A Human Centered Approach to Redesign Prefab and Modular Bamboo Houses

Dipanka Boruah

Abstract Bamboo is one of the sustainable building materials in the world. Due to its durability, flexibility, low cost, lightweight, resiliency, easily cultivated and processed, bamboo is widely used. The building construction technique of bamboo is traditional and requires less time to construct. Bamboo along with metal can be used as a prefabricated (prefab) and modular building structure. The components of prefabricated houses can be constructed off-site, assembled and finished on site. Due to cheaper cost and time-efficiency, a prefab and modular housing system is the desirable strategy for quarantine center, isolation center, and temporary shelter for flood-prone areas. The aim of the research study is to redesign prefab and modular design houses using Bamboo material. The objectives include the study of traditional houses in Northeast India, different prefab and modular construction methods across the world, existing problems, physical properties of bamboo, treatment, and its uses. The methodology adopted for the study is divided mainly into three processes—Inspiration, Ideation, and Implementation. The Inspiration process includes a study from different works of literature of the concept of traditional housing, prefab structures, and different materials used with the HCD approach. Ideation includes the concept generation and ideas gathered and used in redesigning the prefab and modular bamboo houses. The initial Implementation or testing is done in the NID Assam campus and the performance analysis is carried and collected on the campus. This paper introduces a human-centered approach to the design and fabrication techniques of prefabricated modular bamboo houses, which can meet modern building requirements.

Keywords Prefabricated structure · Modular construction · Human centered design · Sustainable solution

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D. Chakrabarti et al. (eds.), *Ergonomics for Design and Innovation*, Lecture Notes in Networks and Systems 391, https://doi.org/10.1007/978-3-030-94277-9_81

1 Introduction

Human centered design (HCD) is an approach for design and implementation of a solution which based other qualitative research of user's observations, needs and desires of people. While most of people are spending their lives within the built environment and social sustainability ahead of user well-being, comfort, and satisfaction. There is limited works of HCD approaches on construction techniques for house. Within the building construction industry, there are many construction methods those are: prefabricate and modular. Modular system in building means the modules that are built in an industry as partially finished, but that arrive on site and either that is placed or stacked. Modular architectural system has many benefits: (i) speed of erection, (ii) flexibility to allocate, (iii) cost effective, (iv) energy efficiency, and (v) low maintenance. The bamboo is very lightweight, flexible, tough, high tensile, cheap material as compared metal. It is a substitute for wood, cement, and other building materials as it is weather-proof and disaster-proof. A piece bamboo combines many nodes where transverse dipharm occurred between two nodes (Fig. 3b). Modular technique using bamboo is also an innovative and vernacular architectural system in the world. Bamboo has a demand in the construction industry to build architectural design due to its strength, durability and aesthetic value. In addition, structural properties of the bamboo is its strong fiber, which double compressive strength of concrete and conceptually the strength- to- weight ratio of steel in tension [1]. On the other hand, prefab means the system such as panelized system, prefab component that are built within the industry and arrive on-site ready to put together. An example of prefab method is Airship Hangars in Orly, France which was made of prefab repetitive concrete arches and massive enclosure allowed for the storage [2]. Prefabs are typically used in large-scale affordable housing or where on-site construction is difficult [1]. Now a day people is expanding its use to different geographical locations such as public infrastructure and roads. Prefab houses have been installed to build new hospital and quarantine centers through the covid-19 pandemic. Prefab construction is much faster than traditional construction because various functions can be completed simultaneously in the same duration [3]. The Sustainable Materials Lab, NID chooses to take up the challenge of designing bamboo made prefab and modular house as a quarantine facility in the campus within the short period. Emphasis was on creating design intervention by using locally available materials with the help of prefab and modular fabrication method.

