NERC of Biomaterials
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Engineered Bamboo Composite: Opportunities and Challenges as a Construction Material

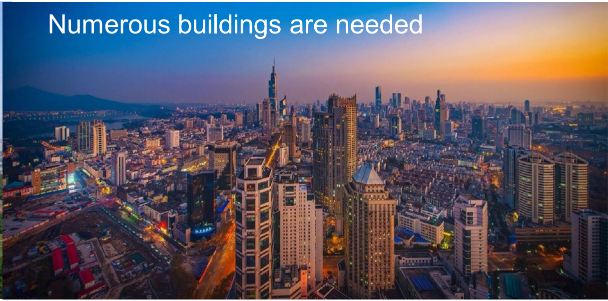
Huang Dongsheng, Professor & PhD

National Engineering Research Center of Biomaterials
SouthFOR Innovations for Biomaterials and Structures
E-mail: dshuang@njfu.edu.cn

Outline

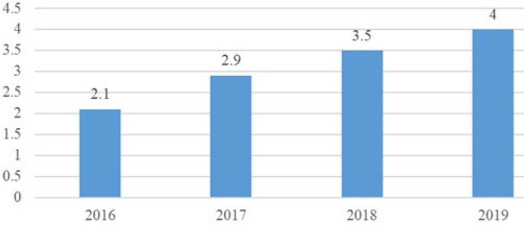
1. Why Engineered Bamboo Composite (EBC)
2. EBC as a Construction Material
3. Challenges
4. What shall we do

Why Engineered Bamboo Composite (EBC)

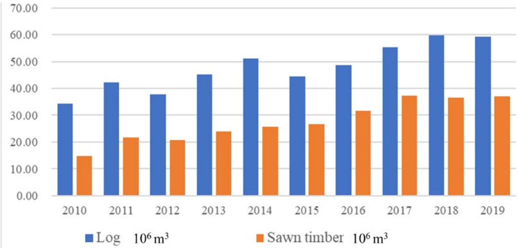


We need to reduce the consumption of mineral resources, but to use renewable resources as possible as we can, such as bamboo and wood instead.

Opportunities for EBC buildings



Overall floorage of wood building constructed in China, 2016-2019 (10^6 m^2)



Wood products import of China, 2010-2019

Cutting down trees is severely restricted due to the policy of environmental protection. Lumber production at home cannot support the needs of building constructions.

China has the largest bamboo reserves in the world. To use bamboo as construction material might reduce the demands of wood products.

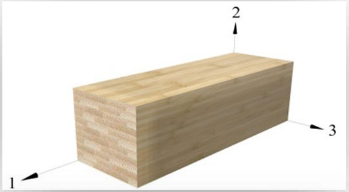
Bamboo as a Construction Material

China has long tradition of bamboo housing. Traditional bamboo house: low strength and stiffness, poor durability.

What is EBC

Engineered Bamboo

Bamboo-based composites designed for structural applications having specific mechanical properties and more than 50 years of durability in dry use.



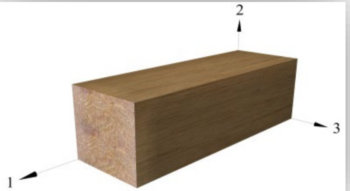


Table 1. The characteristic values of strength and elastic modulus for PSB in different grades

