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The Experimental Research on the Flexural Behavior of Steel Plate Strengthened Pre-stress Glue-lumber Beams

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Abstract: In this paper, the experimental research was conducted on the flexural behavior of 18 steel plate strengthened pre-stress glue-lumber beams (the steel plate was fixed by glue or glue & screws), and compared it with ordinary steel plate strengthened glue-lumber beams (simplified as OB). The results showed that, compared with OB, when the 2mm or 3mm thick steel plate was glued, the bearing capacity was similar, while when 4mm thick was glued, there were no separation between glue-lumber and steel plate, and the bearing capacity improved by 19.5%; when the same thick steel plate was glued and fixed it by screws, its bearing capacity had no much difference, while the probability of out-of-plane stability increased. With the increase of steel plate thickness, the beam deformability increased, and compared with OB, the deflection decreased obviously, and the pre-stress had no influence on beam stiffness. The section strain of steel plate strengthened pre-stressed glue-lumber beam was accorded with plane section assumption, therefore, for this kind of member, on the basis of tensile and compressive failure mode, the bending capacity calculation formula was proposed, and compared it with experimental results, the average error between theoretical value and experimental value was no more than 10%.

Keywords: *steel plate strengthened pre-stress glue-lumber beam; flexural behavior; experimental research; failure mode; bearing capacity calculation*

1. Introduction

In General, to improve beam bearing capacity and stiffness, different kinds of new materials were arranged on the bottom of strengthened glue-lumber beams, like metal, FRP and so on[1-2]. While in common, because of the big difference of strength between lumber and new materials, the materials strength was often not fully used and the beam had big deformation after bending. To decrease the strengthened beams deformation, in this paper, the device for pre-stress application was prepared, and a new kind of composite member, named steel plate strengthened pre-stressed glue-lumber beam was formed, for which, the compression was bore by glue-lumber and the tensile was bore by steel plate, so the bearing capacity was improved, the deformation was decreased, besides, the lumber and steel plate strength was fully used.

At present, for pre-stress lumber beams, the pre-research mainly concentrated on two aspects: one was tensioning wire, and the other was tensioning fiber materials. For the former, in [3], the pre-stress apply method of beam string was proposed, and by 1:2 model experiment, confirmed that the stiffness of this member was larger than ordinary lumber beams; in [4], the grooves were opened on beam top and bottom surface, and put steel bars in them, then irrigate resin, and the pre-stress was applied by tightening the nuts which in the steel bars ends; in [5], the finite element analysis that on bending behavior of pre-stressed glue-lumber string beams was conducted, and compared with lumber beam of same section, the ultimate load was increased by 109.37%~157.32%. For the latter, in [6-8], the experimental research on pre-stress fiber materials strengthened lumber beams was conducted, and a pre-stress apply method, named pre-bending method, was proposed, and by theoretical analysis, the calculation method that on the basis of plane section assumption was given. In conclusion, the above research provided a reference for the acquaintance of pre-stress influence on lumber beams stress and deformation performance, while there were no research on steel plate strengthened pre-stress lumber beams, and for pre-stress apply by steel bars, it need to open grooves in beam bottom surface, which break beam integrality, complicate pre-stress application, and hard to popularize.

In this paper, there were 18 beams (6 groups), in which, the steel plates were fixed by glue or glue and screws, to research the influence of steel plate thickness, screws arrangement or not on beam failure modes, bearing capacity and deformability, and then, compared it with the ordinary steel plate strengthened beams that proposed in [9]. Besides, bending capacity calculation formula for steel plate strengthened pre-stress glue-lumber beams was built, to facilitate the promotion for such members.

2. Experiment basic information

2.1 Material property

The glue-lumber material was scotch pine, and the steel plate was Q235, the glue between glue-lumber and steel plate was HBS-JZG. The materials physical and mechanical properties were obtained from current code experiments result [10-11].

2.2 Experiment design and grouping

The beam section size was 50 mm×150 mm, and the span was 2850 mm, and the beam span direction was along lumber longitudinal direction, without finger-joint influence.

In this experiment, there were two steel plate strengthened methods: first, only glue was used, which simplified as "g"; and second, both glue and screws were used, which simplified as "s". According to the steel plate fixation method and thickness, the 18 beams were divided in several groups, the detail information was shown in Table.1 and Figure.1.

