STUDY OF SHORT-TERM FLEXURAL BEHAVIOR FOR GLUE-BAMBOO AND LUMBER BEAMS UNDER DIFFERENT PRE-STRESSED STATES

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ABSTRACT

After a new kind of steel-lumber composite member, named as pre-stress glue-bamboo and lumber beam, was proposed by project team, the bending test was conducted on 12 groups of pre-stress glue-bamboo and lumber beams and 4 groups of ordinary glue-bamboo and lumber beams, and from the ways of failure mode, ultimate load, load-deflection curves and load-strain curves, the influence of pre-stressing tendons number and pre-stress value on glue-bamboo and lumber beams were researched. The result showed that: under the same pre-stress value, with the increase of pre-stressing tendons number, the beam ultimate load and stiffness increased. Under the same pre-stressing tendons number, with the increase of pre-stress value, the beam ultimate load increased, and the stiffness of pre-stressed beams was better than ordinary beams, while the change was small. Compared with ordinary beams, under the same section size, the bearing capacity of pre-stress beams was 1.76~5.66 times of ordinary beams. With the same bearing capacity, pre-stress could save bamboo-lumber composites 13.28%~51.98%, and reduce cost 1.95%~39.61%. Finally, the bearing capacity calculation formula for this kind of member was proposed and verified, which provide a reference for practical engineering.

KEYWORDS

Glue-bamboo and lumber beams, Flexural behaviour, Bearing capacity calculation formula, Pre-stressed

INTRODUCTION

As a kind of excellent building materials, named bamboo and lumber composites, its productivity and strength was higher, its processing was easier, and its toughness was better. [1-2] To let it fully used, especially in the long–span structures, the pre-stress glue-bamboo and lumber beam was proposed by project team, [3] and the materials selection was studied. As a kind of pre-stress flexural member composited by steel and lumber, the pre-stressing tendons number and pre-stress value had a big influence on beam flexural behaviour, so it was necessary for further research.

So far, the research at home and abroad mainly focused on the material properties of bamboo and lumber composite, the flexural behaviour and failure modes of glue-bamboo beams and glue-lumber beams, the flexural behaviour of pre-stress lumber beams, etc. In paper [4], taken small-sized China fir, wood sticks and waste bamboo strip as raw materials, its physical properties, production process and mechanics property were studied. In paper [5], through 10 bamboo beams, the flexural behaviour of this new kind of beams was studied mainly from the aspect of structure member. In paper [6], the pre-stress was applied by tightening the nuts in steel ends, pre-stress glulam and traditional glulam beam were compared. In conclusion, there was no research on pre-stress glum-bamboo and lumber beam, while the above research provided a reference for this paper.

In this paper, the bending test was conducted on 12 groups of pre-stress glue-bamboo and lumber beams and 4 groups of ordinary glue-bamboo and lumber beams, and from failure mode, ultimate load, load-deflection curves and load-strain curves, the influence of pre-stressing tendons number and pre-stress value on glue-bamboo and lumber beams was researched, based on it, the bearing capacity computation formula for this kind of member was proposed.

1. TEST GENERAL SITUATION

1.1 The physics and mechanics behvior of bamboo and lumber composites

In this test, the composite material of reconsolidated bamboo and poplar was glued by PuBang structural glue, a kind of one-component liquid polyurethane adhesive, and combined to 1750-level pre-stressing tendons. And according to current test methods [7], the compressive test was conducted on cylinder specimens with a size of 100 mm×100 mm×300 mm to get its physics and mechanic behavior, as shown in Table 1.

Tab. 1 - Glue-bamboo and lumber blocks along the grain compressive strength test data

items	Ultimate load/ kN	Ultimate compressive strain / MPa	Elastic modulus
Average value	392.76	48.34	10777.75
Standard value	35.17	4.37	1399.41
Variable	0.0896	0.0904	0.1298

Note: all the data in Table 1 was average value.

The tensile test was conducted on 6 pre-stressing tendons, whose length was 200mm, standard distance was 70mm. And its physical and mechanical behavior were obtained, as shown in Table 2.