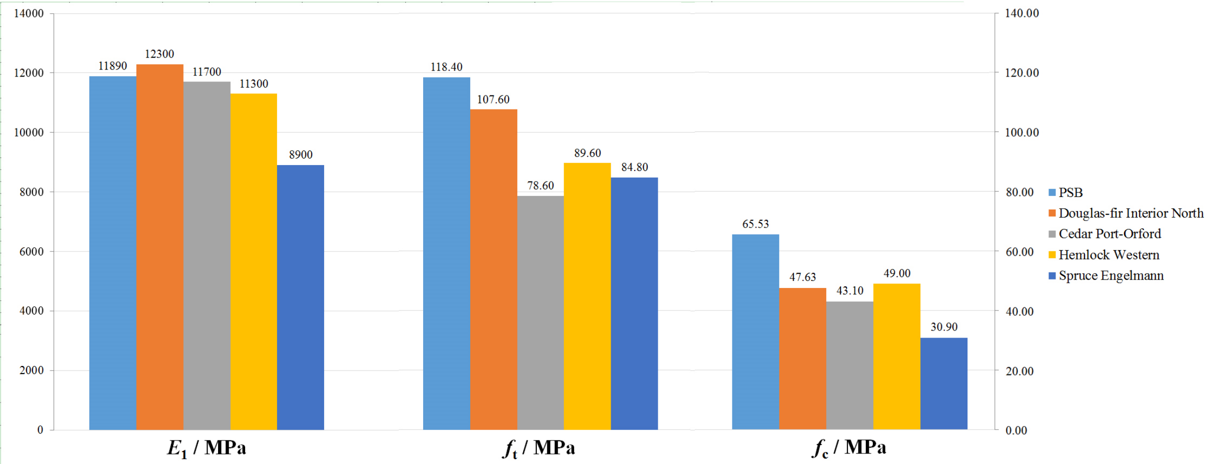
Mechanical properties	E9	E10	E11	E12	E14	E16
Tensile modulus parallel to the grain $E_{t,0}$ / MPa	9000	10000	11000	12000	14000	16000
Flexural modulus parallel to the grain E_m / MPa	6500	7700	9000	10200	11500	13000
Tensile strength parallel to the grain $f_{t,0}$ / MPa	74	82	90	98	106	114
Compressive strength parallel to the grain $f_{c,0}$ / MPa	72	78	84	91	97	103
Shear strength parallel to the grain $f_{s,0}$ / MPa	5	5	8	8	12	12
Flexural strength parallel to the grain f_m / MPa	65	76	87	98	109	120
Tensile strength perpendicular to the grain $f_{t,90}$ / MPa	3	3	4	4	5	5.0
Compressive limit strength perpendicular to the grain $f_{c,90}$ / MPa	22	26	30	34	38	42
Compressive strength perpendicular to the grain $f_{ce,90}$ / MPa	25	30	35	40	45	50

Table 2. The characteristic values of strength and elastic modulus for LVB in different grades

Mechanical properties	E8	E9	E10	E11	E12	E13
Tensile modulus parallel to the grain $E_{t,0}$ / MPa	8000	9000	10000	11000	12000	13000
Flexural modulus parallel to the grain E_m / MPa	6000	6600	7100	7600	8200	8700
Tensile strength parallel to the grain $f_{t,0}$ / MPa	69	76	83	90	97	104
Compressive strength parallel to the grain $f_{c,0}$ / MPa	43	46	49	52	55	58
Shear strength parallel to the grain $f_{s,0}$ / MPa	5	5	7	7	9	9
Flexural strength parallel to the grain f_m / MPa	65	72	79	86	93	100
Tensile strength perpendicular to the grain $f_{t,90}$ / MPa	2	2	3	3	4	4
Compressive limit strength perpendicular to the grain $f_{c,90}$ / MPa	10	10	10	11	11	11
Compressive strength perpendicular to the grain $f_{ce,90}$ / MPa	14	14	14	16	16	16

Mechanical properties of EBC

Comparing the mechanical properties with that of commonly used wood products



Opportunities of EBC as an Construction Material

① Tourist service, NANJING, China
② Filed camp, Shaowu, China
③ House in Sichuan for earthquake disaster rebuild
④ Office building in Nanjing, China
⑤ A concept design of EBC overcrossing,

Challenges

1. How to make bamboo composite with stable properties to meet the requirements of construction engineering?
2. Design philosophy of EBC structures?

   (1) Ultimate state-based analysis of EBC components (nonlinearity)

   (2) Connections

   (3) Long term properties (creep sensitive to ambient environment)
3. Economy and acceptability

Researches on EBC manufacturing technique

Researches on constitutive properties of EBC

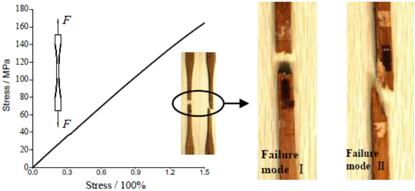


Fig. 3. Stress-strain relationship and failure modes of tension in axis-1.