2 Literature Studies

2.1 Traditional Houses in Northeast India

There are three types of bamboo houses in Northeast India. They are (i) Ikra is called Assam Type House (Fig. 1a), (ii) Mud House (Fig. 1b), and (iii) Chang House (Fig. 1c)

(a). Ikra house (b). Mud house (Andharia, 2020) (c). Chang house

Fig. 1 Traditional houses in Northeast India

[5]. Ikra House are easy to construct, maintain and economical. The construction method is a frame structure which consists of vertical component (wall) using bamboo and wood frame. The walls are covered with mud and cement plaster. The roofs are covered with galvanized iron (G.I.) sheet. On the other hand, longevity of mud plater house is too short. It needs to be replaced once every two years due to wear off with lashing rain. In addition, the concept of Chang House was adopted by the Himalayan civilization but due to heavy rainfall in Brahmaputra river valley, people have widely accepted this stilts form of construction. This house has two parts, lower part is used to provide shelter for domestic animal and upper part is used for habitual space.

This house has two parts, lower part is used to provide shelter for domestic animal and upper part is used for habitual space. This stilt structure also helps in protection from wild animal as well as flash flood in the bank of river Brahmaputra.

2.2 Prefab and Modular Construction Method in Building

The history of prefab construction house has more than 300 years of in the world. The first component of prefab component of building were manufactured in 1624 and those shipped to the fishing village of Cap Anne in Massachusetts, USA [6]. Prefab construction method consists of many factory built components which are assembled at the site to construct the overall unit [2]. Modular, panelized and precut construction are included under prefabricated construction. This method of construction has brought a major change in the development of construction industry. It ensures the economy, strength and environmental performance of the structures [7]. All prefab and modular houses are showing in the Fig. 2a–f [8–13].

Similarly, a modular building can be constructed more than fifty per cent of faster than traditional construction methods [14]. It can be more affordable than on site building and shorter time consuming. A young designer from Manila developed a special modular housing model called ‘Cubo’, which solves housing models in the Philippines. This housing model can be constructed within four hours [15].

Fig. 2 Various prefabricated and modular houses in the world

2.3 Physical Properties of Bamboo

The physical characteristics of bamboo are hollow woody plant belongs to a grass family, the scientific name is Gramineae and sub family is Bambusoideae [16]. There are fifteen hundred bamboo species all over the world, Bambusa balcooa, Bambusa tulda, Koko bamboo, Mokalm bamboo etc. are the most usable bamboo species among them [17]. They are found across Asia, Africa and America and the percentage of 65, 28 and 7 respectively as shown in Fig. 8a. The morphology of the bamboo plant consist of branches, sheaths, culms, flower, leaves, rhizomes, and roots are stated in the Fig. 3b [19].

The mechanical properties of bamboo are mentioned below:

- Résistance to external forces. This force depends on the magnitude and manner of loading i.e. tension, comparison, shear, bending etc.
- It has wonderful tensile strength. Bamboo are closely correlate with specific gravity and density.

The mechanical properties of bamboo are correlated with specific gravity and density. The strength and stiffness of bamboo culms compared with other building materials. In the Table 1 [8], the strength and stiffness increases with specific gravity.

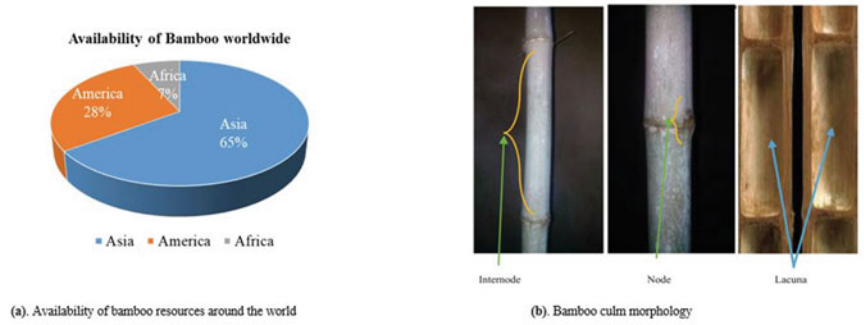

Fig. 3 Physical properties of Bamboo

Table 1 Comparing the efficiency of materials for strength and stiffness

Material	Strength (Nmm-2)	Weight by volume	Ratio	Stiffness (Nmm-2)	Weight by volume	Ratio
Concrete	8	2400	0.003	25000	24000	10
Steel	160	7800	0.02	210000	7800	27
Wood	7.5	600	0.013	11000	600	18
Bamboo	10	600	0.017	20000	600	33