Tab. 2 - Pre-stressing tendons tensile strength test data

items	Ultimate load/ kN	Ultimate compression strain / MPa	Elastic modulus/ $\times 10^5$ MPa
Average value	66.13	1719.25	2.09
Standard value	0.545	14.170	0.068
Variable coefficient	0.008	0.008	0.033

1.2 Test grouping

To research the influence of pre-stressing tendons number and pre-stress value on glue-bamboo and lumber beams, 36 beams were processed with a size of 3150 mm×80 mm×100 mm, and were divided into 12 groups (3 of each group). According to different research aims, the beams weres divided into 2 batches (named A, B). For A batch, keep the pre-stress value of each group same, and change pre-stressing tendons number, to research its influence on beam stress behaviour, the basic information is shown in Table 3.

Tab. 3 - Basic information of the A batch

No.	Size /mm	Pre-stress value /kN	Tendons strain/$u\varepsilon$	Tendons stress /MPa	Tendons No.
$L_{0\text{-}1}$			0	0	2
$L_{0\text{-}2}$	3150×80×100	0	0	0	4
$L_{0\text{-}3}$			0	0	6
$L_{1\text{-}1}$			126	25.830	2
$L_{1\text{-}2}$	3150×80×100	1.987	63	12.915	4
$L_{1\text{-}3}$			42	8.610	6
$L_{2\text{-}1}$			252	51.66	2
$L_{2\text{-}2}$	3150×80×100	3.975	126	25.830	4
$L_{2\text{-}3}$			84	17.220	6
$L_{3\text{-}1}$			378	77.490	2
$L_{3\text{-}2}$	3150×80×100	5.962	189	38.745	4
$L_{3\text{-}3}$			126	25.830	6

Note: For $L_{m\text{-}n}$, the m represents pre-stress value, m of 1,2,3 respectively presents to 0, 1.987kN, 3.975kN, 5.962kN; the n represents pre-stressing tendons number, n of 1,2,3 respectively presents to 2, 4, 6.

For B batch, keep the pre-stressing tendons number of each group same, and change pre-stress value, to research its influence on beam stress behavior, the basic information was shown in Table 4.

Tab. 4 - Basic information of B batch

No.	Size /mm	Pre-stress value /kN	Tendons strain/$u\varepsilon$	Tendons stress /MPa	Tendons No.
$L_{0\text{-}1}$		0	0	0	
$L_{1\text{-}1}$	3150×80×100	1.987	126	25.830	2
$L_{2\text{-}1}$		3.975	252	51.66	
$L_{3\text{-}1}$		5.962	378	77.490	
$L_{0\text{-}2}$		0	0	0	
$L_{1\text{-}2}$	3150×80×100	1.987	63	12.915	4
$L_{2\text{-}2}$		3.975	126	25.830	
$L_{3\text{-}2}$		5.962	189	38.745	
$L_{0\text{-}3}$		0	0	0	
$L_{1\text{-}3}$	3150×80×100	1.987	42	8.610	6
$L_{2\text{-}3}$		3.975	84	17.220	
$L_{3\text{-}3}$		5.962	126	25.830	

Note: For $L_{m\text{-}n}$, the m represents pre-stress value, m of 1,2,3 respectively presents to 0, 1.987kN, 3.975kN, 5.962kN; the n represents pre-stressing tendons number, n of 1,2,3 respectively presents to 2, 4, 6.

Besides, the bending test was also conducted on 4 groups ordinary glue-bamboo and lumber beams, and its basic information was shown in Table 5.

Tab. 5: Basic information of ordinary Glue-Bamboo and Lumber Beams

No.	Size /mm	Pre-stress value /kN	Tendons strain/*uε*
L_{100}	3150×80×100	0	0
L_{140}	3150×80×140	0	0
L_{180}	3150×80×180		
L_{220}	3150×80×220		

Note: For L_{h}, h represents beam section height.

2. TEST RESULT AND ANALYSIS

2.1 Failure modes

After the loading finished, from beams test results, there were mainly three kinds of failure modes, shown as following:

① The tensile failure of bamboo and lumber composites: for this mode, it mainly appeared in beam tensile area, especially nearby finger joint area, and the bamboo or lumber was broken, which was the most common failure mode, as shown in Figure 1.

