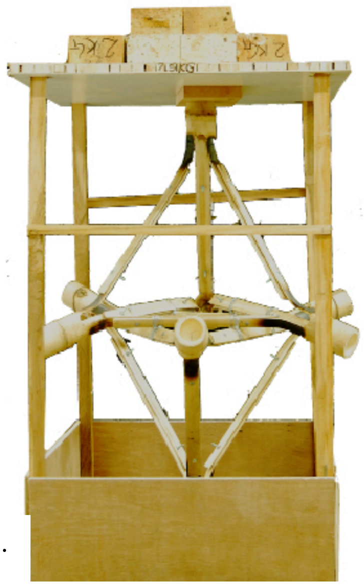

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7.4 Analysis and inferences:

The testing specimen – system is analyzed under certain parameters, as follows:

7.4.1 Load transfer:

As shown in figure 46, the load is applied to the node at the top gradually. From the node, it is transferred to three sides adjacent to the upper node and then in turn to the rest of the three sides of the same module. Both the modules are connected in such a way, that they have six points of contact. Hence, the load is transferred to the second module through these six points and then in turn to the rest of the sides and to the bottom node and finally to the contact surface at bottom, as shown in figure 46.

7.4.2 Behaviour of each of the nodes and sides:

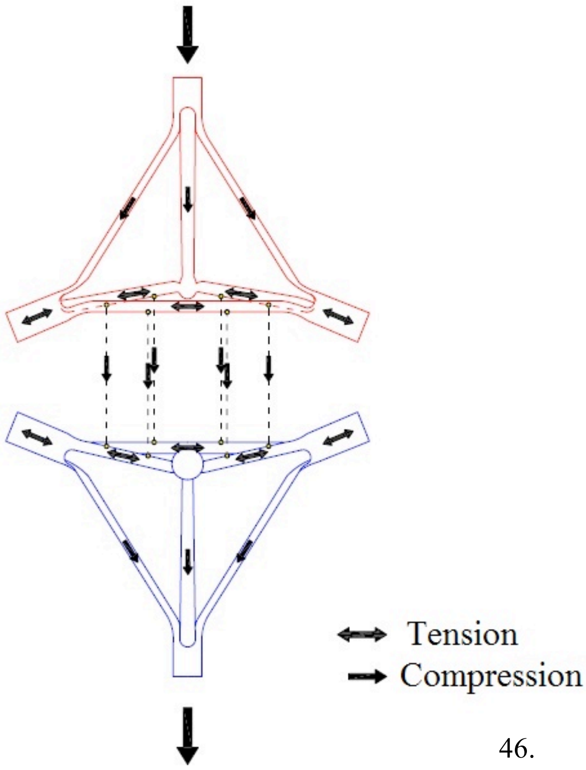
As shown in the figure 47, a gradual deflection is observed at the ends of each of the strips adjacent to nodes. The behaviour of the system at three different loading is illustrated here, though each step of the testing procedure is recorded systematically. The black solid line in figure 47 represents the behaviour of the testing specimen subjected to loading of 10 kg. The blue dotted line represents the behaviour of the system at 55 kg loading and the red dotted line represents behaviour of the system at loading of 80 kg. The nodes are deflected up to 10 degrees, for the same loading condition. The reduction in the height of the module is recorded up to 4 cm, when the amount of loading is 80 kg, as shown in figure 47. Noticeable deflection is observed at the bent junctions and at the nodes while liner stretches of the strips express minimal deflection possibly due to overlapping of the strips in the module.

7.4.3 Failure:

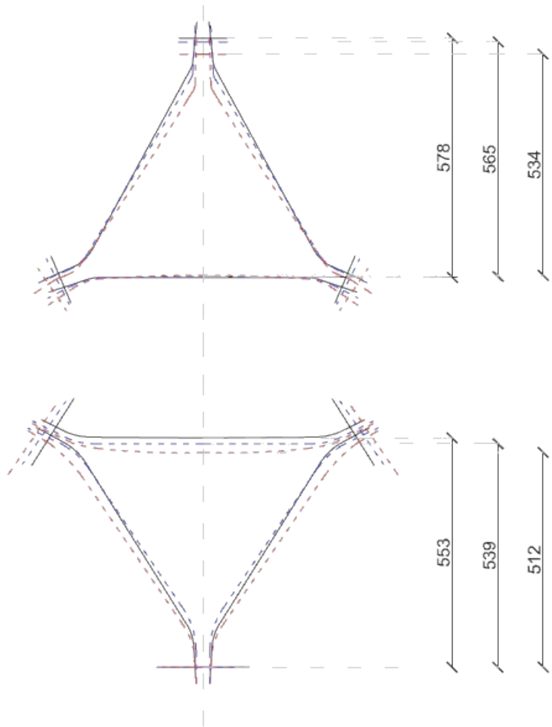
The system fails by the rupture at a bent junction near bottom node of the top module. Observed rupture occurred at a point where the strips are not overlapped and in addition the fibres at the bent junctions are exposed to fire during the bending process. If one analyzes the load transmission diagram, the bottom module shows more amount of deflection than the upper module. But the rupture occurs at the bent junction of upper module. The system failed when the loading was 85 kg.

7.4.4 Strength to weight ratio:

This ratio expresses the efficiency of the material or object. Strength to weight ratio is strength (force per unit area at failure) divided by its density.
-



46.



47.

