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TWO-BY-FOUR HOUSE CONSTRUCTION USING LAMINATED BAMBOOS

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ABSTRACT: Using similar technical details of timber two by four construction, the authors have completed the construction of three two-story single family houses in China using laminated bamboo. The load carrying vertical studs, beams and girders were made with laminated bamboo elements, or GluBam, whereas the sheathings were constructed with laminated bamboo sheets, or plybamboo. The first demonstration house has a foot square area of about 130 sqm. , and total building area of about 250 sqm., whereas the second and third had a total building area of about 100 sqm. The design attempts are to construct these modern bamboo houses essentially following the design requirements set in design codes such as the building codes for light-frame wood buildings in North America. This paper presents the details of the design and some special considerations for construction. To quantify the structural performance of bamboo trusses, girders, columns, and shear walls, experimental studies are underway, and the results to date are reported in this paper.

KEYWORDS: bamboo; two-by-four; glubam; plybamboo; light-frame, house

1 INTRODUCTION

Light-frame wood structures have historically performed well with regard to life-safety under natural hazards such as earthquakes. Properly built wood frame structures can withstand major earthquakes and hurricanes without collapse. Many modern timber buildings have even survived showing no visible signs of damage. The advantage of wooden buildings is based on low self-weight, ductile joints and in general very regular building geometry. Being lack of forest resources in China due to over-logging in last century, alternative resources need to be considered. Bamboo has several advantages as a green material that has had and still is positively influencing our lives. Some of these advantages include its high strength to weight ratio which is comparable to that of steel and wood. The short maturation duration of bamboo allows for renewable architecture to turn over more rapidly [1].

After the success in building the world's first truck-load safe modern bamboo bridge [2], the authors took another endeavour to explore the possibility of building modern residential houses using laminated bamboo, or glubam, an award winning technology invented by the authors. In 2009 alone, the authors designed and built three demonstration houses using glubam technology, following similar procedures as the so-called 2x4 construction. This paper provides an overview.

2 DEVELOPMENT OF LAMINATED BAMBOO - GLUBAM

The main components for making the load-bearing structural components were laminated bamboo elements, trademarked as GluBam [3], made from approximately 30 mm thick bamboo veneer sheets or plybamboos with a planner dimension of 2,440 mm long and 1,220 mm wide, using a processing method invented by the authors. The process involves cutting; finger-jointing the sheets; surface preparations, painting with two-part epoxy adhesive and pressure-hardening for more than 24 hours.

Bamboo veneer sheets or plybamboo sheets are similar to plywood except using bamboo as basic materials, and are well established industrial products in China. There are two typical types of bamboo veneer sheets, the thin layer lamination and thick layer lamination. The thick layer laminated bamboo sheets are made by pressure gluing a few layers (typically three layers) of relatively thicker (about 5~7 mm) bamboo strips. The top of the line products can make flooring plates, which became available in North America and world wide market recently. The thin layer laminated bamboo sheets typically have a thickness of about 10 to 15 mm, and are

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made by laminating approximately 2 mm thick bamboo strip mats. They are mass produced and mainly used as concrete formwork in China. Based on extensive review of the existing bamboo products available in China and careful comparison of their costs and known properties, the authors adopted the thin layer laminated veneer bamboo sheets with modifications of the configuration of thickness and fiber orientation. The 28 mm thick plybamboo sheets used to make glubam were manufactured at a facility in Hunan Province, China, based on the specifications developed by the authors. The sheets contain the same amount of bamboo strips oriented in the longitudinal and the transverse directions. The strips were weaved into mats and prepared by local farmers before bringing to the factory. At the factory, the mats were cleaned and dried in a kiln. Then the mats were saturated in phenol formaldehyde resin. The resin saturated bamboo strip mats were finally stacked and pressed under a temperature of 150°C, using a procedure similar to manufacturing plywood [4].

Basic material properties shown in Table 1 were obtained by conducting significant amount of material tests following conventional testing methods for timber materials. The tests were conducted according to the Chinese standards [5,6], which are identical to the methods used in the US [7]. Comparison of the main mechanical properties between the laminated bamboo and values of typical fir or pine woods from the Wood Handbook by Forest Products Laboratory [4] shows that generally, bamboo and laminated bamboo have identical mechanical properties as common woods, however, heavier and harder than wood and wood products. It should be pointed out that the glubam material is essentially a bi-directional bamboo fiber composite matrix.