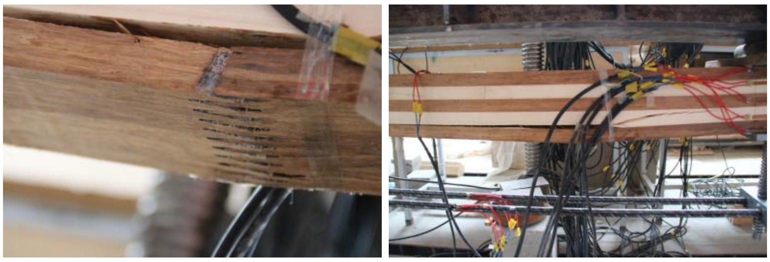

Fig. 1 - The tensile failure in finger joint ($L_{2\text{-}2\text{-}1}$)

② The tensile failure of pre-stressing tendons: for individual beams, the tensile failure of pre-stressing tendons was appeared in deviator. The reason was that for one beam pre-stressing tendons, it had a size deviation, which would let oversize strain appeared in one tendon, besides, there was stress concentration in the contact position between this tendon and deviator, so tensile failure was easily appeared in this tendon, as shown in Figure 2.

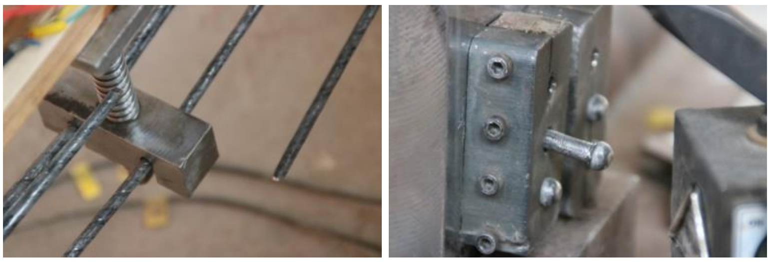

Fig. 2 - The tensile failure of pre-stressing tendons ($L_{3\text{-}2\text{-}3}$)

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③ The local compression failure in beam ends: in anchor device position, the concentrated moment was bigger, therefore, when the load bigger or there were finger joints in beam ends, the local compression failure in beam ends appeared, as shown in Figure 3.

Fig. 3 - Local compression failure in beam ends ($L_{1\text{-}3\text{-}1}$)

The failure modes of all beams were shown in Table 6. The change of pre-stressing tendons number and pre-stress value had little influence on a beam failure mode, and the failure was mainly caused by finger joints. While the subsequent analysis showed that with the increase of pre-stressing tendons number and pre-stress value, the tensile failure near finger joints was not avoided, but it could be put off.

2.2 The pre-stressing tendons number influence

2.2.1 Ultimate

Under different pre-stressing tendons number, the beams ultimate load and failure modes were shown in Table 6.

Tab. 6 - The ultimate load under different pre-stressing tendons number

Pre-stress value /kN	No.	Tendons number	Failure mode	Ultimate load /kN	Average ultimate load /kN
0	$L_{0\text{-}1}$	2	③	13.5	15.1
			①	16.91	
			①	14.89	
0	$L_{0\text{-}2}$	4	③	22.47	20.72
			①	20.6	
			①	19.09	
0	$L_{0\text{-}3}$	6	①	27.7	28.14
			①	27.65	
			①	29.07	
1.987	$L_{1\text{-}1}$	2	①	22.15	25.38
			③	29.23	
			①	24.76	
1.987	$L_{1\text{-}2}$	4	①	26.78	28.54
			③	29.53	

			①	29.31	
1.987	$L_{1\text{-}3}$	6	③	29.65	31.17
			③	32.69	
			①	21.81	
3.975	$L_{2\text{-}1}$	2	③	24.87	26.32
			①	27.57	
			①	26.52	
3.975	$L_{2\text{-}2}$	4	①	27.1	32.05
			③	36.29	
			③	32.76	
3.975	$L_{2\text{-}3}$	6	③	32.91	35.27
			①	38.13	
			③	34.77	
5.962	$L_{3\text{-}1}$	2	③	28.47	28.86
			①	27.83	
			①	30.28	
5.962	$L_{3\text{-}2}$	4	③	38.19	39.61
			①	38.54	
			②	42.1	
5.962	$L_{3\text{-}3}$	6	③	30.06	42.27
			③	41.22	
			①	43.32	

Table 6 shows that under the same pre-stress value, with the increase of pre-stressing tendons number, the beam ultimate load increased. Compared to the beams with 2 tendons were arranged, when 4 tendons were arranged, the ultimate load increased about 12.45%~37.25%; when 6 tendons were arranged, the ultimate load increased about 22.81~86.3%.

