SHEARING BEHAVIOR OF STRUCTURAL INSULATED PANEL WALL SHELLED WITH BAMBOO SCRIMBER

Wang Xue-hua

Lecturer
College of Furniture and Industrial Design
Nanjing Forestry University
Nanjing, People's Republic of China
E-mail: xuehua3099@sina.com

Wu Zhi-hui

Professor
Nanjing Forestry University
Nanjing, People's Republic of China
E-mail: wzh550@sina.com

Wang Xiao-huan

Associate Professor
Beijing Forestry Machinery Research Institute
Beijing, People's Republic of China
E-mail: wxh811118@126.com

Song Sha-sha

Lecturer
Beijing Forestry University
Beijing, People's Republic of China
E-mail: songsui_1688@126.com

Cao Yong-jian

Associate Professor
Guangdong Academy of Forestry
Guangzhou, People's Republic of China
E-mail: wayne_cao@live.ca

Ni Jun

Senior Engineer
Suzhou Crownhomes Co., Ltd.
Jiangsu Province, People's Republic of China
E-mail: ni.jun@crownhomes.cn

Sun Quan-yi

Senior Engineer
Dalian Quacent New Building Materials Co., Ltd.
Liaoning Province, People's Republic of China
E-mail: ray.quacent@gmail.com

* Corresponding author
† SWST member

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*Fei Ben-hua**†
Professor
International Centre for Bamboo and Rattan
Beijing, People's Republic of China
E-mail: feibenhua@icbr.ac.cn

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Abstract. In this study, shearing behavior of a structural insulated panel (SIP) wall, which consisted of a Styrofoam core board, shell panel of bamboo scrimber, and frame of Spruce–Pine–Fir dimension lumber, was tested under monotonic and cyclic loads. Results showed that the SIP wall failed at similar positions under two loading modes, although more serious destruction occurred under cyclic than monotonic load. There was a linear relationship between load and displacement at the initial loading stage, which indicated that the wall worked under the elastic state. At a later loading stage, bearing capacity and rigidity decreased as a result of wall slip. Shearing strength under monotonic and cyclic loads was 20.0 and 15.8 $kN \cdot m^{-1}$, respectively, which met the requirement of the standard code for design of timber structures. Energy consumption of the SIP wall covered with bamboo scrimber was 11,556.6 $J \cdot m^{-1}$.

Keywords: Bamboo scrimber panel, SIP wall, monotonic and cyclic loading, shearing behavior.

INTRODUCTION

The structural insulated panel (SIP) is a prefabricated building material that has been the topic of interest among researchers in recent years (Ali et al 2013). Compared with traditional light-frame wood structures, SIP building systems have advantages in insulation properties, acoustic performance, seismic performance, and material use (Edward and Keith 2006; Kermani and Hairstans 2006). SIP is a sandwich-style structural panel used as a building member such as a wall, roof, or floor for concrete, steel, and wood frame structures in Europe, North America, and Japan (Smith 2010; Qu 2012). It is usually manufactured with two layers of rigid materials as shells and a thicker layer as a core. The core of SIP is usually nonstructural and ridged, commonly made of plastic foam such as expanded polystyrene or polyurethane (PUR) foam. Various materials, such as metal, cement, gypsum, oriented strandboard (OSB), are suggested and applied as SIP shells by researchers and manufacturers (Porter 2004; Miller et al 2005; Porter 2009; Zhang et al 2009; Yan et al 2010; Smith 2010; Brown 2013). However, studies using bamboo-based panels as SIP shells have not been reported.

Bamboo is a fast-growing and resourceful biomass material in China. Given the increasingly serious shortage of wood resources in China, bamboo would be an effective alternative resource of wood. There are various bamboo-based products such as bamboo curtain plywood, bamboo mat plywood, bamboo glulam (Wang and Jiang 2003). Bamboo scrimber, which is obtained by reorganizing and remolding bamboo, is one of the new and more competitive bamboo products (Yu 2012).