***Table 1** Beam groups information*

Group	Beam No.	Steel plate thickness /mm
PBgd-2	PBgd-2(1)	2
	PBgd-2(2)	
	PBgd-2(3)	
PBgd-3	PBgd-3(1)	3
	PBgd-3(2)	
	PBgd-3(3)	
PBgd-4	PBgd-4(1)	4
	PBgd-4(2)	
	PBgd-4(3)	
PBsd-2	PBsd-2(1)	2
	PBsd-2(2)	
	PBsd-2(3)	
PBsd-3	PBsd-3(1)	3
	PBsd-3(2)	
	PBsd-3(3)	
PBsd-4	PBsd-4(1)	4
	PBsd-4(2)	
	PBsd-4(3)	

Note: in Table.1, "PB" represents pre-stress beam; "g" represents the steel plate was fixed only by glue; "s" represents the steel plate was fixed by glue and screws; "d" represents the steel plate was fixed in beam down surface; the number after "-" represents the steel plate thickness (unit: mm); the number in bracket represents beam amount number. For example, for "PBgd-4(1)": this was a pre-stressed beam, and the 4mm steel plate was arranged in beam down surface and fixed only by glue, and this was the first beam of this group.

a. Fixed by glue *b. Fixed by glue and screws*

***Figure 1** Beam composite form*

2.3 Longitudinal pre-stress application device and transverse forcing device

For steel plate strengthened glue-lumber beams, to pre-stress application, a longitudinal tension device was designed in this paper, as shown in Figure.2 and Figure.3.

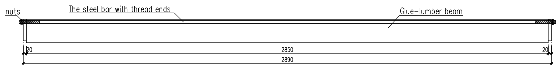

***Fig.2** The front view of longitudinal pre-stress application device*

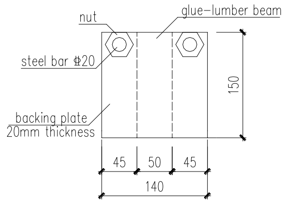

***Figure 3.**The side view of longitudinal pre-stress application device*

From front view could know: across backing plates, the steel bars were fixed in beam end section, and there were a certain length of thread in steel bar's two ends. Then, the tension stress could be controlled accurately by nuts tightening circle number, and the aim of pre-stress application on steel plate strengthened glue-lumber beams was realized. From side view could know: the size of backing plate was 150 mm×150 mm×20 mm, and was arranged in center of beam, and there were two holes to let steel bars (diameter:20 mm) across it, so the steel bars could be fixed steadily and the pre-stress could be applied uniformly. The actual device was shown in Figure.4.

***Figure 4.**Actual pre-stress application device*

In order to realize the pre-stress application and uniform bond between glue-lumber and steel plate, the longitudinal pre-stress application device and transverse forcing device (which proposed from [15]) was used cooperatively, as shown in Figure.5.

***Figure 5.**Transverse forcing device*

This pre-stress application method had following advantages: had no destruction in beam section; for pre-stress application, the steel bar was tensioned along longitudinal direction, which let beam height decreased, and convenient for construction and actual application; the backing plates made the stress uniformly passed to glue-lumber beam, which let the local compression failure caused by stress concentration be avoided.

2.4 Pre-stress control and data collection

When steel bars were tensioned, the beam top was in tension, and the beam bottom was in compression. To avoid the stress exceed material ultimate strength, the beam top and bottom strain need to be controlled. By compression and tension strength and elasticity modulus of scotch pine, could obtained the ultimate compression strain was 1100 με, and the tension strain was 850 με, and the steel bars max stress at this time was only 20% of its design strength, which was far from its ultimate strength. The pre-stress application process was finished by either beam top or bottom strain reached to ultimate value. Besides, the strain data was red from the static stress and strain test and analysis system DH3816, and the inverted arch value was measured by tapeline.

3. Experiment results and analysis

3.1 Main experiment phenomenon

For pre-stress beams whose steel palates were fixed only by glue, their representative failure modes under bending were shown in Figure.6.

From Figure.6 could know, when 2 mm or 3 mm steel plates were affixed, the brittle failure caused by beam bottom tension stress was appeared; when 4 mm steel plates were affixed, the ductile failure caused by beam top compression stress was appeared, without tackless. The reason was that, after pre-stress application, there was cooperation deformation between steel plates and glue-lumber, so there were initial tension stress in steel plates, and the steel plates yielding was prior to OB. After yielding, the steel plates quit job in advance, then the tension stress was borne by bottom layer glue-lumber, until cracking appeared, the stress released instantly, and the tackless appeared, which led failure mode changed from beam top compression to bottom tension when 3 mm steel plates were affixed; and led the beam top wrinkles appeared before glue reached to its strength when 4 mm steel plates were affixed.

PBgd- 2(2)

PBgd-3(2)

PBgd-4(1)

Figure 6.*The failure modes of beams fixed by glue*

For pre-stress beams whose steel plates were fixed by both glue and screws, their representative failure modes under bending were shown in Figure.7.