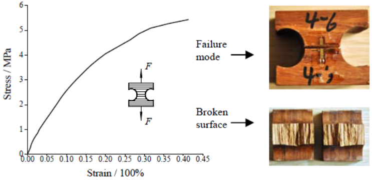


Fig. 4. Stress-Strain relationship and failure mode of tension in axis-2

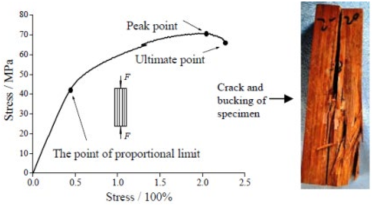


Fig. 5. Stress-strain relationship and failure mode of compression in axis-1

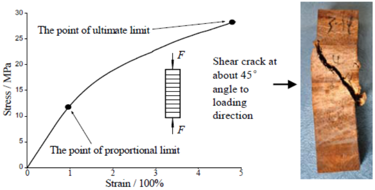


Fig. 6. Stress-strain relationship and failure mode of compression in axis-2

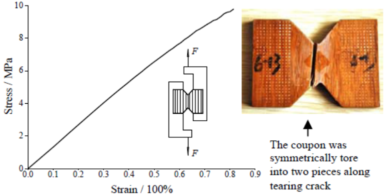
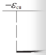


Fig. 7. Stress-strain relationship and failure mode of shearing-parallel-to-grain

Constitutive nonlinearity could result in nonlinear responses of EBC members in the ultimate state

Ultimate state-base

Failure mode

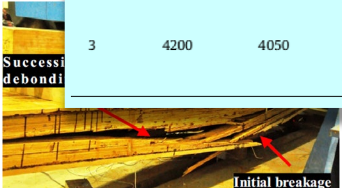


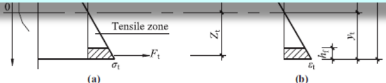
Comparing the results of tests to that of calculations.

No.	a (mm)	Ultimate load (kN)		Ultimate deflection (mm)	
		Test values	Calculation values	Test values	Calculation values
L1-1	450	57.14	66.37	39.14	50.05
L1-3	450	58.47		43.25	
L1-4	450	64.89		50.24	
L2-2	450	63.88	66.54	40.24	50.13
L2-3	450	63.89		46.48	
L2-4	450	58.82		29.31	
L2-5	450	54.25		38.82	
L1-2	350	84.81	85.33	49.29	53.21
L1-5	350	76.03		48.49	
L1-6	350	75.36		48.92	
L2-6	350	80.17	85.56	50.04	53.29
L2-7	350	70.05		49.32	
L2-8	350	73.28		33.48	
L2-9	350	74.27		34.38	

Comparison the results of experiments and analyses.

Category	Lengths/mm	Spans/mm	Labels of specimen	Ultimate load/kN			Ultimate deformation/mm		
				Experiment	Mean of experiments	Calculation	Experiment	Mean of experiments	Calculation
1	3600	3450	C1-1	141.00	145.38	143.02	140.11	139.99	148.02
			C1-2	147.34			139.96		
			C1-3	147.81			139.89		
2	3900	3750	C2-1	194.84	185.22	174.02	136.05	129.16	128.21
			C2-2	189.72			130.94		
			C2-3	171.10			120.48		
3	4200	4050	C3-1	231.07	220.15	215.85	125.65	123.46	124.14
			C3-2	208.55			118.78		
			C3-3	220.83			125.94		