Zhang et al (2012) showed a higher compression and tension strength for bamboo scrimber than that for larch and spruce. The specific modulus of elasticity (MOE) and modulus of rupture (MOR) of bamboo scrimber were 50% and 120% higher, respectively, than that of wood scrimber (Zhu et al 2004). Also, because of smooth and various grains, bamboo scrimber has a strong decorative effect (Zhu and Zang 2011). However, bamboo scrimber is mainly used as nonstructural components currently such as flooring, veneer. Reports about bamboo scrimber used as structural components were seen only in exemplary buildings. There are currently few reports about bamboo scrimber used as a SIP shell panel.

To take full advantage of the SIP system and bamboo scrimber, bamboo scrimber should be used as the shell panel of a SIP wall. In this study, a SIP wall shelled with bamboo scrimber

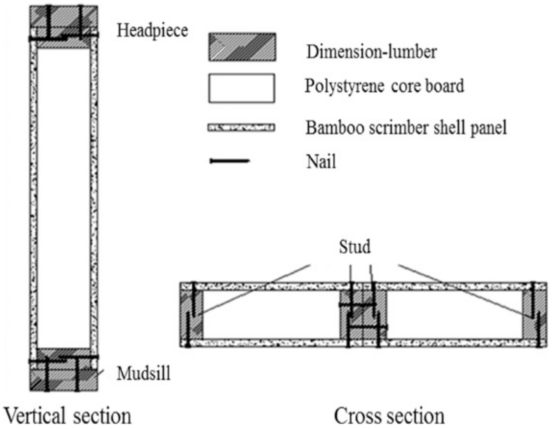


Figure 1. Section of SIP wall.

was tested under monotonic and cyclic loads. The failure phenomenon was observed, and shearing parameters were calculated to investigate the shearing performance to provide information for bamboo scrimber used in a SIP system.

MATERIALS AND METHODS

Materials

Bamboo scrimber used for SIP shells was made of *Neosinocalamus affinis*. The SIP panel contained two shell panels and one core board. The bamboo scrimber shell panel was 2440 × 1220 × 6 mm (length × width × thickness). The polystyrene core board was 2364 × 1144 × 89 mm (length × width × thickness). PUR adhesive was used to bond the shell panel and core board according to ASTM (2004). The distance from shell edge to core edge was 38 mm. The groove formed by the shell panel and core board was filled with dimension lumber (Fig 1).

Parameters for wall members are listed in Table 1. Parameters for connectors are listed in Table 2.

The SIP wall sample consisted of two SIP panels and eight dimension lumbers, which were composed of headpiece, mudsill, and studs. Headpiece and mudsill consisted of two pieces of dimension lumber, respectively. Midstuds between two SIP panels consisted of two pieces of dimension lumber, and the right and left stud consisted of one piece of dimension lumber, respectively. The sizes of dimension lumbers are listed in Table 1. Dimension lumbers and shell panels were connected by nails. The wall and load beam and the wall and groundsill were connected by screw bolts. Hold-downs were fixed between the left and right stud and mudsill (Fig 2). Connectors between the hold-down and left and right stud were tapping screws, and those between the hold-down and mudsill were screw bolts.

Loading Method

Only horizontal load (no vertical load) was applied during testing. Monotonic load testing was loaded according to ISO (2011). The loading program was controlled by force; load increased sustainably until the SIP wall wrecked. Loading rate was set at 6 kN/min.

Cyclic load testing was loaded according to ISO (2010). The loading program for cyclic load testing was controlled by displacement. The ultimate displacement obtained in monotonic load

Table 1. Parameters of wall members.

Part	Material	Size		Property parameter
Frame	Dimension-lumber (Spruce–Pine–Fir)	Headpiece (upper)	2440 × 113 × 38	MOE: 9650 MPa
		Headpiece (lower)	2440 × 89 × 38	
		Stud	2364 × 89 × 38	
		Mudsill (upper)	3000 × 89 × 38	
		Mudsill (lower)	3000 × 113 × 38	
Core board	Polystyrene board	2364 × 1144 × 89		Density: 20 kg/m^3, tensile strength: 140 KPa
Shell panel	Bamboo scrimber	2440 × 1220 × 6		MOE (longitudinal/transverse): 4545/1965 MPa

Table 2. Parameters of connectors.