2.2.2 Load-deflection curves

Under the same pre-stress value (1.987kN), the beam load-deflection curves under different pre-stressing tendons number was shown in Figure 4. In which, the x represents beam mid-span deflection, and taken initial moment deflection as zero, and download was plus direction; the y represents load. For other beams that of different pre-stress value, their load-deflection curves tendency was similar with Figure 4, only numerical differ, so in this paper only above results were given.

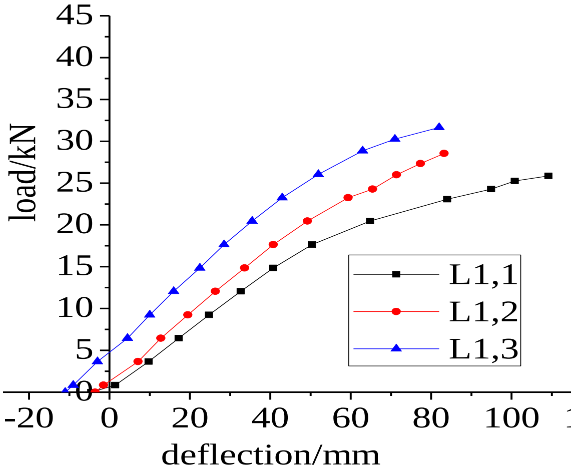
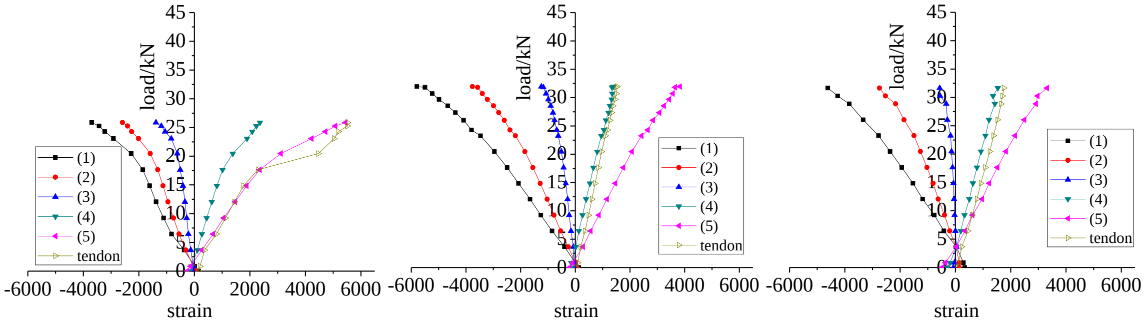


Fig. 4 - Under the same pre-stress value (1.987kN), the beam load-deflection curves

Figure 4 shows that, when the load was less than 60~70% of ultimate load, the curves were basically linear, then the beam stiffness gradually degenerate. With the increase of pre-stressing tendons number, the stiffness increased, that was to say, under the same load, the deflection was smaller. When the load reached to ultimate load, the deflection of each beams had not much difference.

2.2.3 Load-strain curves

To research the strain development law of beam each laminates and pre-stressing tendons, according to the trisection position strain value, the load-strain curves were given, as shown in Figure 5. In which, (1) ~ (5) represents laminates number. And the x represents strain value, taken tensile as positive, and the unit was με; the y represents load, and download was plus. Similarly, in this paper, only the dates that under the pre-stress value of 1.987kN were given.



L$_{1\text{-}1}$ *L*$_{1\text{-}2}$ *L*$_{1\text{-}3}$

Fig. 5 - Under same pre-stress value (1.987kN), the beam load-strain curves

Figure 5 shows that, with the increase of pre-stressing tendons number, the strain distribution of each laminates was more uniform, which conducive to make full use of materials strength.

2.3 The pre-stress value influence

2.3.1 Ultimate

Under the different pre-stress value, the ultimate load and failure modes was shown in Table 7.

