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Bamboo reinforced prefabricated wall panels for low cost housing

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ABSTRACT

With the increasing population there is a tremendous exploitation of natural resources to produce conventional building materials such as bricks, cement and reinforcing bars. This exponentially increases their prices and also deteriorates the environment by production of large amount of greenhouse gases. So, there is a need to develop cheap and sustainable infrastructure. This paper presents an alternative sustainable infrastructure component – prefabricated bamboo reinforced walls beneficial for low cost housing. To determine the potential of these panels in the construction industry, the strength analysis along with the cost estimation and environmental impact analysis were also carried out for these panels. It was observed that these walls are 56% lighter in weight, 40% cheaper and have good strength as compared to partition brick walls. The benefits of these walls over the traditional brick walls were observed to be significant, through which it can be concluded that these wall panels have a great potential for low cost housing.

1. Introduction

Even though the industrialization was started century ago, but still mankind is unable to provide shelter to all. Housing problem is at alarming level with millions worldwide without shelter especially in developing countries. As per the report of Ministry of Housing and Urban Poverty Alleviation, Government of India, the housing shortage in India itself was estimated as 18.78 million at the beginning of 12th Five Year Plan (2012–17) [1]. With the ever increasing population there is already a tremendous exploitation of natural resources, which has increased the price of conventional building materials substantially. Millions of people across the world are living below poverty line without proper shelter. This brings a lot of pressure on Government to provide cheap alternative solution to this group of people.

Beside this, the production of conventional building materials such as steel, cement and bricks involves high energy consumption and production of greenhouse gases which damages the environment. The average temperature worldwide has reached alarming levels causing the glaciers to melt and increase in the sea level. Due to which various coastal regions are at the verge of drowning underwater. Countries such as Maldives have already lost a large chunk of their land due to global warming [2]. In the UN climate change conference (Paris, 2015), it was decided to limit the temperature increase by 1.5 °C above pre-industrial levels which requires a lot of reduction in carbon dioxide emission into the atmosphere [3]. Thus there is a great need to look out for alternative materials for construction industry which should be cheap, sustainable, environmental friendly and must have satisfactory structural properties.

Number of studies has been undertaken to look out for such unconventional building materials. In the last few decades' number of materials such as kevlar, polyster, carbon fibers, metal alloys were looked upon as a building material [4]. However, the production of such materials is a complex process which cannot be manufactured at a village level from the locally available materials and technologies. To resolve the problem of housing shortage, which is predominant for the people living below poverty line, it is essential to develop building technologies which can be used at a village level from the locally available materials to construct the building components such as beams, columns, slabs and walls at a much cheaper cost than the traditional building materials. Also with the increasing population and shortage of land it is imperative to look for multi-storied structures and prefabricated technology is one of the best options for that.

In the present study, a new approach to develop one such building component – walls have been presented by the authors. These wall components are prefabricated, cheap, made from sustainable materials such as bamboo and fly ash and have a great potential in the construction industry.

2. Bamboo as an engineering material

Bamboo is a giant grass with more than 1200 species, some of them growing at a phenomenal growth rate of 91 cm per day as per the

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Table 1
Comparison of different properties between bamboo and steel [7].

Sl. No.	Property	Steel	Bamboo
1	Density (kg/m^3)	7850	(515–817) for different species in Green Condition (640–758) for different species in Air Dry Condition [8]
2	Modulus of Elasticity (N/mm^2)	2×10^5	(0.61–15.01)x10^3 for different species in Green Condition (3.77–21.41)x10^3 for different species in Air Dry Condition [8]
3	Grading for Structural Utilization	As per its Yield stress, ultimate tensile stress, elongation.	As per diameter, taper, straightness, inter nodal length, wall thickness, density and strength, durability and seasoning [8]
4	Compression Strength	Mild Steel - Compression in column bars:130 MPa	(25–100) [9] MPa
5	Tensile Strength	Mild Steel - Permissible stress in tension 140 MPa (upto 20 mm dia) 130 MPa (over 20 mm dia)	(100 – 400) [9] MPa
6	Bending Strength	0.66*yield stress	(70–300) [9] MPa
7	Factor of Safety (F.O.S)	1.15–Structural member for limit state of collapse	For safe working stresses of bamboo [8] 4–Extreme fiber stress in beams 4.5–Modulus of elasticity 3.5–Maximum compressive stress parallel to fibers
8.	Ratio of tensile strength (N/m^2) to specific weight (N/m^3)	5326	Six times greater than steel [4]

Guinness Book of world records [5]. Bamboo has a great economical advantage as it reaches to its full growth in few months [4] and is abundantly available in tropical and sub-tropical regions of the world. Production of every ton of bamboo consumes about a ton of atmospheric CO_2 in addition of releasing fresh oxygen in the atmosphere [6]. Bamboo is found to be about 50 times more energy efficient as compared to steel in terms of energy required to produce them [4]. Bamboo is pliable, lightweight, has excellent tensile strength and has a very good weight to strength ratio which makes it highly useful against high velocity winds and earthquakes. Table 1, discusses the comparison between steel and bamboo properties.

