RESEARCH DEVELOPMENT OF GLUED LAMINATED BAMBOO (GLUBAM) AND CROSS-LAMINATED BAMBOO AND TIMBER (CLBT)

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Abstract
In this paper, the author reports the extensive research studies by the author's team on the development of glued laminated bamboo, or glubam, a bamboo-based glulam. Research findings indicate that the glubam has similar mechanical properties as timber and can be used as substitute to timber-based glulam. Several demonstration projects were also executed exhibiting the suitable constructability of glubam structures. Inspired by the recent advancement of cross-laminated timber or CLT in Europe, the author's team recently is developing cross-laminated bamboo and timber, or CLBT (or CLTB). Pilot tests for manufacturability and mechanical performance of CLBT panels were carried out and the results demonstrate the good behavior of the CLBT as building slabs and panels. CLBT is promising for integrating the use of bamboo and fast-grown trees, both are quite abundant in China and elsewhere.

Keywords:
Bamboo, glued laminated, glubam, cross-laminated bamboo and timber, CLBT, material properties, structural behavior, design, construction

1 INTRODUCTION

Similar to wood, bamboo is also a bio-based material with natural fibers. The use of bamboo as building and structural materials can be traced back as long time as wood. Its natural properties are quite comparable to those of wood. However, the original geometrical shape of bamboo culms makes it difficult to be used in modern construction. Based on abundant material and existing production technology in China, a new type of laminated bamboo that can be used as structural elements are invented by the author with a trademark of glubam, and has been applied in practice for more than 10 years [Xiao et al. 2010; 2013]. Recently, admired by the great success of cross laminated timber (CLT) in Europe and elsewhere, the author combined bamboo and timber and developed cross laminated bamboo and timber (CLBT or CLTB).

This paper presents a summary of the author's recent work on research and development of glubam and CLBT.

2 GLUBAM AND CLBT MATERIALS

Glubam is a kind of two-step pressure glued laminated bamboo lumber, with the second process similar to wood-based glulam [Xiao et al. 2010; 2013]. Glubam beam or column element is manufactured by gluing together layers of elements cut from ply-bamboo boards. For long-span glubam elements, the ply-bamboo boards with limited length need to be lengthened during cold pressing procedure, usually, using finger jointing technique.

According to the different thickness of bamboo strips, ply-bamboo board can be divided into two types: thick strip ply-bamboo board laminated by bamboo strips of about 5 mm thick, shown in Fig.1 (a) and thin strip ply-bamboo board laminated by bamboo strips of about 2 mm, shown in Fig.1 (b). The thick ply-bamboo boards can be treated with carbonization to satisfy the requirements for out-door structures. The direction of the strips in thick strip ply-bamboo are normally all along longitudinal direction, while the configuration of strips in thin strip ply-bamboo are more complicated, the ratio of longitudinal grains and transverse grains is typically 4:1, for the applications in glubam beams or columns [Xiao et al. 2013].

(a) Glubam made from thick bamboo strips *(b) Glubam made from thin bamboo strips*

Fig. 1 Glubam made with different bamboo strips

Since there is currently no standards or specifications for testing glubam, the studies of the material properties of glubam are based on specifications for timber materials. Tab. 1 summarizes the main mechanical properties of the two types of glubam materials.

Tab. 1 Main mechanical properties of glubam

Property (MPa)	Thick layer glubam	Thin layer glubam
Longitudinal compression $f_{C,x}$	73.0	51.0
Longitudinal tension $f_{t,x}$	85.0	83.0
Shear parallel to glue line $\tau_{x,z}$	16.9	16.0
MOE (bending around z axis)	11200	9400
MOR (bending around z axis)	119.5	99.0

The CLBT is made by glue laminating under pressure the layers of glubam board and standard timber lumber elements. The orientation of the lumbers can be predetermined to satisfy design requirement. Fig.2 shows the examples of CLBT. The author's team has successfully made CLBT with the combinations of SPF and popular lumbers with different glubams.