Duration of experimentation	– 09:36 minutes
Amount of load when the system failed	– 85 kg
Weight of the testing specimen	– 1.2 kg
Length of the testing specimen	– 600 mm

Strength to weight ratio[xv] of the testing specimen = $\frac{\text{Force / unit area}}{\text{Density}}$

= 704.57 N Mt. /Kg.

The strength to weight ratio, derived here exhibits the structural potential of the system, developed using tetrahedrons. The system can take up to 705 Newton force per kg. The results suggest that the particular system can be utilized for various structural applications.

7.4.5 Further scope of the study:
The results of the study might vary, if similar experiment is done using advanced laboratories with more precise devices to measure and calibrate. In addition, it is not advisable to conclude anything with single experiment, as novel methods and approaches are adopted here. A series of experiments should be performed to evaluate the methodology and results.

Different experiments can also be executed using the same methodology. For an instance, the width of strips, length of strips, sizes of the module, orientation of modules and types of joineries etc can be altered or modified, for a series of experimentation.

Various components/ modules and systems explored using various techniques, can also be tested further. In addition, only compression test has been performed here. Other tests such as tension, shear, bending and torsion can also be performed, using advanced laboratories.

8. Conclusion:

"Bamboo", having inherent innovation potential, is a ray of hope for the designers and architects who strive for sustainable, eco friendly and renewable building material. It is possible to create a new structural identity of the material bamboo. The bamboo split sections have a great proven potential to be used for various structural applications. Experimentation with the derived methodology can open up endless possibilities for exploration of various components, modules and systems.

The results of the study can be divided into two major parts: Systems and Forms. Different kind of forms (resulted) can either be directly utilized for their optimum functional usage or may be further optimised for other desired utilisation. And different systems can be propagated further, keeping its functional value in mind which can be utilized as various structural and non structural elements. These kind of different explorations lead us to the better understanding of material conservation, where the excess material usage can actually be cut down, by using bamboo split sections in place of full bamboo.

Through this research, the concept of component – module – system opens up the possibilities of customized mass production in industrial scenario to enhance the usage of bamboo as a building material.

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Endnotes:

[i] Experimentation: the act, process, practice, or an instance of making experiments.

[ii] Exploration: a systematic search for the truth or facts about something.

[iii] Bamboo split sections: various sections, cut from bamboo.

[iv] Component: one of the parts that make up a whole.

[v] Module: independent part composed of one or more components.

[vi] System: something made up of many interdependent or related parts.

[vii] Bamboo culture: bamboo even has a big influence on the regional cultures in many countries and places where bamboo resources are abundant, "Bamboo Culture" as a concept is only acknowledged in some countries in East Asia, like China, Japan and Korea.

[viii] Structural potential: the potential of the object for utilization of that object in any structural application.

[ix] Industrial revolution: this revolution was the transition to new manufacturing processes in the period from about 1760 to sometime between 1820 and 1840. This transition included going from hand production methods to machines, new chemical manufacturing and iron production processes, improved efficiency of water power, the increasing use of steam power, and the development of machine tools.

[x] Industrialization: it is a process that happens in countries when they start to use machines to do work that was once done by people.

[xi] Parameters: a rule or limit that controls what something is or something should be done.

[xii] Propagation: to cause to increase in number or amount.

[xiii] Permutations-combinations: arrangement and selection of things.

[xiv] Uniformly distributed load: UDL is a special type of distributed load where the load is constant over a certain distance.

[xv] Strength to weight ratio: strength to weight ratio is a material's strength (force per unit area at failure) divided by its density. It is also known as specific strength. It compares the weight of the structure itself to the amount of the weight it can carry without collapsing.

Figure captions:

Figure 01: Dome construction out of split bamboos by Yona Friedman.

Figure 02: A bamboo dome by students of Aachen University, Germany.

Figure 03: Modern bamboo connection by Shoei Yoh, Japan.

Figure 04: *"Truss me"* collection by Sandeep Sangaru, India.

Figure 05: Zeri pavilion by Simon Velez, Columbia.

Figure 06: Wind and Water cafe by Vo Trong Nghia architects, Vietnam.

Figure 07: Various bamboo split sections, used by craftsperson till now.

Figure 08: Selected bamboo split sections for study.

Figure 09: Selected permutation- combination for study.

Figure 10: Selected combination for detailed study.

Figure 11: Resulted components/ modules/ systems.

Figure 12 - 16: Explored modules – Tying.

Figure 17 - 21: Explored modules – Splitting and cutting.

Figure 22 - 24: Explored modules – Bending: Three strips.

Figure 25 - 27: Explored modules – Bending: Two strips.

Figure 28 - 31: Explored systems – Bending: 90 angle component.

Figure 32 - 35: Explored modules – Bending: Platonic solids.

Figure 36: Full bamboo section – three strips – 60 degree

Figure 37: Tetrahedron

Figure 38: Selected testing specimen.

Figure 39: Selected testing apparatus.

Figure 40: Behavior of the system, when fixed between two platforms.

Figure 41: Behavior of the system, after 10 kg.

Figure 42: Behavior of the system, after 40 kg.

Figure 43: Behavior of the system, after 60 kg.

Figure 44: Behavior of the system, after 80 kg.

Figure 45: Behavior of the system, after 85 kg.

Figure 46:Load transmission diagram – testing specimen

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Figure 47:Deflection diagram – testing specimen