2.1. Bamboo in the construction

Performance of bamboo as a construction material was studied as early as 1914 by Prof. H.K. Chow [10]. In that study small diameter bamboo and bamboo splits were used as reinforcement material for concrete applications. However, elaborative research started only after 1950's with research projects on bamboo as reinforcement in concrete. The issues such as debonding of concrete, water absorption, fungus attacks, and coefficient of thermal expansion were predominant and not much further research was carried out. Later in 1995, Prof. K. Ghavami again started a number of mechanical tests using bamboo as reinforcement in concrete [11]. It was observed that bamboo considerably increased the load bearing capacity of the composite. Also, many researchers across the world have proven that bamboo can be considered as an alternative to steel as a tension element [4,6,9–13,15,16] due to its excellent tensile strength as compared to its weight.

2.2. Bamboo in walls

Walls usually occupy the largest area of a building and require large amount of construction material. Traditionally bricks are used in walls which increases the dead load of a building considerably and also further affect the seismic performance of the building. However, bricks increase the wall cost considerably and also causes land degradation by consuming the top fertile soil. When bamboos are cut into tiny strip and are woven, it enhances its tensile strength which makes it suitable for wall panels [4]. These bamboo strips based wall panels can provide an alternative to traditional brick walls.

Over the period of time, bamboo based walls are used in the rural regions where mud plaster is often used over a bamboo based grid. However, these walls are not durable for regions having heavy rainfall. Over the last few decades, researchers have proposed different improvements for such walls and have achieved significant performance of such structures. Dash et al. [14] have shown a scientific approach of constructing a bamboo reinforced concrete house which involves the bamboo frames made up with bamboo strips weaved inside and joined together with nuts and bolts and then plastered using cement mortar. However, such type of housing concept is not suitable for multi-storey structures.

Bamboo based walling system was developed by Vengala et al. [15] which was made from bamboo grids, bamboo columns and a steel wire mesh. It was concluded that such type of walls can sustain the most severe conditions likely to be experienced during the life span of the structure. Design of different types of bamboo based wall panels was discussed by Paudel [16] such as Quincha walls with bamboo poles, Grid wall system etc. The strengths, weaknesses, opportunities and threats of promoting bamboo for housing were also discussed. It was observed that bamboo is an excellent building material suitable for different economic groups as it offers a range of building options. Bamboo walls provide good thermal comfort compared to modern concrete as discussed by Dash et al. [14]. Indian Plywood Industries Research and Training Institute (IPIRTI) have developed a two story house using bamboo at Bangalore. The house has split bamboo grid and wire mesh plastered with cement mortar as walls and bamboo columns providing the support and the ceiling was made up of light bamboo mat used with corrugated sheets. These types of houses are suitable for earthquake prone areas as discussed in the study. Widyowijatnoko [17] developed a low cost house using prefabricated bamboo reinforced components consisting of bamboo reinforced concrete partition wall panel of size 4×30×110 (cm^3), bamboo reinforced formwork panel, bamboo reinforced door-window frame and steel reinforced concrete tie beam. Study observed that the properties of bamboo are excellent as compared to that of steel. It was also observed that the bamboo reinforcement improves the tensile strength of prefabricated panels [17].

3. Development of a prefabricated bamboo reinforced wall panel

Residential multi-storey buildings usually have the ceiling height at 3000–3600 mm. Frame structures are usually preferred for such structures with walls acting as partition walls that are built at a later stage. Thus to test the feasibility of proposed alternative partition wall a 50 mm thick prefabricated panel 2440 mm long, 300 mm wide has been developed. The sizes of such prefabricated panels can be varied based on the requirements.

Fig. 1. Bamboo mesh.

3.1. Preparation of bamboo mesh

Bamboo strips were obtained by finely cutting the bamboo culm (Bambusa Balcoa) and were 3–5 mm thick. Bamboo mesh outer frame was first crafted with two layers of bamboo strips connected together by steel wires. This frame was then weaved with bamboo strips inside hand woven in a crisscross pattern for a size of 2390 mm long by 250 mm wide. The crisscross pattern was such that the size of each box was approximately 50 mm by 50 mm (shown in Fig. 1) to allow for the smooth passage and bonding of cement mortar. The bamboo mat was then sun dried for extracting the moisture present in the bamboo strips.