(a) CLBT with thin-strip glubam as surfaces *(b) CLBT with thick-strip glubam as surfaces*

Fig.2. CLBT with different glubam outer layers

3 INVIRONMENTAL IMPACT OF BAMBOO

The influence on environment of certain material is an important aspect in today's trend towards a sustainable construction industry. It is well known that timber has less carbon and environmental impacts than other industrialized materials including concrete, steel, aluminum, etc. The main reason of timber being "greener" owes to its less processing energy consumption and more carbon dioxide storage. The author's team conducted an investigation on environmental impact of glubam at the author's production base located in Hunan Province, where moso bamboo abounds [Xiao et al. 2013]. It was shown that glubam, similar to timber, is a carbon negative material, and its production consumes lower energy amount than cement by about 75%, however slightly higher than timber.

4 BEHAVIOR OF GLUBAM COMPONENTS

Up to date, the author's team has conducted a large number of tests on various types of glubam structural components. This paper provides a brief summary.

4.1 Glubam girders and beams

Static test of glubam girders (Fig.12) show their excellent bearing capacity [Xiao et al. 2010; Li et al. 2018]. The use of FRP to reinforce the soffit of the girders can further enhance the load carrying capacity of glubam girders. It is found that due to the unidirectional alignment of the bamboo fibers, horizontal shear splitting may occur in the thick strip glubam girders, whereas tension or compression failure typically governs the failure modes of the thin strip glubam girders. It is also noted that the finger joints play a significant role in the failure process.

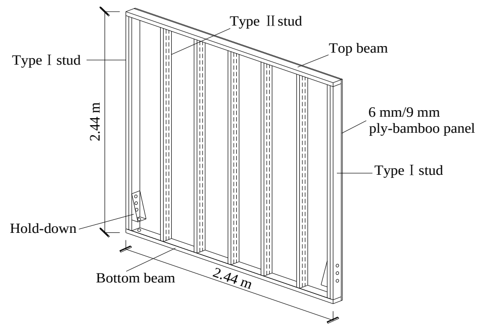
The fatigue experiment was also conducted, and it was shown that the repetitive loading reduced the bearing capacity of glubam girders approximately by 10% due to the development of weaknesses in finger-joint and gluing face. If the upper value of cyclic load is less than the design value, there was no distinct reduction in the stiffness of specimens compared with the static tests. The excellent flexibility of bamboo may have contributed to the fine stability of glubam beams in aspect of dynamic response during the fatigue loading.

4.2 Glubam columns

Axial compression tests of glubam columns were also conducted and the results are compared with the design code equations, including those specified in the Chinese "Code for design of timber structures" and the US "National Design Specification for Wood Construction". It is shown that the loading capacities of glubam columns exceed the code specified values.

4.3 Lightweight frame shear walls

One of the possible usages of glubam is in lightweight frame low-rise buildings for residential houses. Significant numbers of experimental tests were conducted by the author's team [Xiao et al. 2015; Gao and Xiao 2017; and Wang et al. 2017], to study the lateral loading behavior of shear wall panels made with glubam sheets and glubam, wood or light gauge steel frame studs. Fig.3 shows the typical configuration of lightweight shear walls.



Studs: glubam, SPF or light gauge steel; Sheathing panels: glubam or OSB.

Fig.3. Typical configuration of lightweight frame shear walls

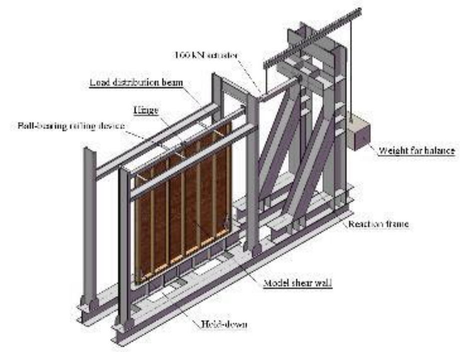


Fig.4. Test setup for lightweight frame shear walls.

Experimental testing program was carried out using the testing setup shown in Fig.4.

Tests show that good seismic performances were obtained for the lightweight frame shear walls with three types of stud frames (glubam, wood or light gauges steel) sheathed with glubam panels. As an example, Fig.5 shows the lateral force and deformation hysteretic relationship of a shear wall specimen with glubam frame and panel.