* Ratio = strength or stiffness/weight by volume

2.4 Raw Bamboo Treatment Methods

Treatment of bamboo is a very important stage to increase its longevity and protects from termites and insects. In addition, the process is to increase the dimensional stability and retain strength, fire resistance, improve aesthetic quality. In this process need three main materials: Borax or sodium borate with water ($NA_2B_4O_2.10H_2O$), Boric acid (H_3BO_3) in (1:1.5) ratio. The treatment process can be done through various conventional methods such as traditional or nonchemical treatment methods, which are for clump curing, water soaking, and fire (smoking) treatments (Fig. 4) that followed by indigenous people but the effect of these treatments is limited. In culm curing method, fresh and matured bamboo culms along with leaves are stored in shaded place for 10 days to 25 days and in this process bamboo, culms discharge starch contents due to respiration in tissues and leaves. Thus, this method is always used before utilizing the bamboo (Fig. 4a). In Asia and South America, a common method is diffusion or soaking method (Fig. 4b) whereas harvested bamboo poles with high moisture content (above 50%) are either submerged or running water with stones on top of them for 10 to 20 days in diffusing of the starch, sugar and other active water soluble ingredient [20]. However, the process using smoke to prevent insects from the bamboo. The bamboo can be stored above the fireplace and bamboo culm will blacken. The effect on durability is limited (Fig. 4c) [21].

Fig. 4 Traditional treatment method for harvest bamboo

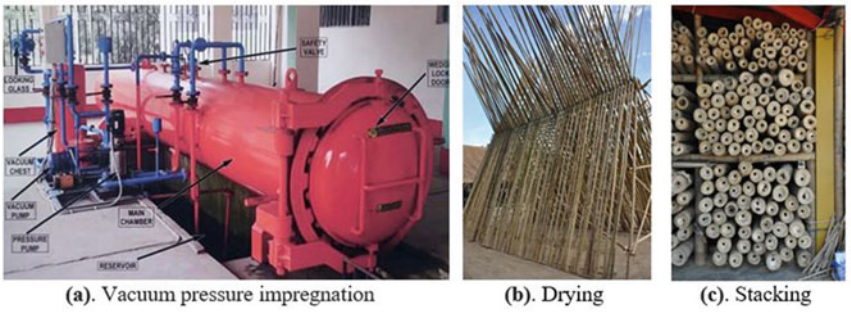

Fig. 5 Vacuum pressure impregnation treatment for bamboo and drying

Besides a custom design equipment to treat bamboo chemically, which protects a harvest bamboo from fungi, bacteria and other insects is called as vacuum pressure impregnation treatment for bamboo. A technical parameter is prepared during the treatment process of bamboo in the equipment shows in the Table 2. After putting the harvested bamboos in the equipment, the borax with water ($NA_2B_4O_2.10H_2O$) solution is impregnated deep into the pores of bamboo with help of vacuum and pressure (Fig. 5a). Once the bamboo poles are chemically treated, bamboo are kept for air drying in direct sunlight in a prolonged time (Fig. 5b) about 7 to 30 days.

Table 2 Technical parameters as in vacuum pressure integration treatment plant for bamboo

Sl. No.	Description	Unit
1.	Size of the cylinder (main chamber)	Dia-3′6″ and Length-22’
2.	Capability of cylinder for withstanding vacuum	650 mm Hg
3.	Creating maximum pressure	14 Kg/cm^2
4.	Loading and drilling time	30–45 min/cycle
5.	Vacuum time	15–25 min
6.	Pressure time	80 min
7.	Discharging time	20 min

Later the bamboo poles are left to dry slowly in a shaded and dry place until they are used for bamboo construction (Fig. 5c).