3.2. Treatment of bamboo mesh

Lime water treatment was used to prevent the degradation of bamboo which occurs due to fungus production and termite attack as cellulose is present in bamboo. This type of treatment is one of the cheapest and most conventional methods. After the lime water treatment bamboo mats were sun dried again to remove the moisture as bamboo is prone to water absorption which further degrades its engineering properties. Bamboo mesh must be treated first to protect it from moisture internally as well as externally. Also, the bond strength of bamboo mats with mortar is dependent on the different types of epoxies (for external protection) used on bamboo with further coating of selected sand particle sizes. Researchers have studied the behavior of bamboo bond strength with concrete under the different types of epoxies such as Araldite, Araldite with binding wire, Tapecrete P-151, Sikadur 32 Gel, Negrolin, Negrolin with sand, Negrolin with sand and wire. It was observed that the Sikadur 32 gel gives the best results [4,18]. In the present study, Sikadur 32 LP epoxy, an alternate to Sikadur 32 Gel was used. However, such epoxy treatment is expensive which can be further reduced by using cheaper treatments such as asphalt paints, tar based paints, bituminous materials to make bamboo impermeable [4]. Fig. 2 shows the lime water treated bamboo mat coated with epoxy and sand particles. Sand particle sizes passing through 4.75 mm and retained on 2 mm sieve sizes were bonded with epoxy to increase the bond strength of bamboo with mortar in the present study.

3.3. Wall panel casting methodology

As the cement mortar is a thick binder it has been preferred instead of concrete. A layer of 20 mm of cement mortar was first laid in a mould of size 2440 mm long and 300 mm wide. The treated bamboo mat was then placed on it and again cement mortar was poured on the mat. The mortar was placed in such a way that it passes through the crisscross pattern of bamboo mat and the total thickness of panel is 50 mm. Guidelines as prescribed by IS:2250 (Indian Standard - Code of Practice for preparation and use of masonry mortars) [19] were followed for the preparation of mortar and IS:2116 [20] (Indian Standard - Specification for sand for masonry mortars) were followed for sand utilized in the mortar. A detailed methodology for selecting the design mix of mortar has been discussed in Section 6. The developed bamboo reinforced prefabricated wall panel is shown in Fig. 3.

Fig. 2. Lime water treated bamboo mat coated with epoxy and sand.

3.4. Wall panel connections

The panels can be laterally connected by high strength steel wire loop boxes. These loop boxes have steel wires in a circular loop at one end and a triangular loop at the other. The loop boxes are casted along with the panel edges such that the adjacent wire loops of two panels overlap over each other at the edges during interconnection between two panels. Then these panels are interconnected by placing a reinforcing bar inside the wired loops by using a high strength grout to complete the connection as shown in Fig. 3. The vertical connections of panels to slabs can be done by using 12 mm dowel bars as shown in Fig. 3. These bars are casted along the center of the panel and are connected with the triangular edge of the loop box wire. The panels are then connected in the slabs by grouting the bars inside the hollow spaces left in the slabs.

4. Cost & dead load analysis

Walls generally occupy the largest surface area of any construction and especially in the multi storey structures. Thus, the cost of a structure can be considerably reduced if the cost of wall is reduced. Table 2 shows the rates obtained from Delhi Schedule of Rates (DSR-2014) of various building materials used in the cost analysis [21]. The cost analysis of a conventional brick wall with the proposed prefabricated wall panel system for a 2440 mmx2440 mm wall has been compared in this study. From the cost analysis as discussed in Table 3 it is observed that the cost of proposed wall system is about 40% cheaper than conventional brick wall system. Also, further cost reduction in the walls made from prefabricated panels could also be achieved by using cheaper chemical treatments for bamboo such as cement paste coating, asphalt paints or tar based paints and by utilizing the cheaper alternative to dowel bars for connections such as metal plates. The discussed brick wall calculation is based on a single wall system used generally as partition walls in framed structures.

In contrast to conventional brick walls, the proposed prefabricated wall panel system is much more eco-friendly as it involves natural products such as bamboo which absorbs greenhouse gases and releases oxygen which is useful to reduce the global warming. Even though the bamboo consumption is less in walls but its usage actually reduces the consumption of environmental degrading building materials such as cement and bricks. Moreover, in these panels fly ash was used as a replacement of cement which further reduces carbon footprint.