Table 1: *Properties of Glubam*

In-plane compressive strength (MPa)	54
In-plane tensile strength (MPa)	20
Bending strength (MPa)	75
Elastic modulus (GPa)	9.4
Density (kg/m^3)	880

3 CONSTRUCTION OF MODERN BAMBOO BUILDINGS

The authors at the Institute of Modern Bamboo, Timber and Composite Structures (IBTCS) of the Hunan University directed Prof. Xiao have developed several new technologies using bamboo in modern construction. This paper reports the mile-stone projects of building modern bamboo residential houses, including one in the famous Black Bamboo Park (the Zizhu-Yuan Park) in Beijing. The projects integrate all the newly invented bamboo technologies and products.

All of the structural members were prefabricated in Changsha, Hunan province and then transported to the construction sites. Figures 1 to 4 illustrate the construction process of bamboo demonstration building at the Black Bamboo Park in Beijing. The wall framings are consisted of laminated bamboo studs, top plates, bottom plates and headers. Standard studs in exterior walls of this two-story building typically have a cross section of about 40 mm by 84 mm, roughly equal to the size of 2×4 lumber used in the North America. However, the exterior wall studs used in the Beijing project are 40 mm by 140 mm (or 2 in. by 6 in.). The stud spacing is 406 mm in exterior walls of the first floor, whereas 610 ㎜ in the second floor.

Figure 1: *Installation of modular wall panels*

Figure 2: *Insulation wools of wall panels*

Figure 3: *Floor system*

The walls are filled with heat-insulation wools. The bottom plates and top plates of wall framing usually act as a fire-stopping. The walls are sheathed with bamboo panels that are attached vertically to the wall frame. The panels are connected to the wall frame studs and top and bottom plates using nails spaced 150 mm on center along the panel edges and 300 mm along the intermediate studs. The exterior cladding include waterproof underlayment, wire mesh and stucco mortar cladding surface. The gypsum boards are typically attached to framing with screws spaced 305 mm on center along the panel edges and intermediate studs to form the interior sheathing of walls. The roof trusses are erected and installed on the load-bearing walls of the second story. Wood blocks are typically used to maintain the spacing of 610 mm between the trusses.

Figure 4: *Installation of roof trusses*

Figure 5 exhibits the three two-story demonstration glubam houses completed in 2009.

(a)

(b)

(c)

Figure 5: *Completed glubam 2x4 houses: (a) 250m^2 house completed in February 2009; (b) 100m^2 tea house built in Black Bamboo Park in Beijing in August 2009; (c) 120m^{2}mountain house in Cailun Forest, Leiyang, Hunan Province, completed in November 2009.*

4 CHARACTERISTICS OF GLUBAM STRUCTURE

4.1 TWO BY FOUR SYSTEM

A typical structure of light-frame building resists lateral loads through the use of horizontal floor or roof diaphragms and vertical shear walls [8]. The walls standing perpendicular to the lateral load collect the force and transfer it to the horizontal diaphragm. The horizontal diaphragm distributes the force to the shear walls parallel to the lateral load. The shear walls then transfer the load to the foundation. A schematic diagram of the functioning of structural panels against lateral loads is shown in Figure 6.

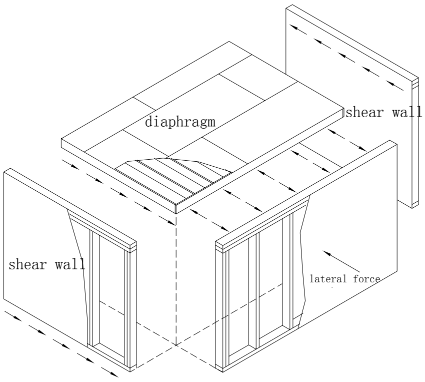


Figure 6: *Transfer of lateral loads through diaphragm to shear walls*

The shear wall, designed as a deep, cantilever beam, provides the support for the diaphragm. Therefore, the load the shear wall must be designed to resist is that of shear in the diaphragm at its support. The frame of a wall designed to support gravity loads can be transformed into a shear wall with the addition of two elements. These elements are sheathing panels, either oriented strand board or plywood and in our case the plybamboo, attached to one face of the wall and a double end stud at each end of the wall. The components of a shear wall are presented in Figure 7.