3 Methodology

The research focuses on necessity of post disaster infrastructure, quarantine center for pandemic, isolation center for hospital, and temporary shelter for flood-prone areas in developing country like Northeast India. Tim Brown of IDEO (a global design and consulting organization based in California) argues in this case about how to design for change, what needs a new idea, and how to build a house that is less expensive and time-efficient [22]. His proposal belongs to a three phased process: *Inspiration, Ideation and Implementation* that process is called Human Centered Design. A HCD approach solves when a problem does not exist abstractly in a society, but there is always from some's suggestion of scenario on people need. However, Norman [23] defined in his book titled The Design of Everyday, HCD as an approach that puts human needs, capabilities, and behavior first, later designs to apply those needs, capabilities, and ways of behaving [24].

4 Contextual Study

A pilot study was carried out to find out shortcoming scenarios of rural, semi urban and urban areas in India. Low-cost housing settlement are affected by floods created by the river Brahmaputra, Barak and other small rivers in Assam. Flood victims use a banana raft to get from their submerged home to higher ground (Fig. 6a) [25].

In the Fig. 6b, a doctor checking a patient's health status and real scenario of Covid-19 pandemic in Uttar Pradesh, a person having oxygen and sitting on street bench (Fig. 6c) [26]. Literature survey of various factors associated with people health and lifestyle were carried out. The temporary shelter for the healthcare facilities, disaster

Fig. 6 Contextual studies of flood affected, open house medical check-up and worst Covid-19

resilient house and quarantine or isolation center for pandemic situation. The shelter can be operated as another activity after completion of earlier activities.

5 Design Brief and Formulation of Design Problem

Based on observation during the field visit and discussion with people, it will be viable and socially acceptable using locally available vernacular materials and having consideration of social sustainability. During the observation, it has been found that there are many challenges with existing traditional construction houses such as unavailability of skilled labor. Therefore, people do not prefer to construct the bamboo house easily in a short period of time as a temporary purpose. In addition, the jointing system is very difficult and complicated in bamboo. The Fig. 2a shows the construction techniques of modular house in India are metal framed structure with bamboo mat board walling and whole framed structure rests on raft foundation. For constructing of framed structure it is required to use welding machine with skilled manpower. Also the metal framed structure does not carry on a truck without dismantling the metal framed structure.

Need of current practice on the redesign and development of prefab and modular house in hospital, highland, bank of river as quarantine center, isolation center and temporary shelter for flood affected areas in Assam, Northeast India. In this regard, a design proposal was proposed to solve for these people in India.

- Substituting brick, wood, steel and cement, bamboo reduces up to 40% and constructing walls, floor, and roof with other alternative materials.
- Cost reduction by using prefabricated components, increasing the speed of construction.
- Low cost and easy to assemble solution.
- A unit can be constructed within 4 to 5 hours.
- Design parameter based on anthropometry and ergonomics standard.

5.1 Concept Generation

The feasibility study was carried out in NID Assam campus for making of Covid-19 dispensary cum quarantine center for the students. The initial sketches were prepared (Fig. 7a–e) to create the next stage of conceptualization. The design maximizes the use of traditional bamboo building techniques, prefab for the walls and solar blinds. The roof provides shade and offers protection from heavy rains.

Based on shortcoming existing prefab and modular houses (Fig. 2a–f), new concept was created. Previous examples of houses are very heavy which was made of concreate, metal and wood. Thus, houses cannot be carried to install. A temporary modular housing is removal structure that is located on a site for a limited period