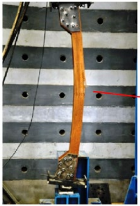




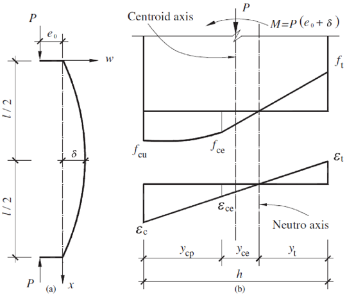
$$= \frac{1}{4} t\lambda_1 k_p \left[(y_p + y_c) - y_c \right] + \frac{1}{3} t\lambda_2 k_p \left[(y_p + y_c) - y_c^3 \right]$$

$$+ \frac{1}{2} t\lambda_3 \left[(y_p + y_c)^2 - y_c^2 \right]$$

Inelastic analysis of columns under eccentrically compressive loading

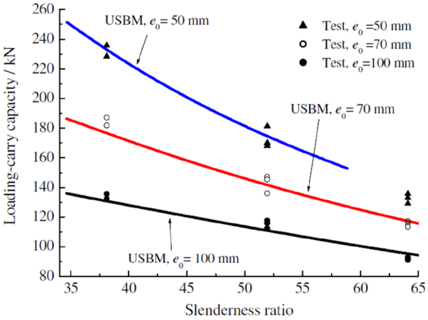


$$M_s = \frac{1}{4} b\lambda_1 \Phi_p^2 [y_{ce}^4 - (y_{ce} + y_{cp})^4] - \frac{1}{3} b\lambda_2 \Phi_p [y_{ce}^3 - (y_{ce} + y_{cp})^3] + \frac{1}{2} b\lambda_3 [y_{ce}^2 - (y_{ce} + y_{cp})^2]$$

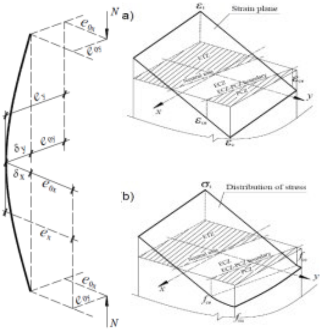


$$Pe = M = M_s + \frac{bk_p}{3}(E_c y_{ce}^3 + E_t y_t^3)$$

$$\delta_p = \frac{l}{4}\varepsilon_{tu}\left(\frac{1}{y_{tu}} - \frac{2}{h}\right)L_p$$



Inelastic analysis of columns under combined biaxial bending and compression



modelling

$$P=\frac{b_1-b_2}{2a\left(b+b_2\right)}\cdot\frac{f_t+f_{ce}}{E}$$

$$Q=-\frac{1}{b+b_2}\cdot\frac{f_t+f_{ce}}{E}$$

$$R=\frac{1}{2\left(b+b_2\right)}\cdot\frac{\left(b_1+b_2\right)f_t+\left(b_1-b_2-2b\right)f_{ce}}{E}$$

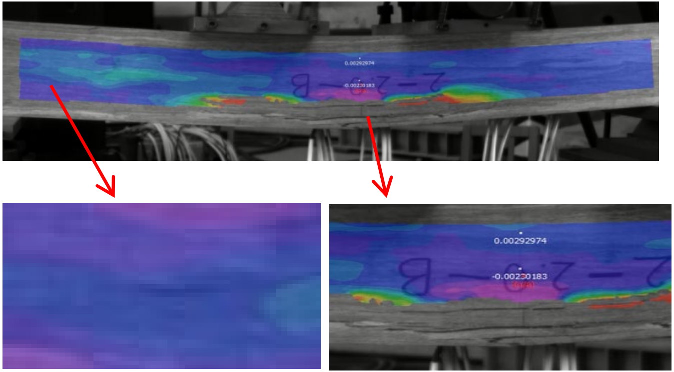
Table 2. Comparison of the Ultimate Load-carrying Capacities of the Test Samples from the Calculations and Tests