Since the dead load of a building significantly impacts its performance under the earthquake load, a dead load analysis was also carried

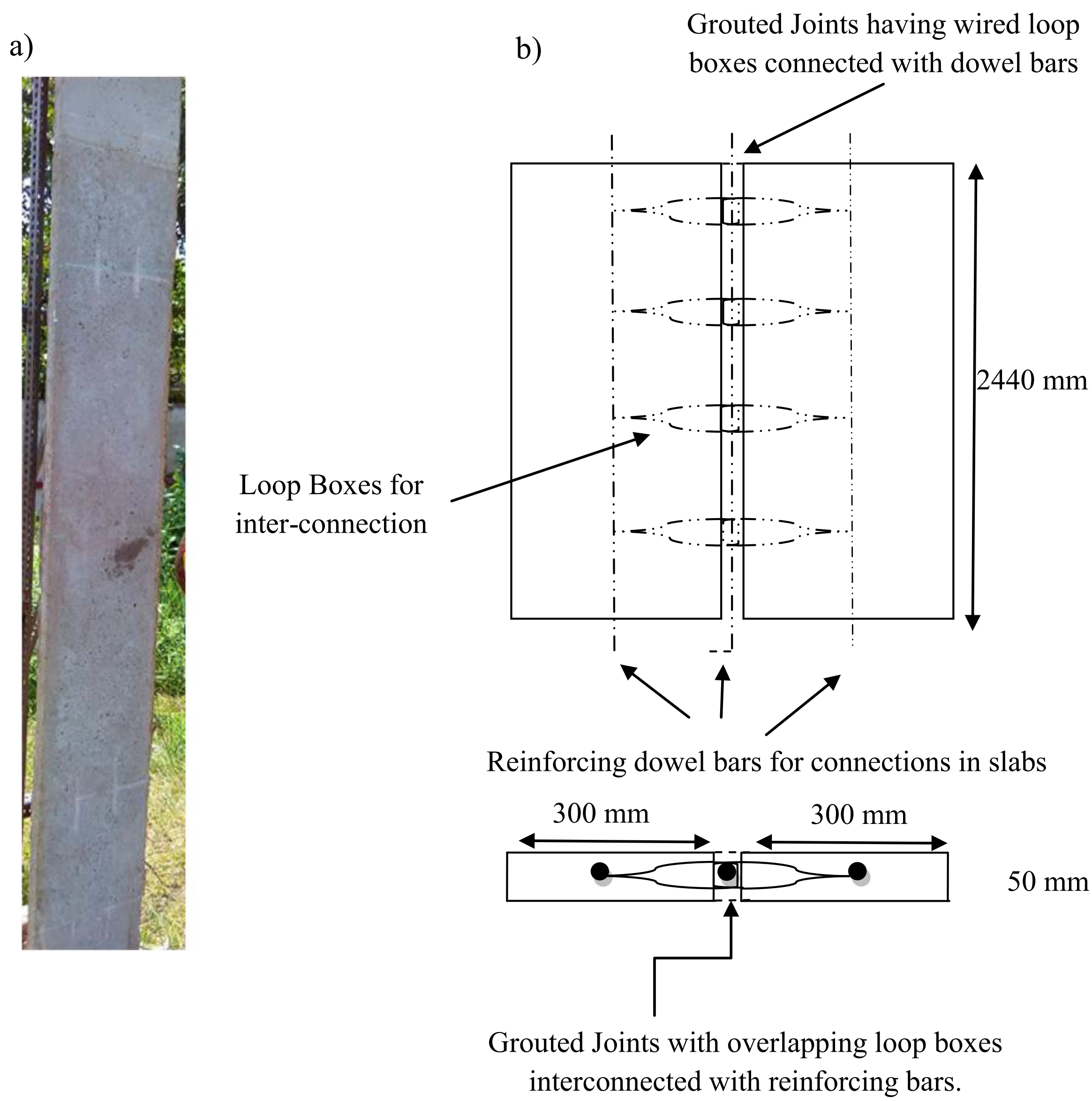

Fig. 3. a) Bamboo reinforced prefabricated wall panel, b) Schematic diagram of Interconnected Panels.

Table 2
Rates of various building materials (1 USD=Rs. 67.40 as on 03/03/2016).

Building material, unit	Rate per unit, Rs
Portland Cement, /t, [19]	6300
Fine Sand, /cu.m, [19]	700
Brick, /1000 Nos., [19]	5000
Fly Ash, /cu.m, [19]	8
Bamboo Mesh, /m^2	10
Epoxy, /kg [19]	150
Dry Hydrated Lime, /qt	230
Dowel bars, /qt	4500

out in this study. The dead load comparison is shown in Table 4. It was observed that the proposed prefabricated wall panels are around 56% lighter in weight as compared to that of a conventional brick masonry wall.