Tab. 7 - The ultimate load under different pre-stress value

Tendons number	No.	Pre-stress value/kN	Failure mode	Ultimate load/kN	Average ultimate load/kN
2	L_{0-1}	0	③	13.50	15.10
			①	16.91	
			①	14.89	
2	L_{1-1}	1.987	①	22.15	25.38
			③	29.23	
			①	24.76	
2	L_{2-1}	3.975	③	24.87	26.32
			①	27.57	
			①	26.52	
2	L_{3-1}	5.962	③	28.47	28.86
			①	27.83	
			①	30.28	
4	L_{0-2}	0	③	22.47	20.72
			①	20.60	
			①	19.09	
4	L_{1-2}	1.987	①	26.78	28.54
			③	29.53	
			③	29.31	
4	L_{2-2}	3.975	①	27.10	32.05
			③	36.29	
			③	32.76	
4	L_{3-2}	5.962	③	38.19	39.61
			①	38.54	
			②	42.10	
6	L_{0-3}	0	①	27.70	28.14
			①	27.65	
			①	29.07	
6	L_{1-3}	1.987	③	29.65	31.17

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			③	32.69	
			①	21.81	
6	L_{2-3}	3.975	③	32.91	35.27
			①	38.13	
			③	34.77	
6	L_{3-3}	5.962	③	30.06	42.27
			③	41.22	
			①	43.32	

Table 7 shows that, under the same pre-stressing tendons number, with the increase of pre-stress value, the beam ultimate load increased. Compared to the beams with 0 pre-stress value, when the pre-stress value was 1.987kN, the ultimate load increased about 10.77%~68.08%; when the pre-stress value was 3.975kN, the ultimate increased 25.34%~61.06%; when the pre-stress value was 5.962kN, the ultimate increased 50.21%~91.17%. The more the pre-stress value, the larger the ultimate load and enlargement.

2.3.2 Load-deflection curves

With the same 4 pre-stressing tendons, the beam load-deflection curves under different pre-stress value number were shown in Figure 6. For other beams that of different pre-stressing tendons number, their load-deflection curves tendency was similar with Figure 6, only numerical differ, so in this paper only above results were given.

Figure 6 shows that, when the load less than 75~85% of ultimate load, the curves were basically linear, after that the stiffness gradually degenerate. The stiffness of pre-stress beam was better than ordinary beam, while with the increase of pre-stress value, the change was little. With high pre-stress value, there was certain buckling in beam top surface, so the ultimate load and whole deformation ability had a certain improvement.

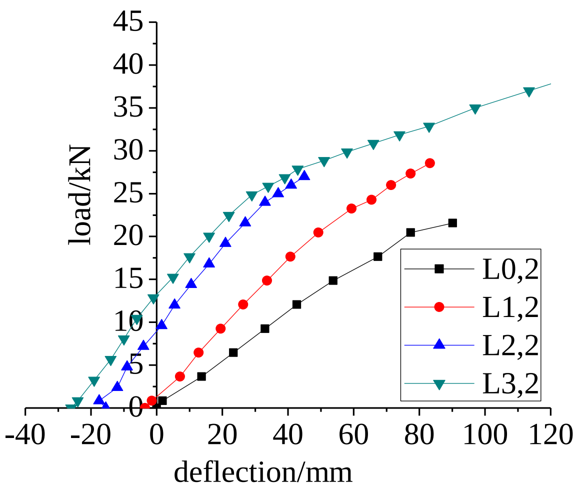

Fig. 6 - Under the same 4 pre-stressing tendons, the beam load-deflection curves

2.3.3 Load-strain curves

To research the strain development law of beam each laminates and pre-stressing tendons, the load-strain curves were given, as shown in Figure 7. Similarly, in this paper, only the dates that under 4 pre-stressing tendons were given.