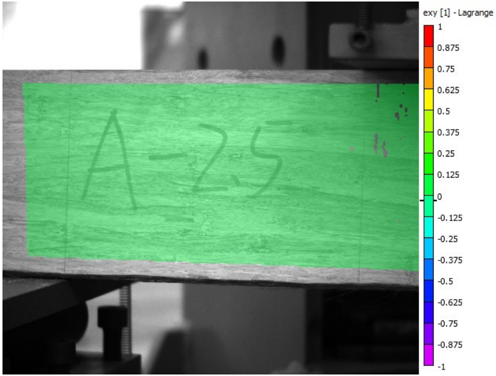
L (mm)	Slenderness Ratio	e_{0x} (mm)	e_{0y} (mm)	Experimental Value (kN)	Calculated Value (kN)	Error (%)
1300	45	40.0	23.1	167	156.7	6.2
		69.3	40.0	134	137.9	2.91
		40.0	40.0	150	171.4	14.27
		56.6	56.6	128	132.3	3.36
		84.9	84.9	90	94.8	5.33
1650	57	40.0	23.1	145	127.9	11.8
		69.3	40.0	103	114.0	10.68
		40.0	40.0	135	136.1	0.81
		56.6	56.6	100	110.0	10.00
		84.9	84.9	75	82.7	10.27

$$N=EAR+\frac{Ea}{3}\left\{a\left(b_1-b_2\right)P-\frac{1}{4}\left[4b^2-3\left(b_1+b_2\right)^2-\left(b_1-b_2\right)^2\right]Q-3\left(2b-b_1-b_2\right)R\right\}-\alpha a\left(2b-b_1-b_2\right)f_{ce}$$

Fracture

We need to answer two basic questions: (1) on what condition will the crack extend? and (2) what crack can the structure tolerant?

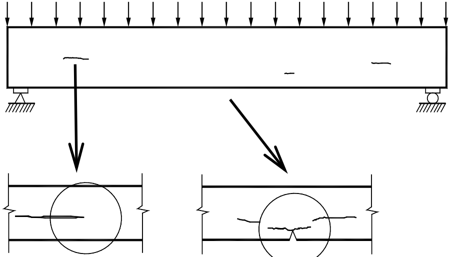




Fracture is the basic failure mode of EBC. Material nonlinearity is caused by micro voids coalesces other than cracking

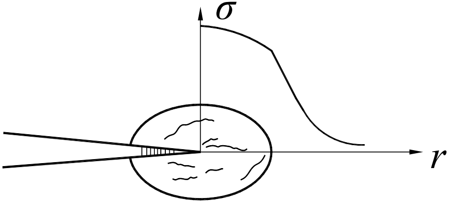
Fracture analysis of EBC is a big challenge

Characteristics of EBC cracking



Mode II crack

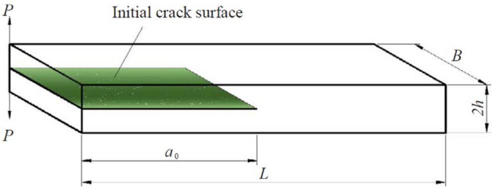
Mode I and I+II crack

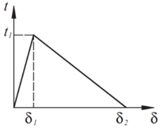


Fracture process zone (FPZ) .

Initial cracks, micro-voids existence in EBC.
Crack propagation, voids coalescence are major damage and failure mechanism of EBC structures.

Analytical model for mode I fracture analysis





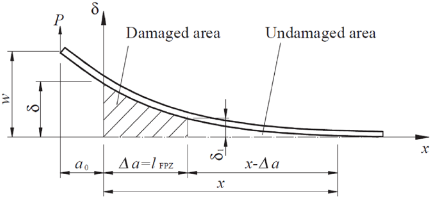
$$\frac{d^4\delta(x-\Delta a)}{d(x-\Delta a)^4}-\alpha^4\delta(x-\Delta a)=0,\ \text{for } \Delta a \leqslant x < +\infty$$

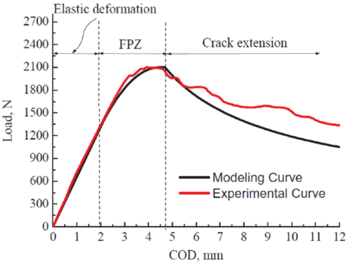
$$\frac{d^4\delta(x)}{dx^4}+\beta^4\delta(x)-\delta_0=0,\ \text{for } 0 \leqslant x \leqslant \Delta a$$