5. Environmental impact assessment

Construction industry is one of the most polluting industries in the world. Production of cement itself contributes about 5% of the global anthropogenic CO_2 emissions [22]. These emissions further affect the world climate which ultimately increases the sea levels. As per the World Climate change agreement (2015), it was accorded to strive for a limit of 1.5 °C rise in global warming [23]. So, it is very much beneficial to adopt bamboo as a construction material at the earliest. Table 5 shows the comparative study carried out by author(s) on annual environmental impact due to the production of bamboo, steel, cement, bricks and fly ash. It was observed that by utilizing bamboo in construction industry, a substantial amount of greenhouse gases (102 million tonnes) could be reduced from the atmosphere yearly. At the same time, replacement of steel by bamboo also reduces the steel demand in the construction Industry. This ultimately reduces the emission of carbon-di-oxide into the atmosphere. A large amount of land and energy could also be saved by using fly ash as a replacement for cement. However, this all could be achieved only when detailed guidelines are framed for such type of constructions.

6. Experimental investigation

Masonry structures are usually affected due to the out of plane collapse of walls due to their brittle behavior during earthquakes. As an

Table 3
Comparative cost analysis (1 USD=Rs. 67.40 as on 03/03/2016).

2440 mmx2440 mm Conventional brick partition wall	2440 mmx2440 mm Prefabricated bamboo reinforced wall (8 Panels)
• Total Bricks–320 Nos. • Brick Cost–Rs 1600.00 • Mortar [1:6 Mix] Cost (Brick Bonding & External Plaster [10 mm])–Rs 1106.00 • Manpower Cost for Brick Bonding & External Plaster (Two mason@Rs 500.00 & one labor @ Rs 350.00) for 8 hrs 1350.00 • Additional Average Cost of Transportation of Bricks, cement and sand to site till 5 km–Rs 650	• One Panel Cost:Rs 309.00 a. (Bamboo mat+epoxy+lime) cost–Rs (10+18+5)=Rs 33 b. Mortar Cost (1:2 mix)–Rs 166 c. Cost for panel connections by dowel bar, loop boxes and grouting per panel–Rs 110.00 • Manpower Cost for panel casting & assembly at site (Two labors for 2 hrs@ Rs350 for 8 hrs) Rs 262 • Additional Average Cost of Transportation of 8 Panels to site till 5 km–Rs 100
Total Cost–Rs 4706	**Total Cost–Rs 2834**

Table 4
Comparison between weight of conventional brick partition wall and prefabricated bamboo reinforced wall.

2440 mmx2440 mm Partition brick wall with 10 mm External Plaster	2440 mmx2440 mm Prefabricated bamboo reinforced wall
• Brick Density–1.9 g/cm3 • Size of Brick-230×110×70 mm • Mortar Mix For Plaster–1:6 • Plaster of 10 mm thickness on both sides	• Size of Panel–2440 mmx300 mmx50 mm • Mortar Mix:1:2 • Bamboo mesh weight–3 kg
Total Weight-1865 kg	**Total Weight–823 kg**

alternative to these brick walls, authors have discussed here-in the potential of bamboo reinforced prefabricated wall panel system. It is also very much essential to study the performance of these wall panels such as panel strength and its flexural behavior before use in the construction industry. A bamboo reinforced prefabricated wall panel was casted by following the methodology as described earlier in the paper. However, to decide the mortar mix, water cement ratio, fly ash content and the number of days of curing a statistical tool namely design of experiment was used. Design of experiment implemented in the software - Design Expert was used to predict the optimized fly ash content as a replacement of cement, based on the different input design points by formulating a statistical model. Face centered central composite design (CCD) method was used in this study to formulate the model. In face-centered central composite design with four factors and five replications, 126 design point and experiment are required [31]. Testing on each cube was considered here as an experiment and each combination of factors was considered here as design point. Design Expert software was used to statistically analyze the response and fit the response surface model. The response considered here is cube compressive strength. Statistical analyses were performed to find out whether the formulated model is appropriate or not. The formulated model is valid in the studied ranges and can only be used in practical engineering applications to approximate complex behavior in those ranges. A detailed discussion about the procedure for formulating a response surface model has been described by Chakrabortty (2008) [32]. The regression equation of response surface model for calculating compressive strength is as follows:

$$\begin{aligned}\mathrm{Ln(Compressivestrength)} = {} & 1.076 + 0.012 \times F.A + 1.716 \times M.P \\ & - 7.59 \times WCR + 0.023 \times C.D \\ & + 0.076 \times F.A \times M.P - 0.010 \times F.A \times \\ & WCR - 4.611 \times 10^{-5} \times F.A \times C.D \\ & + 0.252 \times M.P \times WCR \\ & + 0.015 \times M.P \times WCR \\ & - 1.008 \times 10^{-4} \times F.A^2 - 1.969 \times M.P^2 \\ & + 9.710 \times WCR^2 - 1.534 \times 10^{-4} \times C.D^2 \\ & - 9.373 \times 10^{-5} \times F.A \times M.P \times C.D \\ & - 7.432 \times F.A^2 \times M.P \end{aligned} \quad (1)$$

where:
F.A=Fly ash content and its value ranging from 28–78%.
M.P=Mix proportion (Cement: Sand) and its value ranging from 0.1 to 1.0.
WCR=Water cement ratio and its value ranging from 0.25 to 0.5 C.D=Curing duration in Days and its value ranging from 7 to 90 days.

This model was further validated with experimental results of cement mortar cubes as shown in Table 6. Values of four different factors are selected randomly for validation of the model. Compressive strength of the cubes was predicted for all these test points. Cube samples were casted and were tested in these points. Predicted cube strength was then compared with experimental test results. This model was after validation used to optimize the fly ash content as a replacement of cement in mortar. It was observed that the optimum fly ash content, mortar mix proportion and water cement ratio as obtained from CCD method using PPC cement was 63.71%, 1:1 and 0.25 for 28 days curing time. Mortar cubes casted for these values of

Table 5
Comparative study of different building materials affecting environment per year.

Product	Annual production	Energy involved	Effect on environment
Bamboo	20 million hectare land under cultivation [24], average 1000 poles per hectare [25]	Each year, a hectare of Moso bamboo absorbs 5.1 t of CO_2 [26]	102 million tonnes of CO_2 is absorbed yearly. Further utilization in construction industry will lead to an increase in Bamboo production and reduction in CO_2.
Steel	1662 Million Tonnes in 2014 worldwide [27]	Every ton of manufacture produces over two tons of CO_2 due to burning of fossil fuels. [6]	3324 Million Tonnes of CO_2 is released in atmosphere per year.
Cement	4193 million metric tons worldwide [28]	Every ton of manufacture produces over two tons of CO_2 due to burning of fossil fuels. [6]	8386 million tonnes of CO_2 is released in atmosphere per year.
Bricks	1.23 trillion bricks worldwide [29]	Produces 800,000,000 t of CO_2 each year for 1.23 trillion bricks. [29]	800 million tons of CO_2 each year. [29]
Fly Ash	170 million tons in India [30]	Waste material produced by burning of coal. Produced in large quantities by thermal power plants.	70000 acres of land is presently occupied by ash ponds in India Itself.

Table 6
Validation of RSM model [31].

Fly ash content	Mix proportion (cement: sand)	w/c ratio	Curing days	Predicted from CCD model (MPa)	Experimental result (MPa)
50	1	0.25	7	7.28	7.76
50	0.1	0.5	7	1.34	1.36
50	1	0.5	7	6.26	6.16
50	0.1	0.25	7	1.66	1.84
50	0.55	0.375	31.5	6.81	9.84
50	1	0.5	56	18.56	18.96
50	1	0.25	56	21.61	20.08
50	0.1	0.25	56	3.04	3.36
50	0.1	0.5	56	2.46	2.64
28	0.1	0.25	7	1.55	1.52
28	0.1	0.5	7	1.34	1.36
28	1	0.25	7	4.82	4.72
28	1	0.5	7	4.39	4.4
28	0.55	0.375	48.5	7.75	7.84

Table 7
Prediction of mortar cube compressive strength for various curing days.

Fly ash content	Mix proportion (cement: sand)	w/c ratio	Curing days (MPa)	PPC CCD model predicted results (MPa)
63.71	1	0.25	7	6.2
63.71	1	0.25	28	10.38
63.71	1	0.25	60	17.57
63.71	1	0.25	90	21.62

various factors and tested for their compressive strength gave the experimental strength as 11.6 MPa. This was in close comparison with the predicted compressive strength of 10.45 MPa from CCD model. From the literature it has been also observed that fly ash-cement based structures attains higher strength after larger curing days of time as compared to standard 28 days of curing of only cement based structures. Thus it was essential to further evaluate the strength of optimized fly ash based cement mortar cubes for larger curing days. It was observed from the predicted results that the strength kept on increasing with the curing days till 90 days as shown in Table 7.