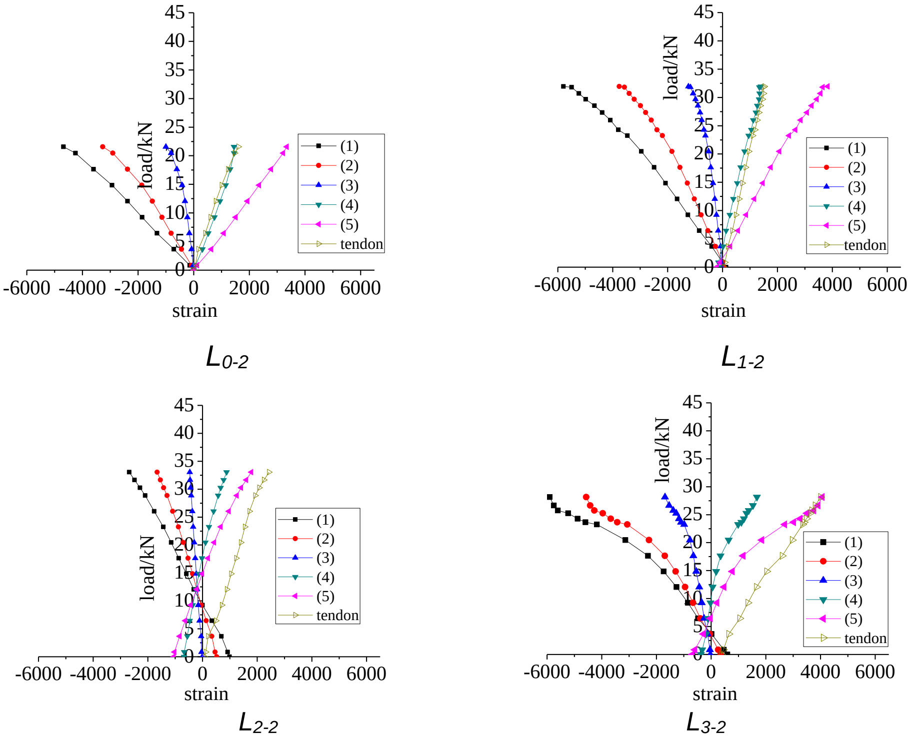

Fig. 7 - Under same 4 pre-stressing tendons, the beam load-strain curves

Figure 7 shows that, in initial loading process, because of the reverse arch action that caused by pre-stress, there was opposite strain in each laminates, and with the increase of load, the reverse arch action was been offset, and the strain had an inversion. With the increase of the pre-stress value, the compression time of laminate 4 and 5 became longer, and the laminates in beam bottom surface also showed certain plastic behaviour, the bamboo and lumber composites force more fully, and the beam ultimate load became larger.

2.4 The comparative analysis of pre-stress beams and ordinary beams

To verify the rationality and economic efficiency of pre-stress glue-bamboo and lumber beams, in this paper, the comparative test was conducted on 4 kinds of ordinary glue-bamboo and lumber beams, and the failure modes and ultimate load were shown in Table 8. Then, the load-deflection curves between pre-stress beams (with the pre-stress value of 5.962kN) and ordinary beams were given, as shown in Figure 8.

Tab. 8 - The ultimate load of ordinary glue-bamboo and lumber beams

No.	Failure mode	Ultimate load /kN	Average ultimate load /kN
L_{100}	①	7.66	7.66
L_{140}	①	25.71	24.66
	①	24.31	
	③	23.97	
L_{180}	①	24	39.86
	①	39.35	
	①	40.37	
L_{220}	①	41.77	42.82
	①	43.86	
	①	33.16	

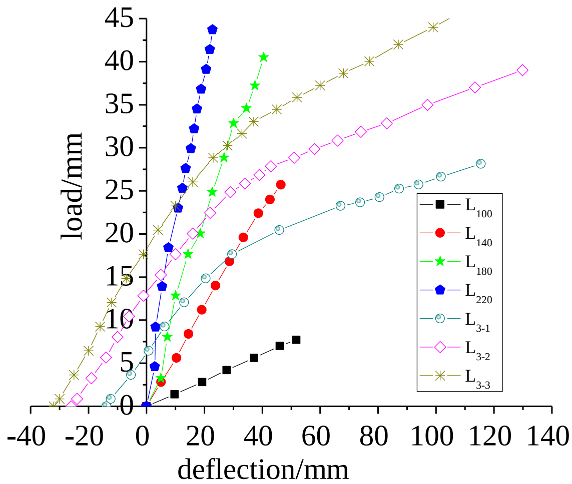

Fig. 8 - The load-deflection curves between pre-stress beams (with the pre-stress value of 5.962kN) and ordinary beams

By comparative analysis one could know, under the same section size, after pre-stress applied, the beam bearing capacity was 1.76~ 5.66 times higher than ordinary beams; under the same bearing capacity, compared with ordinary beam, the pre-stress beam could save material 13.28%~51.98%, and could save cost 1.95%~39.61%. Besides, the pre-stress beams ductility was better than ordinary beams.