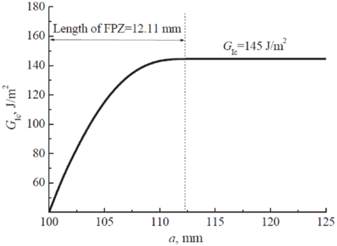
$$\delta_e(x)=A_1e^{-\alpha(x-\Delta a)}+A_2e^{\alpha(x-\Delta a)}+A_3\cos\alpha(x-\Delta a)+A_4\sin(x-\Delta a),\ \text{for } \Delta a \leqslant x < +\infty$$

$$\delta_p(x)=e^{\zeta x}(B_1\cos\zeta x+B_2\sin\zeta x)+e^{-\zeta x}(B_3\cos\zeta x+B_4\sin\zeta x)+\frac{\delta_0}{\beta^4},\ \text{for } 0 \leqslant x < \Delta a$$

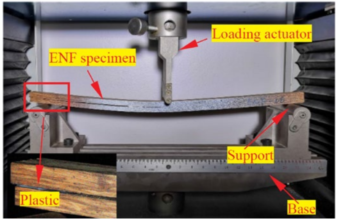
$$G_I=\frac{P^2}{4\zeta^2(B_2-B_4)E_1I}\{\delta_2+2\theta_p(\Delta a)a_0+2\zeta^2[(B_2(\Delta a)-B_4(\Delta a))a_0^2]\}$$

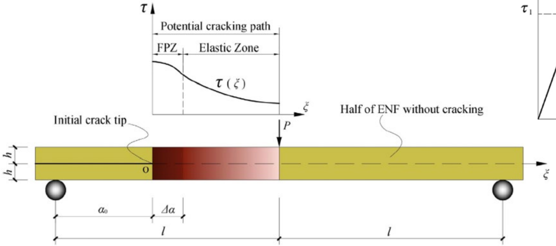


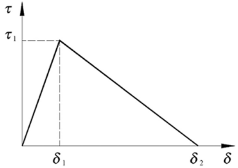


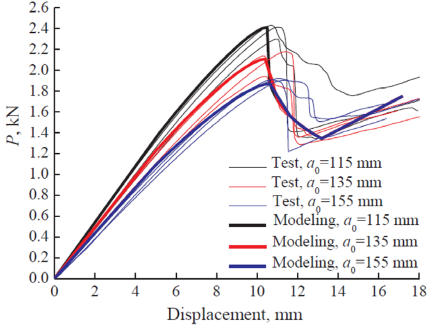


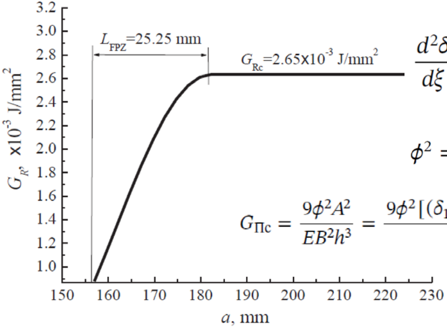
Analytical model for mode II fracture analysis











$$\frac{d^2\delta}{d\xi} + \phi^2\delta + (\beta Q_1 - \eta\tau_0) = 0$$

$$\phi^2 = \frac{8k_2}{E'h},\ \eta = \frac{8}{E'h},\ \beta = \frac{12}{E'h^2}.$$

$$G_{\Pi c} = \frac{9\phi^2 A^2}{EB^2h^3} = \frac{9\phi^2[(\delta_1 - T_0 + \mu Q_e)^2 + (\beta a_0 Q_e/\phi)^2]}{EB^2h^3}$$