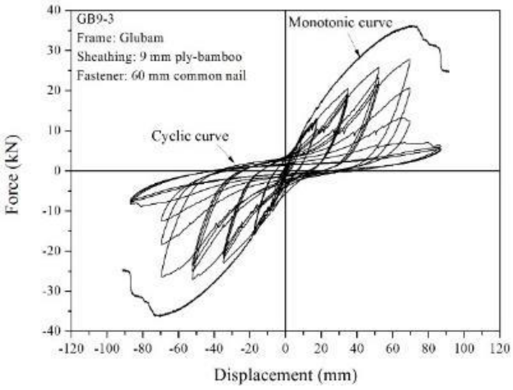


Fig.5. Example of seismic behavior of lightweight glubam shear wall.

The ability of the glubam shear walls can meet the design requirements specified in most timber structure codes. Besides, the processing of this type of shear wall could satisfy the requirements and preconditions of industrial production, as well as easy installation.

An experimental testing of a full-scale room model of the glubam shear wall structure was also conducted on shake table, as shown in Fig.6.

Fig.6. Shake table testing of full-scale glubam shear wall room model.

The test results indicate that the model performed elastically and had essentially no visual damage for 0.3g PGA. The tested glubam house can withstand applications of three different seismic ground motions in the order of 0.5g PGA without collapse. The observed damage remained noncritical for 0.5g PGA. Inter-story drift in the first story was generally below most code required values. After subjecting shakings of 0.5g PGA, the model was retested under a pushover loading condition and showed sufficient deformability. The tests reveal that glubam house can meet the requirements for the seismic intensity of 8 as described in the China Seismic Design Code.

4.4 Connections

Significant number of tests were conducted and are still underway to study the connections between glubam elements, including the sheathing panel connections with framing studs [Li e al. 2014]. Fig.7 shows the test setup for studs and sheathing panels with various types of nails.

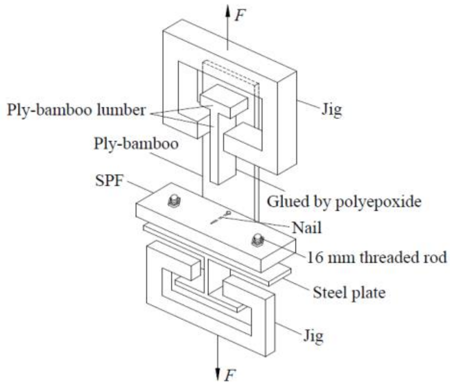


Fig.7. Test setup for nail connections between framing studs and glubam sheathing panels.

Monotonic and cyclic tests of nails applied in timber or glubam stud and glubam sheathing panel shear walls in accordance with ASTM D1761-2006 were performed. Based on Johansen yield theory (European Yield Model) and experimental observations, mechanical models and capacity equations for nail connectors used in wood-frame shear walls with cross prefabricated glubam sheathing panel were studied. Embedment strength of ply-bamboo panel was obtained in accordance with EN 383. The adopted capacity equation based on European Yield Model meets the test results well, in the average and with a reduced scatter. The theoretical and experimental results obtained from the research suggested a capacity model and equations to predict the bearing capacity of timber-bamboo nail connections, indicating that ply-bamboo panels can be used as sheathings for light-weight timber structures, as well as included in existing timber design code [Li et al. 2014].

4.5 Trusses

Full-scale model trusses with two types of configurations and sizes were tested to failure under gradually increased vertical load [Xiao et al. 2014]. The failure of the model trusses was caused by lateral buckling of the top compressive chords. Tests show that the model glubam trusses have adequate stiffness and strength. Analyses were also conducted to model the truss behavior with considering different joint conditions, such as pinned, rigid as well as semi-rigid joint using fictitious members. The analytical results for deformation at the design load level agree with the test results favorably well using all types of joint models. The semi-rigid joint model provides a slightly better prediction to the load carrying capacities of the model trusses. However, the analytical truss model based on pinned joints generally provides conservative prediction to load carrying capacities.