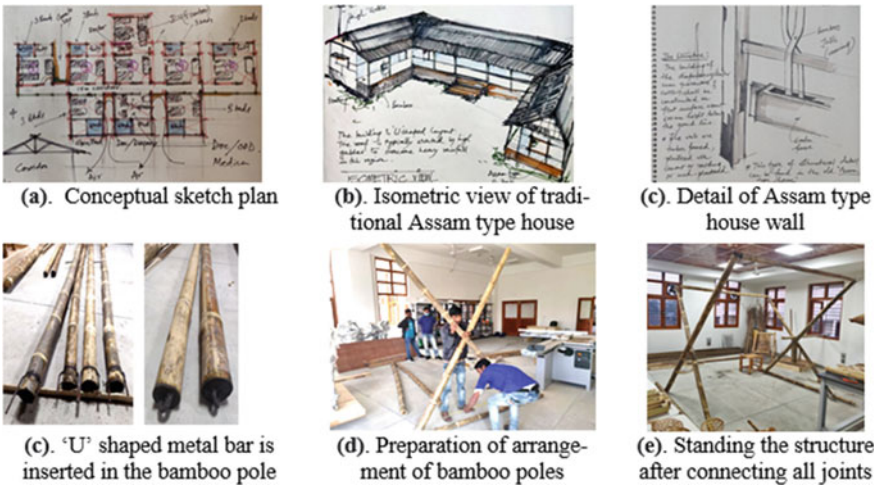

Fig. 7 Temporary shed for dispensary in NID Assam campus

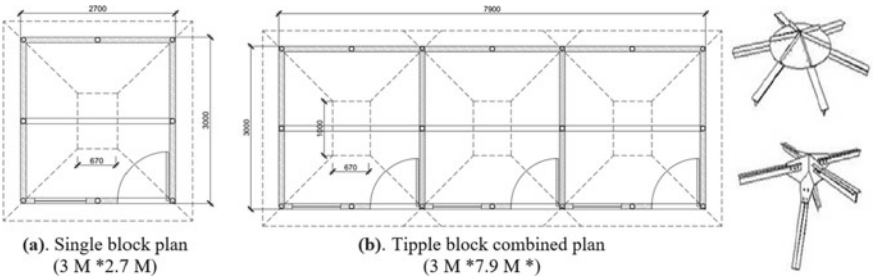

Fig. 8 AutoCAD 2-dimensional plan of prefab and modular house and roof connector

and this is used as a relief shelter and sometimes it can be relocated to multiple sites over time.

Therefore, it should be substantial for re-use. In addition, development of temporary modular housing provides facilities are as follows:

- Two nos. of bed, one table where a gas cylinder can put for cooking, one wardrobe for keeping goods.
- Strong metal connector arrangement is to be fixed for the expansion of units.
- Provision of safety and ergonomic comfort and protect the user from nature.

Two-dimensional CAD modelling was prepared to better understanding of space arrangement and utilities is shown in Fig. 8. The dimensions of a single unit area are 2.7 m × 3.0 m (Fig. 8a) and triple combined block plan of single blocks as detailed components are mentioned in Table 3.

Table 3 Different types of metal component for assembling the prefab and modular house

Component's name	Metal components	Size (L*B*H)	Weight (in Kg approx.)	Requirement (Single unit)
1. Foundation		400 mm *400 mm *400 mm	15	4 nos
2. Column connector		150 mm *75 mm	1.5	4 nos. It is screwed with foundation
3. Corner joiner		200 mm *200 mm *400 mm	6	Total 12 nos. 4 nos. each for plinth, lintel, and roof
4. Wall combiner		200 mm *200 mm	4	Total 12 nos. 4 nos. each for plinth, lintel, and roof
5. T- joint		200 mm *200 mm *200 mm	8	Total 2 nos. 1 no. each for plinth, lintel, and roof
6. S.S. Nut bolt		100 mm *70 mm	0.25	Total 24 nos. 2 nos. each for corner joiner
7. Modular connector		400 mm *400 mm *400 mm	10	Total 3 nos. each for edge of wall while modular house is joined

5.2 Process of Manufacturing of Various Component

The various metal components were (shown in component 2, 3, 4, 5, 7) manufactured individually since craft process like local blacksmith and welding. The size of those components were made as per the standard size of bamboo using jigs and fixtures. Balcooa bambosa and Balcooa Tulda were used for assembling of the house.

Pad foundation is off-site construction technique that was casted before putting into excavation in the earth. Due to cost reduction, time saving, increases of productivity, quality and safety thus this technique is used. The Table 3 gives a detail of components of the structural members.