Thus to test the feasibility of these panels authors used the above mentioned mortar mix, water-cement ratio and fly ash content for casting the panels whose results have been discussed here in next subsections.

6.1. *Rebound Hammer Test*

Rebound hammer test was originally intended for predicting the compressive strength of concrete on site [33]. It is an instrument which applies a punch of certain energy when pressed against a surface as shown in Fig. 4. The hammer is loaded with spring loaded steel mass that applies energy on the surface.

Rebound hammer test correlates well with the masonry strength [34]. It is an excellent tool for evaluating the uniformity of material properties throughout the structure. Hence, for determining the strength of the bamboo reinforced prefabricated panel, rebound hammer test was used. The bamboo reinforced panel was tested at 6 points to evaluate the uniformity of strength. Points were marked at 100 mm from the longitudinal edges. The rebound hammer test values are dependent on the surface characteristics which is further dependent on surface uniformity and texture. Therefore, the average strength values were calculated for whole model. A maximum of 20.3 MPa and a minimum of 13.4 MPa strength values were observed as shown in Fig. 5. It was observed that the average compressive strength for panel was 17.6 MPa. This value was close to the higher limit of stiff bricks

Fig. 4. Rebound hammer test.

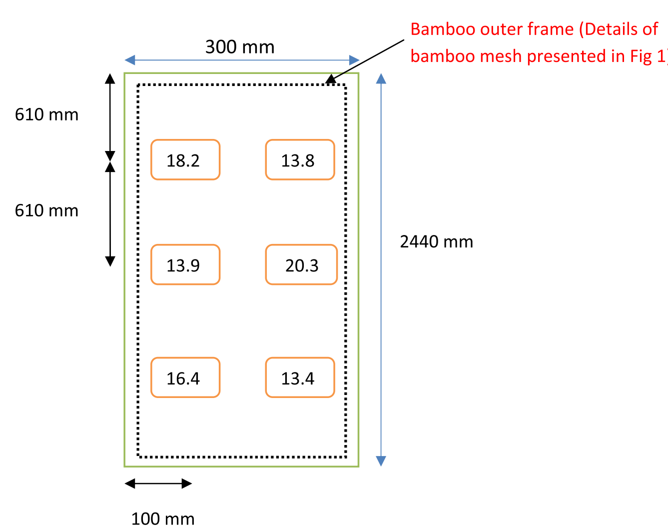

Fig. 5. Rebound hammer test strength values in MPa.

strength of 10–20 MPa as per New Zealand Society for Earthquake Engineering (NZSEE) 2006 [33] and type SW bricks (Severe weathering bricks) whose compressive strength is 16 MPa as per ASTM C62 [35]. Also if compared with masonry mortar strength of 5.2, 12.4 and 17.2 MPa for type N, S and M mortar as per American Society of the

International Association for Testing and Materials (ASTM - C270) [36], the strength of these panels is comparable to type M mortar. From the above values it was ascertained that the panel strength is within the upper limits of Type SW bricks and Type M mortar. Also contemplated was that the panel strength is comparable to high strength bricks and mortars. In literature it has been observed that the masonry compressive strength is lower as compared to its individual brick unit and masonry of similar strengths [33]. It can be thus concluded that the proposed prefabricated bamboo reinforced wall panel has high strength as compared to masonry walls made from Type SW bricks and Type M mortar which is generally used in building construction.

6.2. *Flexural Loading Behavior*

Transverse load test (Specimen Horizontal) was conducted to study the flexural behavior of the panels. Hydraulic jack was used to apply the load and the panel displacements were measured by linear velocity displacement transducer (LVDT) connected with a data logger. Hydraulic jack was placed on top of a steel I-section. This steel I section transferred the load to the panel via the roller supports placed at L/4 from the center where L is the effective length of the panel as per ASTM E-72 [37]. At the top of the center point of the slab and at L/4 distance from the center point two LVDT's were fixed to check the deflection of the panel. The test setup for transverse load test (Specimen Horizontal) is shown in Fig. 6a and schematic diagram of loading is shown in Fig. 6b.