Recently, a new type of hybrid truss system composed of glue laminated bamboo (glubam) for web and upper chord members and steel pipes for lower chords was developed by the author’s research team [Wu and Xiao 2018]. A full-scale space truss model with different configurations was constructed and tested under gravity loads. Different failure modes, such as buckling of web chords, shear fracture of bolted connecting joints and yield of bottom steel pipes, were discussed. Analyses of the structural behavior under static load are compared with the experimental results, showing a good agreement. The experimental results validate that the space truss system is of excellent load carrying capacity. If yielding of the lower chord steel pipes can be realized, the system can also have a large plastic deformation under the ultimate loading condition. Fig.8 exhibits a prototype application of the hybrid truss system in the design of a canopy for an office building entrance.

Fig.8. Steel and glubam hybrid spatial truss system

4.6 Glubam and reinforced concrete composite beams

Similar to the efficient use of timber in the form of composite system with concrete, glubam and concrete composite (BCC) beam/girder system was studied by the author's research team [Shan et al. 2017]. Six types of composite connectors, commonly used in timber-concrete composite (TCC) beams, were tested under direct shear condition. The shear force-slip relationships were measured and all the relevant mechanical properties such as slip moduli and shear capacities were obtained. Compared with typical TCC beam connections, the glubam-concrete composite (BCC) systems present several different characteristics such as the failure model of the BCC exhibited delamination cracking along the lamination layers while the shear failure along the notch of the notched connector series did not occurred. Full-scale glubam and concrete composite girder specimens with a length of 8m were recently also tested, as shown in Fig.9.

Fig.9. Test of glubam and concrete composite beams

Four types of connection details were designed and tested: continuous steel mesh (SM), screw connector (SC), notch connector (NC) and pre-tightening notched connector (PNC). Experimental variables include length and numbers of connectors. All BCC beams with different connections exhibited satisfactory performance under short-term loading conditions. Fig.10 shows an example of a recent construction of a building using the composite system.

Fig.10. Example of composite glubam and concrete

4.7 Flexural tests of CLBT beams

Recently, twenty-four specimens of cross laminated glubam and timber (CLBT) beams were tested, with the testing matrix shown in Tab.2. The two types of glubam (thin strip type and the thick strip type) and two types of timbers (spruce-pine-fir (SPF) and poplar) were laminated into CLBT. The testing configurations include flat bending with the moment parallel to the planar direction (H type testing), and the vertical bending (V-type testing) with the moment perpendicular to the planer direction. Foreach configuration of CLBT and loading method, three repetitive specimens were tested.

Tab.2. Testing matrix of CLBT specimens

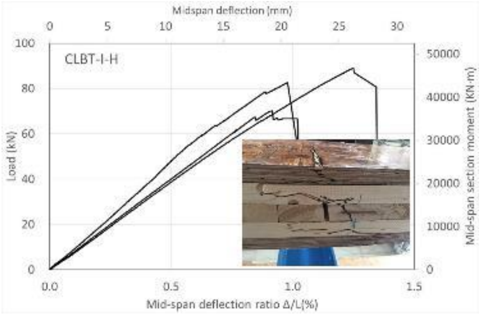
Configuration	Testing type	Dimension (L x B x t)./mm
Thin Glubam-SPF	H	2350×266×154
Thin Glubam-SPF	V	2350×266×154
Thick Glubam (LBL)-SPF	H	1950×266×163
Thick Glubam (LBL)-SPF	V	1950×264×163
Thin Glubam-Poplar	H	2350×266×154
Thin Glubam-Poplar	V	2350×266×154
Thick Glubam (LBL)-Poplar	H	1950×266×163
Thick Glubam (LBL)-Poplar	V	1950×264×163

(a) Flat bending

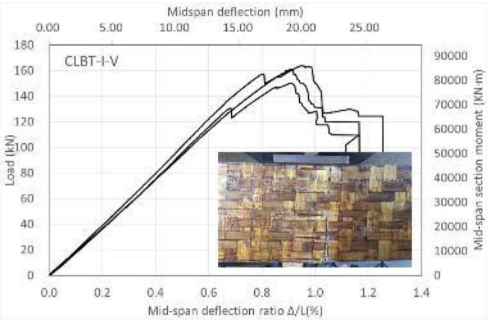
(b) Vertical bending

Fig.11. Testing of CLBT beams

Examples of testing results are shown in Fig.12. Specimens in flat bending tests behaved in an elasto-brittle fashion, as shown in Fig.12(a). Though during the vertical bending tests, CLBT specimens also behaved in a brittle fashion, slightly gradual degradation curves can be observed after the peak load, as shown in Fig.12(b).