5.3 *Prototyping of Redesigned Prefab and Modular House*

Initially CAD modeling (Fig. 9a) was carried to obtain digital data of house. The installation-planning phase for the house involves multiple steps. The preliminary design of this type of house was intended to establish an overall concept for the project and served as guideline for detailed design. As a first step in preliminary design, an attempt was made to redesign and develop a modular house suitable for temporary establishment with due consideration for anthropometric aspects, safety, sustainability and environment friendly. During the design of individual metal, concrete components, along with subsystem connectors (Fig. 9c) of bamboo pole in relation to fit in overall arrangement needs to be considered, its surface treatment with the components. The eight bamboo poles were lashed together to create pyramidal shape of roof structure (Fig. 9e) was placed upon eight vertical bamboo poles where metal components were assembled and those four corner columns were screwed with precast pad foundation (Fig. 9b). In this regard, overall progress has been made in components design through systematic engineering method such as finite element method. Bracing system is applied to prevent shaking and to provide strength to the structures. Bamboo plank are to be used as flooring that will strengthen the superstructure from wind pressure (Fig. 9d).

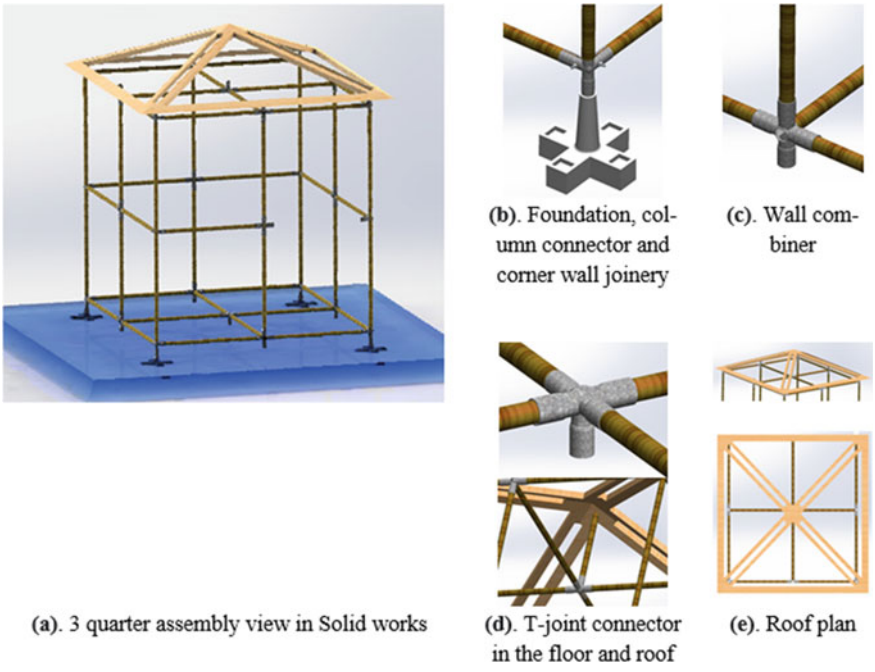

Fig. 9 CAD model and details of assembly model

5.4 *Anthropometrics Parameters on the Newly Designed House*

The newly designed house is considered as the 95th percentile anthropometrics data. CAD detail dimensions of a single block is 3 m length, 2.7 m breath where two single beds fit alongside of left and right direction. However, 0.6 m gaps between two beds where someone can move easily. In addition, one wardrobe fits in a single block. The dimension of door is 2.1 m $\times$ 0.9 m as standard anthropometric standard for architectural house. Single window is placed between two beds which is 0.9 m sill height from the floor level.

6 Conclusion

The research work was aimed a need to redesign prefab and modular design with Indian context. The conceptualization of this house followed in this research work would enhance with the HCD approach. The use of this house using bamboo panels along with metal components facilitate the assembly of structure with respective jointing systems. In this regard, preliminary test on the metal joints with bamboo sub structures are completed in NID Assam campus and performance feedback from artisans and workers has been collected. These houses are designed to showcase improvements to the prefab, modular along with traditional materials to server as models for the future housing concept, temporary shelters such as isolation home for pandemic and other contextual scenarios. The performance feedback, safety and durability and ergonomics design analysis in an actual site will be carried out in the future work.

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