Loading was increased gradually until the panel cracked and finally failed. At different loadings the panel deflections were noted and a load-deflection curve was plotted as shown in Fig. 7. In the panel flexural cracks started appearing around 147 kg load. At 147 kg the deflection at the central point was observed as 29.78 mm which increased rapidly to 35.82 mm at 157 kg load. It was observed that at this load the flexural cracks started widening. A maximum deflection of 43.59 mm was observed at the center of the panel after which the deflection was not measurable due to the deflection value exceeding LVDT working range. However, the load was increased and it was observed that the maximum load at which panel failed was 232 kg. At this load the deflection measured at L/4 distance from the center was observed to be 31.32 mm. Due to the limitation of the equipment (hydraulic jack which was used for applying the load) load was applied gradually in steps (manually). The load reading was noted from the gauge (least count 25 kg) of the hydraulic jack and the displacement was obtained from LVDT data logger display which was then synchronized with time. Instead of manually operated hydraulic jack if a

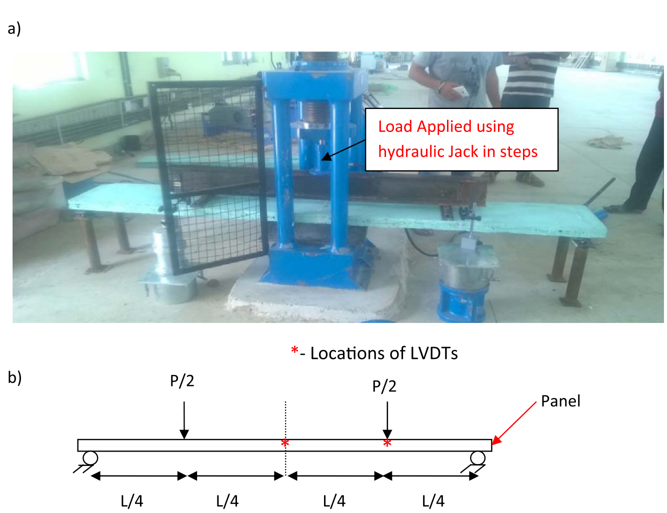

Fig. 6. a) Front view of the transverse load test setup, b) Front view of the transverse load test setup.

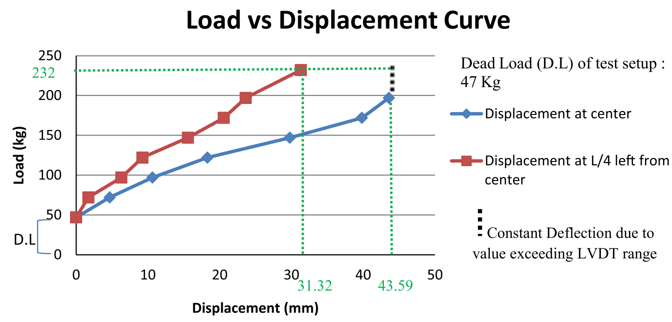

Fig. 7. Load vs deflection curve under transverse load.

computer controlled actuator was used more accurate results can be obtained.

It was observed that the main cause of failure of panel was due to debonding of bamboo mat from the mortar surface. The mortar layer first debonded from bamboo and then the panel failed as shown in Fig. 8. However, this failure is assumed to be due to replacement of cement by high amount of fly ash. It was also observed that similar panels when tested without fly ash did not show debonding failure. It was calculated that the flexural strength (σ=3FL/4bd^2) at 232 kg load was 5.12 MPa.

As compared to un-reinforced masonry structures which are non-homogeneous, inelastic and orthotropic material assemblage constructed from individual bricks and mortar, the above panels have relatively better strength properties.

7. Conclusion

This paper has described a scientific approach for developing a new type of bamboo reinforced prefabricated wall panel system along with the feasibility study as compared to masonry walls. The proposed wall panel system is considerably cheap, lightweight and energy efficient than the traditional brick walls. The advantages of the proposed wall panel system are:

- It reduces the dead weight of walls by 56% as compared to brick wall (5 in. thick). Therefore use of these panels can improve the performance of structure during earthquake.
- It can considerably reduce the carbon dioxide from the atmosphere when mass scale production can be adopted for proposed panels, as it will reduce the consumption of environmental degrading conventional building materials such as steel, cement and bricks.
- Proposed wall system doesn't require sophisticated technical skills, only jointing at site is required.
- Quality control is much easier as prefabricated panels can be manufactured at casting yard.
- The cost of panel is about 40% cheaper than conventional single wall bricks (5 in. thick) which could be further reduced on mass manufacturing of such panels and by utilizing cheap treatment and connection methods.
- Proposed wall system has high strength and flexibility compared to masonry walls.

It was observed that the proposed wall system can considerably reduce the harmful greenhouse gases. However, limited codal guidelines for bamboo as an engineering material, is hindering the mass application of these wall panels. Such type of structures can pave the way for sustainable infrastructure especially for low cost housing segment. However further investigation of parameters such as fire resistance, structural behavior under various loading, water absorption and seismic response etc needs to be studied extensively.

Fig. 8. a) Debonding failure, b) Closer view of debonding failure.

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