PBsd-2(3)

PBsd-3(1)

PBsd-4(1)

Figure 7.*The failure modes of beams fixed by glue and screws*

From Figure.7 could know, with the increase of steel plate thickness, the failure mode changed from beam bottom tension to beam top compression, and without large area tackles. The reason was that screws let the bond between steel plate and glue-lumber more securer. When 2 mm or 3 mm steel plates were affixed, after unloading, both steel plate and glue-lumber had reverse arch, which reveal the steel plate had been yielded, and there was no obvious phenomenon in beam top surface. When 4 mm steel plates were affixed, after unloading, the steel plates and glue-lumber still tightly bond, and there were wrinkles in beam top surface.

3.2 Failure modes

The failure modes of each beam were shown in Table.2.

Table 2.*The failure modes of each beam*

Group	Beam No.	Failure mode
PBgd-2	PBgd-2(1)	Tear failure
	PBgd-2(2)	Beam bottom tension
	PBgd-2(3)	Beam bottom tension
PBgd-3	PBgd-3(1)	Beam bottom tension
	PBgd-3(2)	Beam bottom tension
	PBgd-3(3)	Beam bottom tension
PBgd-4	PBgd-4(1)	Beam top compression
	PBgd-4(2)	Out-of-plane instability
	PBgd-4(3)	Out-of-plane instability
PBsd-2	PBsd-2(1)	Beam bottom tension
	PBsd-2(2)	Tear failure
	PBsd-2(3)	Beam bottom tension
PBsd-3	PBsd-3(1)	Beam bottom tension
	PBsd-3(2)	Out-of-plane instability
	PBsd-3(3)	Out-of-plane instability
PBsd-4	PBsd-4(1)	Beam top compression
	PBsd-4(2)	Tear failure
	PBsd-4(3)	Tear failure

Table.2 showed that there were four failure modes, including beam bottom tension failure, tear failure, beam top compression failure, out-of-plane instability failure. Compared with OB proposed in [15], instead of tackless failure, there was out-of-plane instability failure, whose failure phenomenon was that the beam had an out-of-plane incline, then the supports had an incline, and then the local compression was appeared in three-divide points (as shown in fig.8), besides, there were cracks in bottom layer glue-lumber (as shown in Fig.9). The beam state after out-of-plane instability was shown in Figure.10.

There were two reasons led the appearance of out-of-plane instability. First, in the pre-stress application process, the steel bars were alternately tightening, which may lead to stress difference in two steel bars, and then lead to asymmetrical section stress. Second, the increase of steel plate thickness led its deformability increased, and the plastic deformation in beam top surface was fully developed, and in loading process, the possibility of instability appearance was bigger than beams with thinner steel plate or weaker deformation ability.

Figure 8.*The local appearance of out-of-plane instability*

Figure 9.*The strain gage was broken in tension stress*

Figure 10.*The beam state after out-of-plane instability*

3.3 Failure load

The failure load of each beam was concluded and summarized, and compared it with OB proposed in [15], which was shown in Table.3. In which, "EV" represents "experimental value", "AV" represents "average value".

Table 3.*The Comparison of failure load*

Beam No.	Failure load /kN		Beam No.	Failure load /kN	
	EV	AV		EV	AV
PBgd-2(1)	20.35	21.22	Bgd-2(1)	17.87	22.80
PBgd-2(2)	18.75		Bgd-2(2)	25.97	
PBgd-2(3)	24.58		Bgd-2(3)	24.57	
PBgd-3(1)	23.26	26.52	Bgd-3(1)	25.10	27.46
PBgd-3(2)	30.75		Bgd-3(2)	29.45	
PBgd-3(3)	25.54		Bgd-3(3)	27.81	
PBgd-4(1)	28.64	27.62	Bgd-4(1)	23.21	23.11
PBgd-4(2)	-		Bgd-4(2)	20.35	
PBgd-4(3)	26.60		Bgd-4(3)	25.78	
PBsd-2(1)	26.12	24.58	Bsd-2(1)	-	22.80
PBsd-2(2)	26.60		Bsd-2(2)	25.10	
PBsd-2(3)	21.03		Bsd-2(3)	21.27	
PBsd-3(1)	25.83	26.35	Bsd-3(1)	28.06	27.46
PBsd-3(2)	20.73		Bsd-3(2)	27.96	
PBsd-3(3)	32.50		Bsd-3(3)	22.92	
PBsd-4(1)	28.74	29.27	Bsd-4(1)	24.25	23.11
PBsd-4(2)	29.51		Bsd-4(2)	-	

PBsd-4(3)	29.61	Bsd-4(3)	36.21

Note: for PBgd-4(2), there were some big knags in beam mid-span bottom surface, which led lateral instability appeared in loading process, and did not express its stress characteristics accurately; for Bsd-2(1), the big knag in beam mid-span bottom surface led abnormal data.