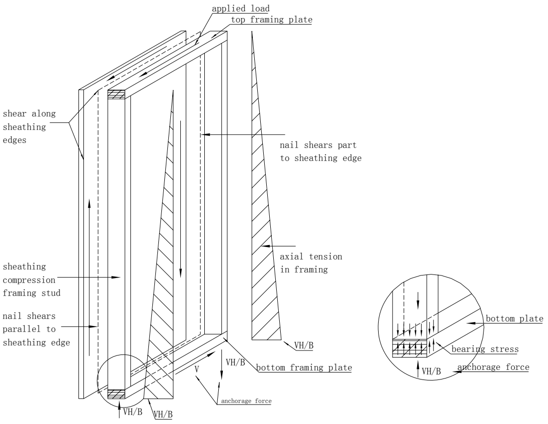


Figure 7: *Forces acting on a shear wall element*

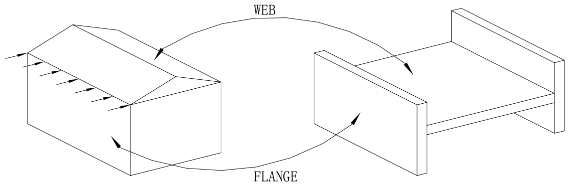


***Figure 8:** Deep beam analogy of modular wall panels*

A diaphragm is a flat structural unit acting like a deep, thin beam. The term “diaphragm” is usually applied to roofs and floors. In a horizontal diaphragm, the sheathing corresponds to the web, and the chords are assumed to be the flanges. The chords are designed to carry axial forces created by the moment. These forces are obtained by resolving the internal moment into a couple (tension and compression forces). As shown in Figure 8, the shear is assumed to be carried entirely by the sheathing material [9].

4.2 SEISMIC DESIGN OF GLUBAM SHEAR WALL

The seismic design of a glubam building is conducted based on similar approach for light-weight frame timber buildings. Due to the lack of sophisticated timber building design code in China, the codes widely used in North America, such as UBC and IBC, are adopted in this research. Based on the static equivalent lateral force method, the base shear, V, can be calculated as,

$$V = CW \tag{1}$$

where, C is the base shear coefficient and W is the weight of the building to be design. Using UBC-97 code [10], V can be calculated as,

$$V = \frac{C_v I}{FT} W \le \frac{2.5 C_a I}{R} W \tag{2}$$

where: $C_v I/RT$=velocity based seismic base shear coefficient, $2.5C_a I/R$=acceleration based seismic base shear coefficient.

For a two story building with a height of about 5m, the period is estimated as 0.19sec. It is further assumed that the building with standard occupancy (I=1) is located in seismic zone 2B. The proposed building site is 10km from a Type B seismic source. Without a geotechnical study, soil type S_D is assumed. Then, one can find that the right hand side of the Eq.(2) controls, and using C_a=0.28 and a conservative value of 4.5 for R, the base shear is calculated as 0.16W.

Using the distribution method given by the following equation (3), the base shear force V can be distributed to each floor, F_x, at a height of h_x.

$$F_x = \frac{(V - F_t) h_x w_x}{\sum_{i=1}^{2} w_i h_i} \tag{3}$$

Table 2 shows the calculation for an example house. In the design, roof dead load D=1.91kN/m^2, floor dead load D=1.24kN/m^2, interior wall dead load D=0.39kN/m^2, exterior wall dead load D=16.29kN/m^2.