Study on Mode I+II fracture

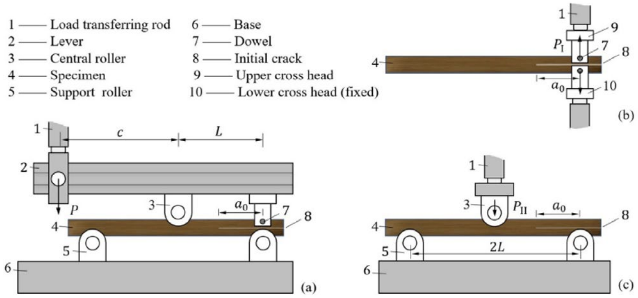
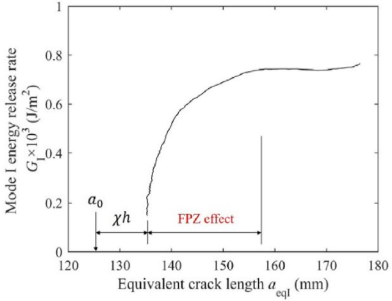
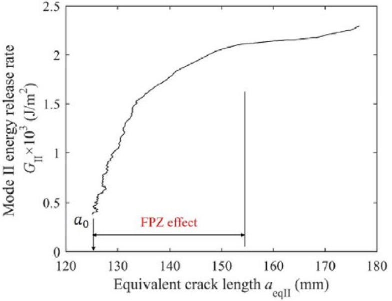
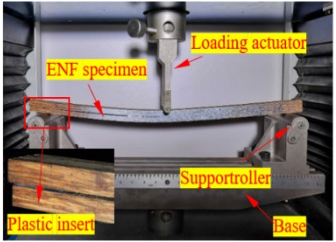


Fig. 1. Schematic illustration for the test method: (a) MMB (b) DCB (c) ENF.

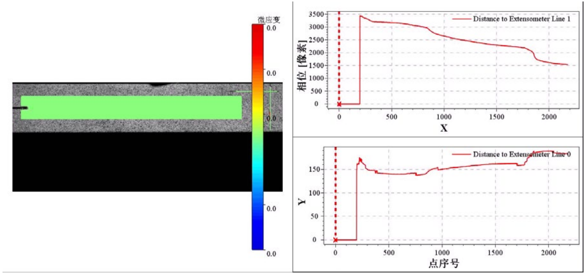




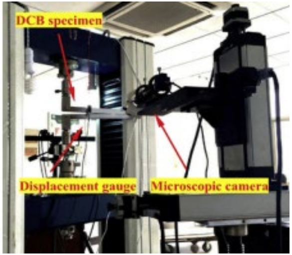
Detecting the crack length by using DIC and high-speed camera technique



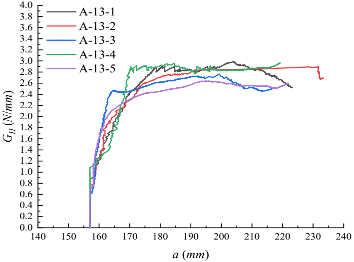
Test of Mode II fracture



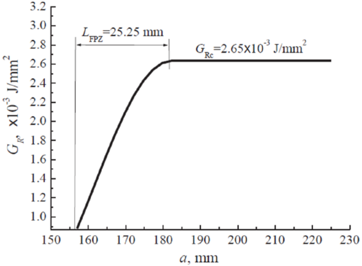
Measure of crack length



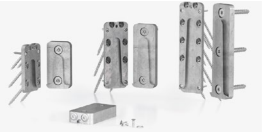
Mode I fracture test (DCB)



Tested R-curve

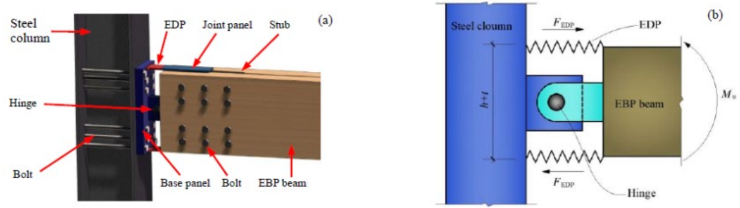


Connection



Different from wood, nail and screw may not be appropriate for EBC connecting. Hence the design and construction of EBC building, to some extend, are different from that of wood buildings. Bolt and dowel connections may be the major joint manners for EBC buildings. Consequently, moment frame probably is a preferable structure style for EBC buildings.

Bolt and dowel types of connection may be the major joint method for EBC structures.