3 THEORETICAL ANALYSIS

3.1 The verification of plane cross-section assumption

To verify the plane cross-section assumption and to research the development law of pre-stress beams trisection position strain, one typical beam in each group was selected to draw its section height-strain curves, as shown in Figure 9. For other beams that of different pre-stressing tendons number, their section height-strain curves tendency was similar with Figure 9, only numerical differ, so in this paper only above results were given.

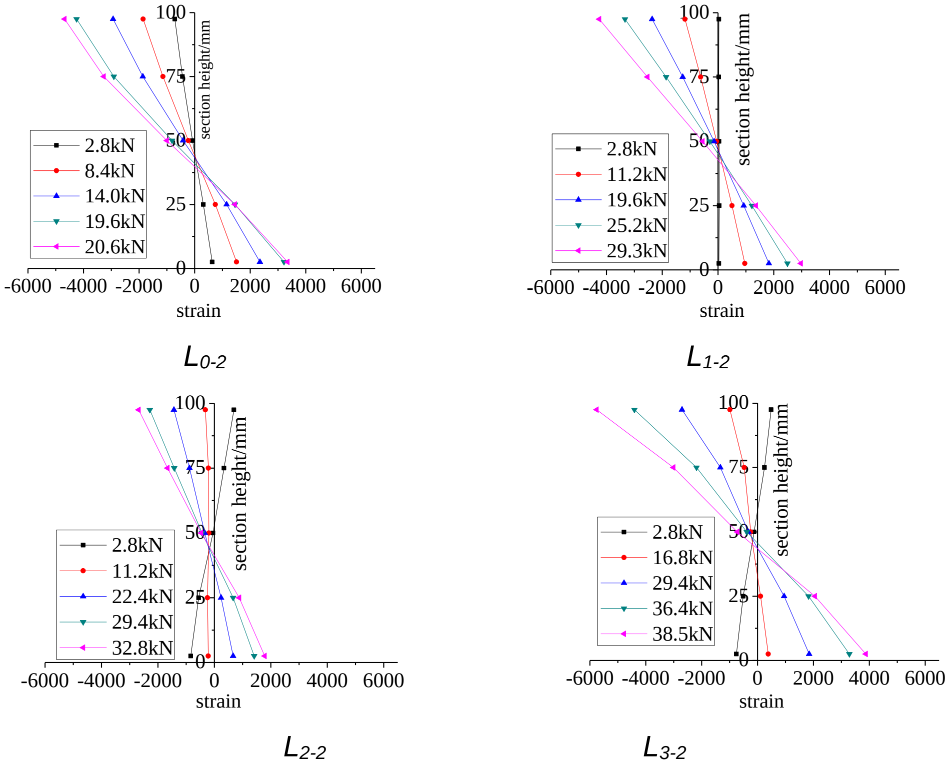

Fig. 9 - The section height-strain curves of pre-stress beams with 4 pre-stressing tendons

From Figure 9 one could know, in load increase process, with the increase of pre-stress value, the beam neutral axis was gradually down. In whole, the pre-stress beams trisection position strain basically conformed to linear, which was accord with plane across-section assumption.

3.2 Bearing capacity checking

The calculation model of pre-stress glue-bamboo and lumber beams was shown in Figure 10.

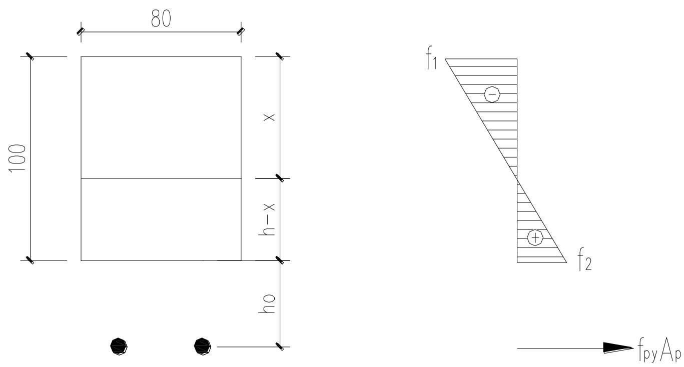

Fig. 10 - The calculation diagram

The tensile and compression strain of bamboo and lumber composites, the tensile strain of tendons, and the load stratified with force and moment balance, therefore, the Equation 1, 2 could be derived.