***Table 2:** Story forces for an example house*

Story	Height h_x	Weight w_x	$w_x\, h_x$	Story force F_x
R	4.88m	170.8kN	833.5kNm	35.0kN
2	2.44m	135.7kN	331.1kNm	13.9kN
1	0			
Sum		306.5kN	1164.6kN.m	48.9kN

4.3 SEISMIC DESIGN OF GLUBAM DIAPHRAGM

The loads to the roof and floor diaphragms that are used for design of the shear walls need to be based on the story forces shown in Table 2. The strength level roof diaphragm reaction can be calculated as follows:

Load to roof diaphragm:

$$w_{ur}=0.042\times 4.88\times 13.5=2.77\text{kN/m}$$

Load to second-floor diaphragm:

$$w_{u2}=0.042\times 2.44\times 14.8=1.52\text{kN/m}$$

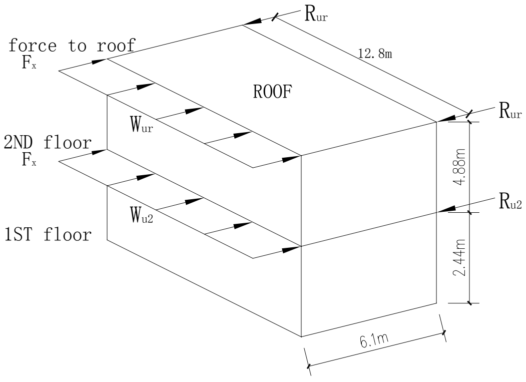


***Figure 9:** Seismic forces to roof and second-floor diaphragms*

In addition, for both the second floor and the roof diaphragms, the seismic forces are significantly higher than those obtained from wind load analysis.

4.4 FULL-SCALE OVERTURNING TEST

The safety of the glubam building was further validated through a full-scale model overturning test. The dimension of the model was 4.88m×3.66×2.44m in plan. The transverse gable walls were made with 3 wall panels, whereas the longitudinal walls were made with 4 wall panels, as shown in Figure 10.

The model was built on a strong steel frame, which was then lifted from one side and to gradually tilt the building until it became almost horizontal. At that position, the model building subjected to the full gravity load in a condition as a cantilever, as shown in Figure 11.

The test was conducted for both the longitudinal and transverse directions of the model building. It should be clarified that the overturning tests were originally aimed at the evaluation of seismic behavior of building systems for temporary usage, such as the shelters for earthquake relief purposes. Therefore, the wall panels were not particularly following the two by four construction, instead, were made with flat stud columns of 50mm wide and 28mm thick spaced at 600mm. This construction detail is much weaker than the two by four system used in building the demonstration houses, thus the tests can be considered as worst case study.

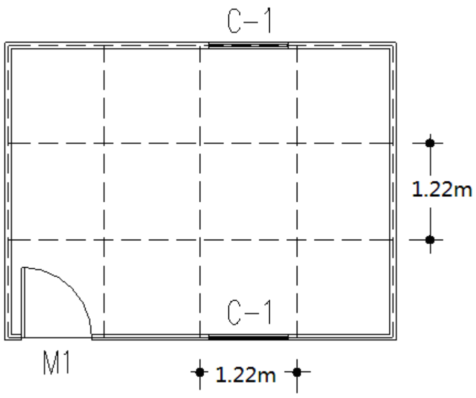
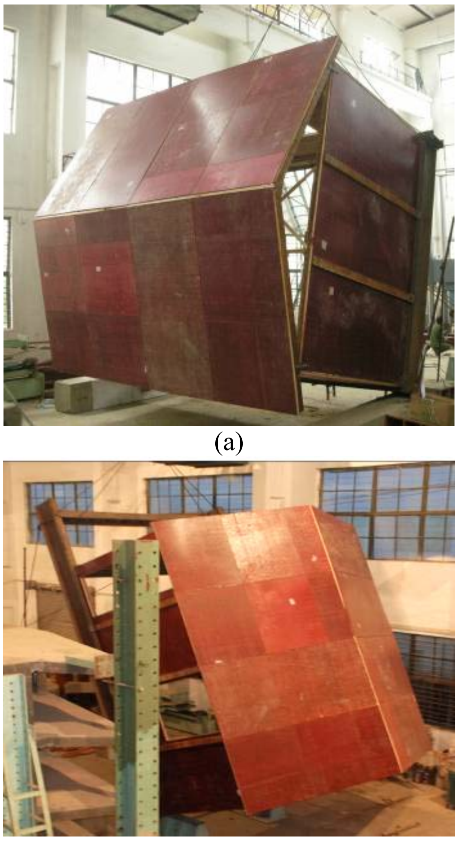


Figure 10: *Full-scale overturning test model plan*



(a)

(b)

Figure 10: *Full-scale overturning testing: (a) in transverse direction loading; (b) in longitudinal direction loading*

The authors have planned a series of shear wall panel tests under cyclic lateral loading, however, the testing results are not fully available yet.