Connector	Parameters	
PUR adhesive	Spreading rate: 180 g/m^2	
Nail	Length: 60 mm, diameter: 4 mm	Distance between neighbor nails: 150 mm
Hold-down	450 × 41 mm (length × width)	Ten holes at diameter 6.5 mm were drilled on side of hold-down. Tapping screws of diameter 6 mm were used to connect hold-down and out-side stud; one hole of diameter 21 mm was drilled on bottom of hold-down. Screw bolt was used to connect hold-down and mudsill
Screw bolt in headpiece	Diameter: 14 mm	Distance between neighbor screw bolts: 400 mm
Screw bolt in mudsill	Diameter: 20 mm	Distance between neighbor screw bolts: 400 mm

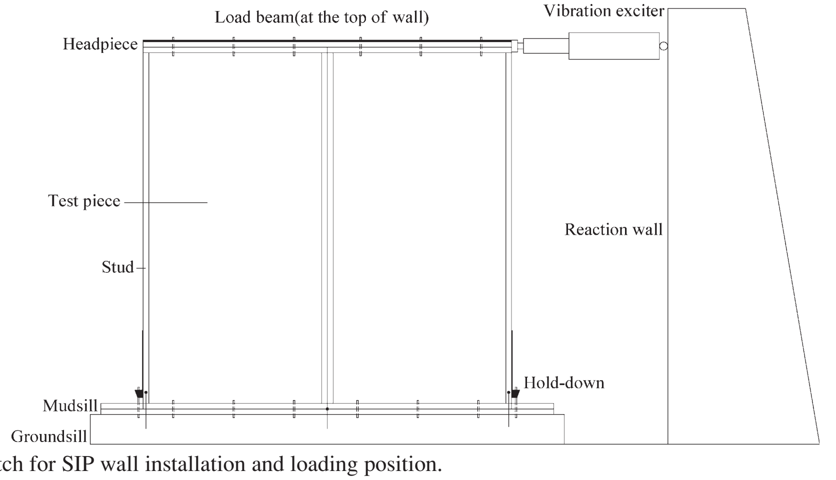


Figure 2. Sketch for SIP wall installation and loading position.

testing was used as control displacement. About 1.25%, 2.50%, 5.00%, 7.5%, and 10.00% of the ultimate displacements were taken as target displacements and loaded in order. Every displacement was repeated one time. Then, 20%, 40%, 60%, 80%, 100%, and 120% of the ultimate displacements were taken as target displacements and loaded in order. Every displacement was repeated three times. Loading rate was set at 100 mm/min.

Shearing Behavior Parameters

A skeleton curve under cyclic load gained according to the first cycle of different target displacements is shown in Fig 3 (the curve with the black box). A displacement-load curve under monotonic load and its symmetrical curve around the base point were also figured.

Shearing behavior parameters were defined according to equivalent elastic-plastic curve (Dolan and Johnson 1996; Hu 2007; Guo et al 2011). The shearing behavior parameters evaluated in this study and their definitions are as follows:

Shearing strength (f_{vd}): shearing strength was shearing capacity of unit length wall, $f_{vd} = F_{max}/L$. F_{max} was the ultimate load of wall under monotonic or cyclic load. In cyclic load, ultimate load was the maximum load in the first loading cycle. L was wall length (2.44 m in this study).

Peak displacement (Δ_{max}): peak displacement was the displacement corresponding with ultimate load.

Limiting displacement (Δ_u): limiting displacement was the displacement when load reached 80% ultimate load after failure or the displacement when the wall was seriously damaged.

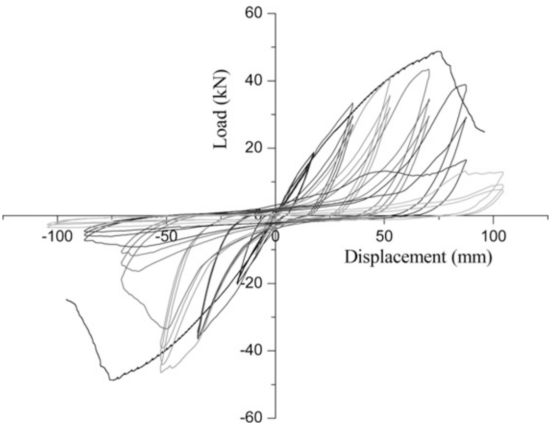


Figure 3. Skeleton curve under cyclic load and displacement-load curve under monotonic load.