$$\frac{f_1 x}{2} b - \frac{f_2 (h-x)}{2} b - \sigma_p A_p = 0 \tag{1}$$

$$M = \frac{f_1 x}{2} b (h_0 + h - \frac{x}{3}) - \frac{f_2 (h-x)[h_0 + (h-x)/3]}{2} b \tag{2}$$

Meanwhile, by triangle similarity, the beam top surface compression strain and beam bottom surface tensile strain met following relationship:

$$\frac{f_1}{x} = \frac{f_2}{h-x} \tag{3}$$

In which: b——Beam section width;

h——Beam section height;

f_1——The bamboo and lumber composites compressive strength design value ;

f_2——The bamboo and lumber composites tensile strength design value;

σ_p——The pre-stressing tendons tensile strength design value;

A_p—— Section area of pre-stressing tendons；

x——Beam compressive zone height；

h_0——Distance between pre-stressing tendons center and beam bottom surface;

M——the moment design value of beam trisection position;

According to the materials strength obtained from test, the trisection position moment calculation value (simplified as CM) could be calculated, and then compared with the moment value obtained from test (simplified as TM), to verity the rationality of above formulas, as shown in Table 9.

Tab 9 - Verification of beam bearing capacity calculation formulas

No.	h_0 /mm	A_p /m^2	x /mm	CM /kN·m	TM /kN·m	CM/TM /%
L_{0-1}	40.1	76.93	46.44	6.87	7.44	92.34
L_{0-2}	43.82	153.86	80.38	11.19	10.30	108.64
L_{0-3}	42.06	230.79	114.32	14.14	13.85	102.09
L_{1-1}	76.22	76.93	46.44	8.86	12.38	71.57
L_{1-2}	75.00	153.86	80.38	14.17	14.66	96.66
L_{1-3}	77.54	230.79	114.32	18.97	14.83	127.92
L_{2-1}	104.42	76.93	46.44	10.41	12.44	83.68
L_{2-2}	101.74	153.86	80.38	16.72	16.38	102.08
L_{2-3}	103.63	230.79	114.32	22.52	16.46	136.82
L_{3-1}	125.86	76.93	46.44	11.59	13.92	83.26
L_{3-2}	127.18	153.86	80.38	19.16	19.27	99.43
L_{3-3}	126.58	230.79	114.32	25.65	21.66	118.42

Table 9 shows that, the average percentage value between calculation moment value and test moment value was 101.91%, which showed a higher coincidence. Thus, if the pre-stressing tendons number and pre-stress value were in the range given from this paper, the above bearing capacity calculation formula could be used for a reference for practical engineering.

CONCLUSION

(1) Under the same pre-stress value, with the increase of pre-stressing tendons number, the beam ultimate load and stiffness increased. Compared to the beams with 2 tendons were arranged, when 4 tendonss were arranged, the ultimate load increased about 12.45%~37.25%; when 6 tendons were arranged, the ultimate load increased about 22.81~86.3%.

(2) Under the same pre-stressing tendons number, with the increase of pre-stress value, the beam ultimate load increased. Compared to the beams with 0 pre-stress value, when the pre-stress value was 1.987kN, the ultimate load increased about 10.77%~68.08%; when the pre-stress value was 3.975kN, the ultimate increased 25.34%~61.06%; when the pre-stress value was 5.962kN, the ultimate increased 50.21%~91.17%. The more the pre-stress value, the larger the ultimate load increase enlargement. The stiffness of pre-stress beams was better than ordinary beams, while with the increase of pre-stress value, the stiffness change was very small.

(3) Compared with ordinary beams, under the same section size, after pre-stress applied, the beam bearing capacity was 1.76~ 5.66 times higher than ordinary beams; under the same bearing capacity, the pre-stress beam could save material 13.28%~51.98%, and could save cost 1.95%~39.61%.

(4) After the verificaton of plane cross-section assumption, the beam bearing capacity calculation formula was given, which provided a reference for practical engineering.

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