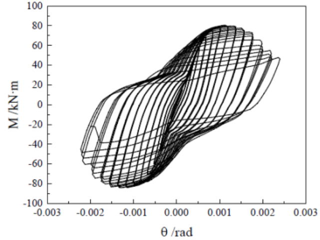
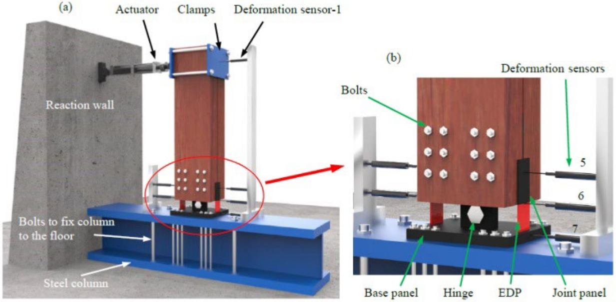


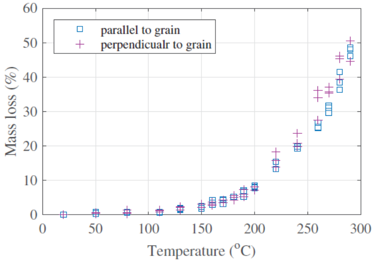
Fig.1 Moment connection for bamboo-steel moment frame; (a) the way of which the connection joints beam and column; (b) working principle of the connection.

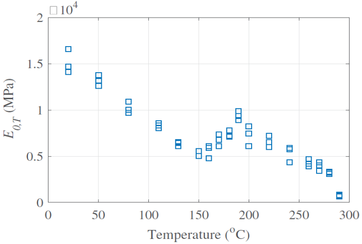
$$M_u = \xi f_u bt(h+t)$$

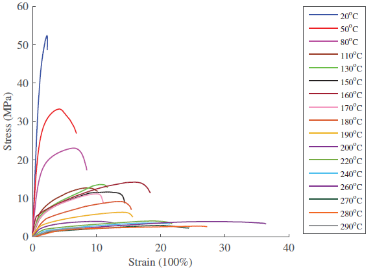
$$\xi = \begin{cases} 0.978 & 6.6 \le \lambda \le 7.2 \\ 0.749 + 1.150e^{-\frac{\lambda}{1.897}} & 7.2 < \lambda \le 16.0 \end{cases}$$

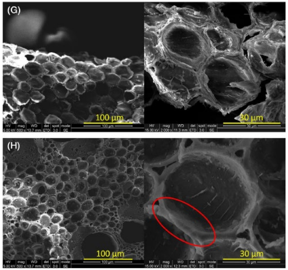


Temperature-depended properties





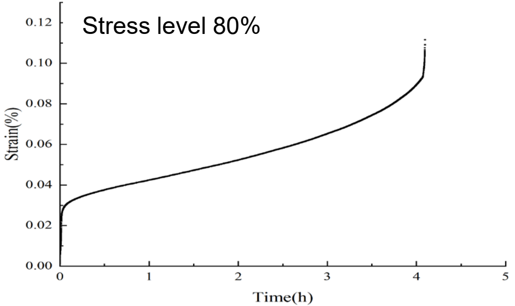


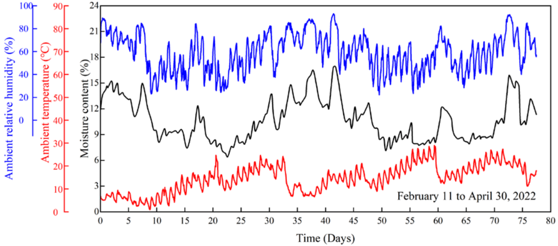


Classical constitutive law based on the assumption of adiabatic prosses no longer validate in case of EBC imposed on high temperature circumstance.

Sensitive to the variation of ambient temperature and humidity: mechano-sorptive creep

Ambient temperature and relative humidity change can drive water moving in or out bamboo materials leading mechano-sorptive creep





What shall we do next?
fill the GAP between material and buildings

The mechanical properties, such as strength, MOE, MOR, etc. are not made as desired.

GAP

1. Performance based manufacturing technique

2. Design philosophy

Solution: Standard of EBC.

THANK YOU