Elastic stiffness (K): slope of the tangent line between base point and 40% ultimate load on rising step of displacement-load curve.

Energy dissipation (E): total absolute area enclosed by hysteresis loop was the wall energy dissipation behavior on the whole length. Energy dissipation behavior per unit length was used in this study.

Results for shearing behavior are listed in Table 3.

RESULTS AND DISCUSSION

Phenomenon of SIP Wall Damage

Failure phenomenon was similar under both monotonic and cyclic loads. There were three stages: elastic, plastic, and failure (as Fig 3 showed). At the initial stage, the load-displacement curve was nearly linear. As load increased, wall displacement and mode slight noise increased. As increasing maximum load occurred, displacement increased rapidly, cracks occurred between the hold-down and wall and the bamboo scrimber panel and mudsill, and bearing capacity of the wall dropped sharply.

Cracks were mainly distributed at the bottom of the SIP wall. Damage at the mudsill is shown in Fig 4. The shell panel where it contacted the mudsill and tacked nails was destroyed under both monotonic and cyclic loads. Under monotonic load, nails connecting the mudsill and bamboo scrimber panel stayed in the mudsill and looked undamaged from the part exposed on the panel surface (Fig 4a). Under cyclic load, nails connecting the mudsill and bamboo scrimber panel were pulled out and bent from the pulling out part. They stayed in the bamboo scrimber panel. The mudsill was destroyed (Fig 4b).

Damage of hold-downs at the left (located diagonal to the vibration exciter) and right (located lower than the vibration exciter) side stud was different under monotonic load. The left one did not appear to be damaged (Fig 5a), whereas the right one was pulled out from the side stud and bent (Fig 5b). Under cyclic load, hold-downs at the left and right were both pulled out (Fig 5c,d) and obviously bent.

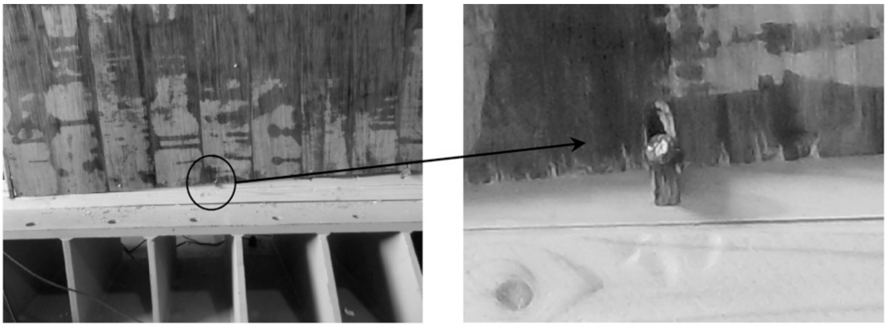
Displacement-Load Curve

The displacement-load curve of the SIP panel under monotonic and cyclic loads is shown in Fig 3. Skeleton curve (the line with black box in Fig 6) under cyclic load was got according to Fig 3. The black line is the displacement-load curve under monotonic load (in the first quadrant); its symmetrical curve around the base point is given (the black line in the third quadrant). The colored line is the displacement-load curve under cyclic load, and the different colors mean different cycles with different control displacements.

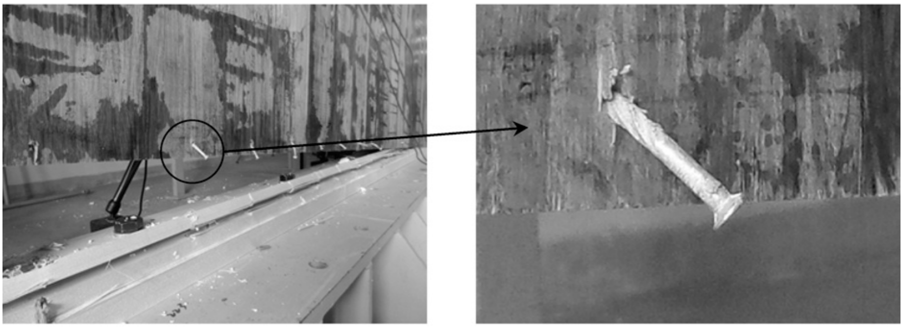
Table 3. Shearing behavior parameters.[a]