5 COMPONENT TESTS

5.1 COLUMNS

Three glubam model columns were made with the same cross-section geometry of square section with 150 mm sides and a length of 1500 mm. The model columns were made by laminating 5 layers of 28~30 mm thick glubam sheets to form a total thickness of approximately 150 mm. The quasi static axial compression tests were conducted using 500 ton universal testing machine with specially manufactured pin end supporting devices, as shown in Figure 11.

Figure 11: *Test setup for glubam columns*

The failure patterns were quite similar for the three specimens which were all split along one laminated surface. Despite this, the ultimate axial capacities for the three columns were 780kN, 720kN, and 750kN, respectively, relatively close to the calculated column capacity based on the timber design equation.

5.2 BEAMS

Large size glubam girders with a section of 600 mm tall and 100 mm wide were tested and reported by the authors, primarily for bridge applications [2]. In previous studies, it was shown that the glubam girder specimens had adequate load carrying capacity suitable for bridge construction. It was also shown that the use of fiber reinforced plastic composites (FRP) in the tension side of the girder can further enhance the capacity and the stiffness.

Small size glubam beams were recently tested to provide experimental background for the two by four construction of houses. Table 3 shows the testing matrix for the glubam beam specimens. The testing parameters include the section size, loading configuration and the existence of carbon fiber reinforced plastic (CFRP) enhancement. The reinforcement ratios of the CFRP shown in the table are calculated as the sectional area ratio of the CFRP to the glubam beam.

Table 4: Summary of small-size glubam beam tests

Beams	Cross section (mm× mm)	Span (mm)	CFRP ratio (%)	type	F_{max} /kN
S1, 2, 3	56×112	2016			27.1
S4,S5	56×112	2016		H*	13.9
S6	56×112	2016	0.1		28.0
S7	56×112	2016	0.5		32.0
S8,9,10	84×160	2240			73.0
S11,S12	84×160	2240		H*	28.5
S13	84×160	2240	0.21		74.0
S14	84×160	2240	0.35		78.0
S15	84×160	2240	0.69		94.0

A four point load method was used to test the beam specimens. The clear distance between the edges of the bearing plate and the nearest loading point was approximately one-third of the length of the test specimen, equal to that between load points. Lateral supports were provided to prevent the lateral torsional buckling of the specimen. Deflections were measured at the positions of load points, reactions and mid-span. Five strain gauges to detect the longitudinal strains for the mid-span section were affixed along the depth of the beam. All the measured data were record simultaneously by a static strain measurement system.

Figure 12 shows the load and mid-span deflection curves for all the small-size beam specimens. Through comparison among the different types of the glubam beam specimens, the quantitative reinforcing effect of CFRP can be clearly identified. The results show that the load carrying capacities of FRP reinforced beams were higher than non-reinforced beams with a range from 2.9%- 28.8%. The test results also reconfirmed the authors' finding that the parallel loading to the lamination is favorable for larger stiffness and load carrying capacity. Further tests are still underway in this testing series.

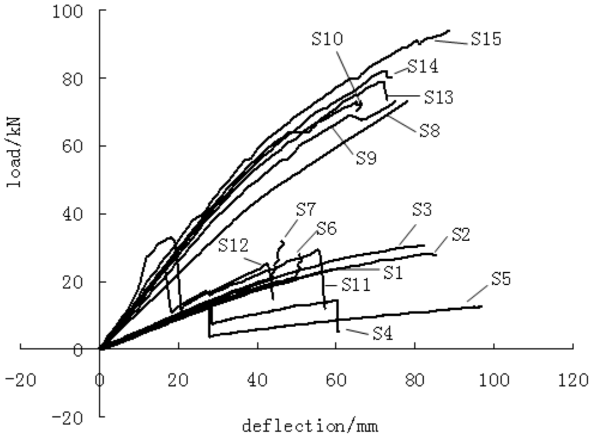
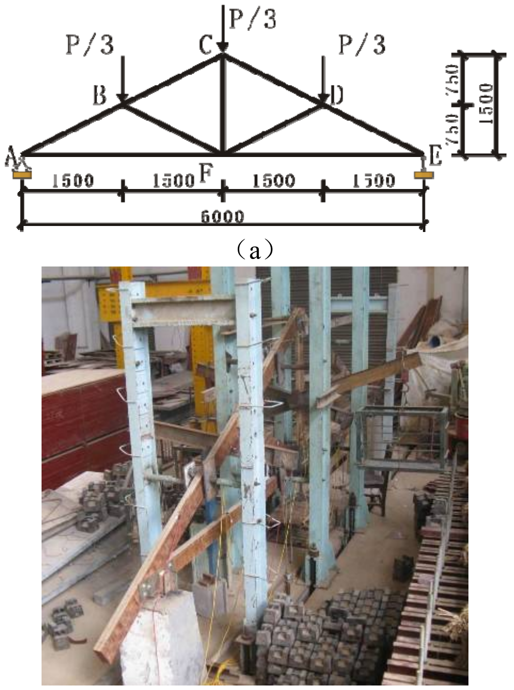