(a) Flat bending results of thin strip glubam and SPF CLBT



(b) Vertical bending results of thin strip glubam and SPF CLBT

Fig.12 Examples of bending test results of CLBT

5 FIRE AND THERMAL STUDIES

5.1 Fire testing of a full-scale model room

A fire simulation experiment of a full-scale room unit model was carried out to study the fire safety of lightweight glue-laminated bamboo (glubam) frame buildings, as shown in Fig.13. The model was adapted from the testing model of the shake table testing, due to the fact that the damage after the tests was minor. Wooden crib with its quantity determined based on typical fire load intensity for residential buildings was stacked and ignited in the experimental room unit. The test was finished after one hour. Temperature histories of several points on walls and upper floor slab, fire behavior of the over-all structure and the damage to the members were examined. Numerical simulation was conducted using fire-driven fluid dynamics software Fire Dynamics Simulator (FDS) developed by National Institute of Standards and Technology (NIST). The simulated results were compared with the experimental observations, demonstrating that the FDS is a useful tool to provide visual simulation of the experimental testing. Fire design measures using gypsum boards and rock wool insulation suggested for the new bamboo building are found adequate from this research.

Fig.13. Fire testing of a full-scale glubam room model

5.2 Thermal performance

Thermal insulation performances of bamboo- and wood-based shear walls in light-frame buildings were recently studied [Wang et al. 2018]. Four specific configurations representing one classical full wood-based configuration, one hybrid bamboo-wood-based configuration and two full bamboo-based configurations with different studs thickness were tested. The thermal conductivity of the materials composing the wall was measured using a hot plate apparatus varying the temperature in the range of 10–50 °C. The anisotropy of the thermal conductivity was analyzed for the wood and bamboo materials. The four specific configurations of the wall were tested in a guarded hot box apparatus in order to determine the thermal resistance and transmittance. Tab.3 lists the main test results of four types of configurations of the walls, in terms of thermal resistance R_t and thermal tansmittance U. The thermal performance of lightweight walls with glubam is almost the same as the conventional walls with OSB and SPF.

Tab.3. Guarded heat box test results

	Wall-1	Wall-2	Wall-3	Wall-4
Wall thickness (mm)	129.9	129.3	129.3	180.4
Sheathing panel	OSB	Ply-bamboo	Ply-bamboo	Ply-bamboo
Frame	SPF	SPF	Glubam	Glubam
Rt (m^2k/W)	2.354	2.236	2.019	2.030
U (W/m^2k)	0.395	0.402	0.457	0.308

The experimental results were also compared with the estimates obtained using the ISO 6946 procedure and a Finite Element (FE) model of the wall, both adopting the thermal conductivity previously measured. A good agreement between the experiments and the models was found with the better results obtained with the FE model.

6 DEMONSTRATION PRJECTS

In last ten years, the authors team also had the opportunities to carry out several important demonstration projects of building glubam bridges, residential buildings, workshops, mobile houses, etc., in China and Arica. Fig. 13 exhibits some examples of the demonstration projects.


(a) Bridge *(b) Residential house*

(c) Hazard relief houses *(d) Workshop building*

Fig.14. Demonstration projects of glubam structures

7 SUMMARY

This paper provides a summary of the more than ten years efforts of the author's research team in developing modern bamboo structures. Glued laminated bamboo or glubam has shown to be a structural system that can be used as an alternative to timber-based glulam. The most recent progress on developing and testing cross-laminated bamboo and timber (can be called as CLBT or CLTB) is also reported in the paper.

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