Load mode	Ultimate load F_{max}/kN			Shearing strength f_{vd}/kN·m^{-1}			Peak displacement $\Delta_{max/mm}$			Limiting displacement $\Delta_{u/mm}$			Elastic stiffness K/kN·m^{-1}			Energy dissipation E/J·m^{-1}
	T	C	AVG	T	C	AVG	T	C	AVG	T	C	AVG	T	C	AVG	
Mon	—	48.8	48.8	—	20.0	20.0	—	74.4	74.4	—	82.5	82.5	—	971.1	971.1	—
Cyc	46.3	43.5	44.9	13.7	17.8	15.8	50.3	70.4	60.3	59.5	67.9	63.7	1194.6	1086.8	1140.7	11,556.6

[a] Mon, monotonic load; Cyc, cyclic load; T, tensile; C, compressive; AVG, average.



(a) Under monotonic loading



(b) Under cyclic loading

Figure 4. Damage situation at bottom of SIP wall.

(a) (b)

(c) (d)

Figure 5. Damage at hold-downs. (a) Diagonal of vibration exciter under monotonic load; (b) lower of vibration exciter under monotonic load; (c) diagonal of vibration exciter under cyclic load; (d) lower of vibration exciter under cyclic load.

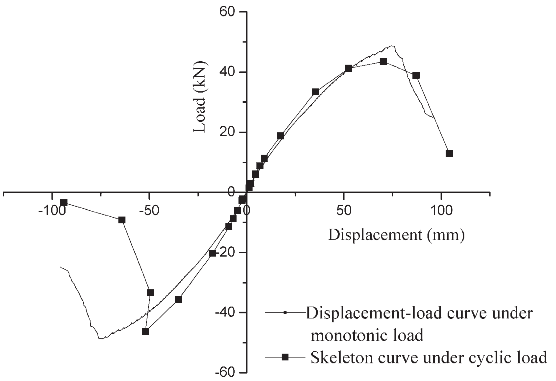


Figure 6. Displacement-load curve under monotonic and cyclic load.

At initial loading, the displacement-load curve was almost linear. The wall worked in an elastic situation. The testing result was similar with a steel plate shear wall under cyclic loading (Guo et al 2011). The area enclosed by a hysteresis loop was small. Rheostriction phenomenon was obvious. During the middle loading, the area enclosed by the hysteresis loop increased. Among the three cycles at one grade controlled by the same target displacement, the latter two had higher contact ratios and lower loads at the same displacement compared with the first one. The phenomenon showed that wall components were damaged with repeated loading, which further lessened wall strength, load capacity, and stiffness. As target displacement increased, the hysteresis loop turned from S shaped to Z shaped at different target-displacement grades and wall slip effect appeared.

Shear Strength

Shearing strength of SIP walls was affected by loading modes and directions (Table 3). Shearing strength was 11.06% lower under cyclic than monotonic load, which might have been caused by damage cumulated under cyclic loading. Shearing strength was 29.98% higher in compression than tension under cyclic load, because pressure was firstly loaded on the SIP wall that had been damaged after reaching ultimate load in this direction, which lessened the ultimate load in tension.

Shearing strength was 20.0 $kN \cdot m^{-1}$ under monotonic load and 15.8 $kN \cdot m^{-1}$ under cyclic load in this study, whereas shearing strength of a light-framed wood wall shelled with 12-mm OSB was 6.53 $kN \cdot m^{-1}$ under monotonic load and 6.16 $kN \cdot m^{-1}$ under cyclic load (Du et al 2013). Shearing strength of an SIP wall shelled with 12-mm OSB was 19.7 $kN \cdot m^{-1}$ (Shim et al 2010) tested by ASTM (2006). Shearing strength requirements of wood walls faced with 6-mm wood-based structural panels in GB (2003) were 3.2 $kN \cdot m^{-1}$. The results show that shearing strength in this study can satisfy the requirements of GB (2003). It was similar to an SIP wall shelled with 12-mm OSB, which tested the same way, and greater than a light-framed wall faced with 12-mm OSB.