Figure 12: *Load and deflection curves for glubam beams*

5.3 ROOF TRUSSES

Glubam roof trusses were experimentally investigated. Figure 13a shows the schematic of a typical bamboo truss (BT) test specimens, as well as the loading condition applied. The test setup is exhibited in Figure 13b. Three identical model trusses were designed and manufactured at the IBTCS laboratory using glubam technology. The test configurations consisted of 6.0 m span truss built with 56×140mm top chords, 56×120mm bottom chords. All web elements were 56×90 laminate bamboo. All three trusses were built with a 6/12 top chord pitch.



（a）

（b）

Figure 13: *Glubam truss test: (a) loading condition; (b) test setup*

As shown in Figure 13b, loads were imposed at the nodes of top chords by weights of steel blocks. The weights placed in a basket were magnified by 3.5 times at the loading points on the chords by means of a lever assembly. The baskets were attached through 1,750mm long steel I-beam to the top chord. The beam was deemed sufficiently stiff. The model truss was attached to concrete pedestal supports. Three pairs of steel frames were used to prevent potential out-of-plane movement of the truss during testing. Deflection at the mid-span was measured for the lower chord.

Test results are summarized in Table 5. Here, P_u is the ultimate load carrying capacity of the bamboo truss (kN); Δ_d is the deflection of truss mid-span at design load (mm); Δ_u is the deflection of truss mid-span at ultimate load (mm).

Table 5: Summary of truss tests

Truss	P_u（kN）	Δ_d（mm）	Δ_u（mm）
BT1	36.0	7.06	27.61
BT2	44.2	7.46	34.26
BT3	42.2	4.79	27.52

The test results (Table 5) show slight dispersions among specimens. It was noticed that truss BT2 reached the maximum ultimate load capacity of 44.2 kN, while the truss BT1 reached the minimum ultimate load capacity of 36.0 kN. The average ultimate load of the three tests is 40.8 kN. The standard deviation of the three specimens is 3.5 kN, and the coefficient of variation of the three specimens is 8.6%. The ultimate loading condition was caused by lateral buckling of the top chord between two of the lateral support steel frames, as exhibited in Figure 14. In the actual two by four glubam houses, the roof purlins are closer than the lateral supports provided for the trusses tested in this study, therefore the tests were kinds of worst case studies.

Figure 14: *Failure of glubam truss*

Presented in Figure 15 are the load-deflection curves for the three glubam truss specimens. The results of the three trusses have linear deflection performance up to twice the design load and obvious deviations from linearity up to three times the design load. The performance is similar to the wood truss tests [12].

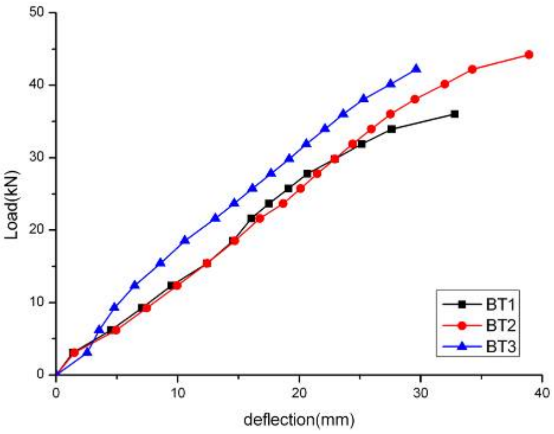


Figure 15: *Load and deflection curves for glubam trusses*

6 IN-DOOR AIR QUALITY TESTS

The structural column, beam and wall panel elements used in the construction of the glubam houses are mainly laminated bamboo materials. In order to confirm whether the materials used in the houses produce harmful gases to affect the indoor air quality and harm the health of the occupants, commissioned by the authors, the Hunan Construction Engineering Quality Inspection Center were invited to conduct a series of indoor air quality testing in the Summer of 2008 on the building shown in Figure 5a, before its completion. The in-door air testing samples were obtained after closing the room in testing for at least 24 hours, according to the testing standards [11].

Measurement and analysis results show that the use of glubam in construction of houses fully meets the human health requirements, in line with living conditions, according to the Chinese National Standards for in-door air quality [11]. The contents of various concentrations of hazardous substances are very low, as indicated in Table 3. It should be further emphasized that the data shown in Table 4 were obtained for the worst case situation where all the glubam materials were exposed.

Table 6: Air quality testing results

Items	Units	Requirement	Test result
Radon	Bq/m^3	≤200.00	4.00
Formaldehyde	mg/m^3	≤0.08	0.03
Benzene	mg/m^3	≤0.09	0.00
Ammonia	mg/m^3	≤0.20	0.02
TVOC	mg/m^3	≤0.50	0.00

7 DISCUSSION ON EMBODIED CO2

It is well recognized that the major greenhouse gases (GHGs) is carbon dioxide (CO2) and the major cause of human activity-generated carbon (C) in the atmospheric is the burning of fossil fuels for energy. Therefore, despite of the unusual widespread cold storm in this past winter, reducing CO2 emission is still one of the most important challenges and responsibilities of all mankind.

Like wood, bamboo is also an organic material, composed of about 50% of carbon. As a natural storage, the CO2 is entrapped in bamboo or wood till the final end of the material usage. Thus, comparing with steel, concrete and masonry, the production (or growth) of wood and bamboo is a carbon negative process. During the growth, bamboo can absorb even more CO2 than trees. Based on a study conducted in China, the annual carbon fixation of bamboo forest is 5.097 t/hm^2/yr, which is 1.46 times of Chinese Fir at the fast growing stage, and 1.33 times of tropical mountain rain forest [13].

A preliminary study is conducted to estimate the embodied CO2 in a two story house with a building area of 100 m^2, for four types of building materials, ie., glubam, timber, steel and concrete. Figure 16 compares the embodied CO2 of 100 m2 houses with four different materials at various stages. Apparently, both bamboo and timber houses have much less embodied CO2 than conventional steel and concrete houses.

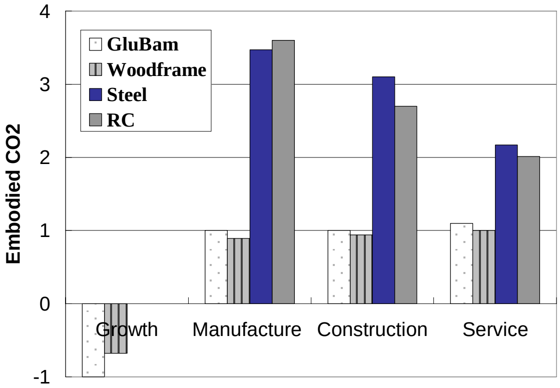


***Figure 16:** Comparison of embodied CO2 in 100 m^2 houses with different structural materials*

7 CONCLUSIONS

A new type of glulam, or glubam has been developed with bamboo as basic materials. Experimental studies were performed to investigate the mechanical behaviors of glubam columns, beams and trusses and the results show that the new material is promising and suitable for structural applications. The laminated bamboo beams were also shown to be able to work with CFRP as a composite material for improved mechanical behaviour.

The research shows a new ways of employing the bamboo resource in sustainable construction. Using glubam and plybamboo, three two-story demonstration residential houses were completed in 2009. It is shown that the two by four construction method and design used in lightweight woodframe structures can easily be adopted in laminated bamboo or glubam construction.

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