Ultimate Displacement

Ultimate displacement was affected by loading modes and directions (Table 3). It was 29.5% higher under monotonic than cyclic load and 17.25% higher in compression than tension under cyclic load. Displacement capacity was greater under monotonic load than under cyclic load. Under cyclic load, the wall was first loaded in compression. Under pressure, wall members produced plastic deformation and brittleness increased, which lowered displacement capacity when loaded in tension. Ultimate displacement of a light-framed wood wall of length 3.6 m faced with 12-mm OSB was 53.98 mm under monotonic load and 48.41 mm under cyclic load (Du et al 2013). The value was close to results in this study (48.8 mm under monotonic load and 44.9 mm under cyclic load).

Elastic Stiffness

Elastic stiffness was the ratio of load and displacement. Elastic stiffness was 17.46% higher under cyclic than monotonic load (Table 3), because a quicker loading rate decreased reaction time and displacement under cyclic load compared with monotonic load. Some elastic stiffness difference was observed at different loading directions under cyclic load (9% higher in tension than in compression). Different loading directions exerted little effect on wall elasticity when load was less than 40% ultimate load. Elastic stiffness obtained in this study (1194.6 kN·m^{-1} in tensile and 1090 kN·m^{-1} in compressive) was close to the light-framed wood wall length 3.6 m covered with 12-mm OSB (1330kN·m^{-1} in tensile and 1090 kN·m^{-1} in compressive) (Du et al 2012).

Energy Dissipation

Energy dissipation of an SIP wall shelled with bamboo scrimber was 11,556.6 J·m^{-1}, about five times that of a light-framed wood wall (Du et al 2012). The area enclosed by a hysteresis loop decreased as target displacement increased and loading time expanded (Table 3).

A wall is an important energy dissipation part of a building. It helps the whole building to decrease the degree of damage in an earthquake, keeps a building in elastic stage, and provides sufficient rigidity when the wall has good energy dissipation capacity. A wall with good energy dissipation capacity can provide a larger damping effect to absorb energy released by an earthquake, decrease earthquake response (displacement, velocity, etc.) on buildings, protect construction and components in a strong earthquake from destruction, and improve building safety. From an energy dissipation point, an SIP wall shelled with 6-mm bamboo scrimber was higher quality than the light-framed wood wall tested by Du et al (2012).

CONCLUSIONS

Failures mainly occurred at the bottom of the wall. Under monotonic load, nails stayed in the mudsill and looked undamaged from the part exposed on the panel surface. The shell panel and mudsill were slightly damaged. The hold-down lower vibration exciter bent under the action of loading. Under cyclic load, nails were forced out and bent at the pulling out part and stayed in the bamboo scrimber panel. The mudsill was destroyed. Hold-downs at the left and right were both deformed.

Displacement-load curve was almost linear at the initial loading stage both under monotonic and cyclic loads. The area enclosed by a hysteresis loop was small. Rheostriction phenomenon was obvious from the displacement-load curve. Wall members were damaged with repeated loading and experienced further lessened strength, load capacity, and stiffness. At different target-displacement grades, hysteresis loop turned from S shaped to Z shaped as the displacement increased and wall slip effect appeared.

Ultimate load, shearing strength, ultimate displacement, and elastic stiffness of the SIP wall shelled with 6-mm bamboo scrimber were 48.8 kN, 20.0 kN·m^{-1}, 82.5 mm, 0.97 MN·m^{-1} under monotonic load and 44.9 kN, 17.8 kN·m^{-1}, 63.7 mm, 1.14 MN·m^{-1} under cyclic load. Energy dissipation under cyclic load was 11,556.6 J·m^{-1}.

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REFERENCES

Ali A, Abdullah A, Anwar MP, Voo YL (2013) Structural insulated panels: Past, present, and future. J Eng Proj Prod Manag 3(1):2-8.

ASTM (2004) D 2559-2004. Standard specification for adhesives for structural laminated wood products for use under exterior (wet use) exposure conditions. American Society for Testing and Materials International, West Conshohocken, PA.

ASTM (2006) E564-06. Standard practice for static load test for shear resistance of framed walls for buildings, American Society for Testing and Materials International, West Conshohocken, PA.

Brown ML (2013) Structural insulated panel system. US Patent 8,522,500.

Dolan JD, Johnson AC (1996) Cyclic tests of long shear walls with openings. Virginia Polytechnic Institute and State University, Timber Engineering Report No. TE-1996-002. Blacksburg, VA. 39 pp.

Du M, Xie B, Fei B, Wang X, Liu Y (2012) Shear performance of wood-frame shear walls with cross brace. Chin J Appl Mech 29(3):314-320 (In Chinese).

Du M, Xie B, Fei B, Wang X, Liu Y (2013) Shear performance of wood-frame shear walls made of domestic material. Journal of Building Mater 16(3):487-490 (In Chinese).

Edward L, Keith PE (2006) Standardization testing of structural insulated panels (SIPs) for the structural insulated panel association, Gig Harbor, Washington. APA Report No. T2006P-33 for the Engineered Wood Association, Tacoma, WA. 40 pp.

GB (2003) 50005-2003, Code for design of timber structures, Beijing, China. 100000.

Guo H, Hao J, Li F (2011) Cyclic test of semi-rigid composite steel frame with diagonally stiffened steel plate shear walls. J Earthquake Eng and Engineering Vibration 31(1):54-60.

Hu G (2007) Study about lateral force resisting performance of irregular wooden shear wall. MS thesis, Tongji University, Shanghai. 84 pp (In Chinese).

ISO (2010) 21581, Timber structures—static and cyclic lateral load test methods for shear walls, Geneva, Case postale 56. CH-1211.

ISO (2011) 22452-2011, Timber structures—Structural insulated panel walls—Test methods, Geneva, Case postale 56. CH-1211.

Kermani A, Hairstans R (2006) Racking performance of structural insulated panels. J Struct Eng 132(11):1806-1812.

Miller D, Griffin Y, Segger M (2005) Carbon foam structural insulated panel. US Patent 11/314,975.

Porter W (2004) Structural insulated panel building system. US Patent 13/050,089.

Porter WK (2009) Structural insulated panel with hold down chase. US Patent 11/425,389.

Qu P (2012) Adaptability of structural insulated panel SIP in northeast cold area. ChengShi Jianshe LiLun Yan Jiu (Electronic Edition), (25) (In Chinese).

Shim KB, Park MJ, Hwang KH, Park JS, Park MJ (2010) Shear performance of hybrid post and beam wall system with structural insulation panel (SIP). Mokchae Konghak 38(5):405-413.

Smith RE (2010) Prefab architecture: A guide to modular design and construction. John Wiley & Sons, New Jersey, NJ. 402 pp.

Wang Z, Jiang Z (2003) Status on standards for bamboo-based panels and its prospect. World Bamboo and Rattan 1(3):5-10 (In Chinese).

Yan S, Liu W, Lu W, Yang H (2010) Study on SIP slab structure residential system. New Building Mater 37(8):35-39.

Yu W (2012) Current status and future development of bamboo scrimber industry in China. China Wood Industry 26(1):11-14 (In Chinese).

Zhang J, Ren H, Zhong Y, Zhao R (2012) Analysis of compressive and tensile mechanical properties. J Nanjing Forestry Univ 36(4):107-111 (Natural Sciences).

Zhang Y, Liu W, Yang H, Lu W (2009) Preparation and analysis of thermal performance of structural insulated panels. Jiangsu Construction (5):77-80 (In Chinese).

Zhu J, Zang H (2011) The new building materials of green building—Restructuring bamboo. New Building Mater 7:44-47. (In Chinese).

Zhu Y, Guan M, Rao W, Zhang X (2004) Research on bending properties of bamboo and wood hybrid scrimber. J Nanjing Forestry Univ 28(4):59-61 (Natural Sciences).