From Table.3 could know, with the increase of steel plate thickness, the beam bearing capacity increased, too. Compared with OB, when 2 mm or 3 mm steel plates were affixed (only glue was used) and pre-stress was applied, the beam bearing capacity had little difference, even slightly smaller; when 4 mm steel plates were affixed and pre-stress was applied, the beam bearing capacity increased 19.5%. The reason was that, after pre-stress application, the steel plates yielding was prior to OB, the beam bottom untimely failure led its bearing capacity decreased. While, when 4 mm steel plates were affixed, the failure mode changed from tackless failure to top compression failure, which led the steel plate strength was fully used and the bearing capacity was obviously improved.

Compared with OB (both glue and screws were used), the pre-stress application had little influence on beam bearing capacity. The reason was that, the use of screws led the bond between steel plate and glue-lumber tightly, and the pre-stress application only led steel plate reached to its yield strength in advance and let the plastic deformation increased, while there were little influence on beam bearing capacity.

3.4 Comparison and analysis of load-deformation relation curves

From beams of each group, select a typical beam to draw its load-deformation relation curve (*P-f*), as shown in Figure.11, then compared it with OB proposed in [15].

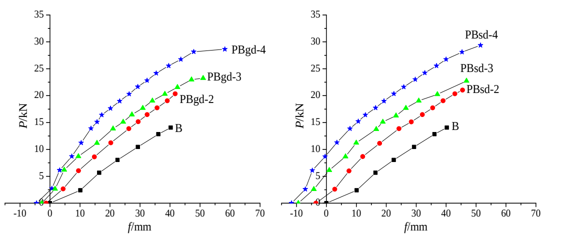

Figure 11.*The "P-f" curves of pre-stress beams*

From Table.3 and Figure.11 could know, for beams whose steel plate was only fixed by glue, with the increase of steel plate thickness, its deformability increased, and what different from OB was that, it had no tackless failure, and deformability was bigger. For beams whose steel plate was fixed by both glue and screws, with the increase of steel plate thickness, its deformability increased, which was same to OB.

For ordinary beams and pre-stress beams, either the steel plate was fixed by glue or by glue and screws, their "*P-f*" curves were shown in Figure.12.

From Figure.12 could know: the pre-stress application had little influence on beam stiffness; under same load, the pre-stress application led beam deformation smaller, there were two reasons: first, the reverse arch caused by pre-stress offset some deflection caused by loading; second, the pre-stress led steel plate yield in advance, and beam reached to failure state earlier. For PBgd-4, its ultimate deformability was obviously improved, the reason was that, for Bgd-4, because of glue strength insufficient, the tackless failure appeared, and then its deformability declined.

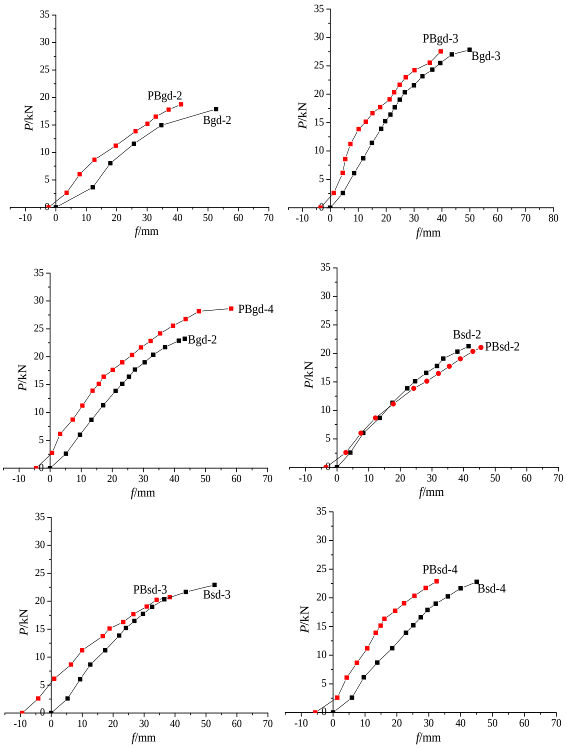

Figure 12.*The "P-f" curves of pre-stress beams and ordinary beams*

4. Theoretical analysis

4.1 Verification of plane section assumption

For beams in each group that listed in tab.1, two typical beams were selected, and their mid-span section-strain relation curves were shown in Figure.13.

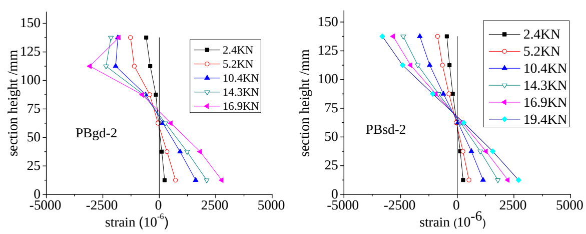

Figure 13.*The mid-span section-strain relation curves of two typical beams*

Form Figure.13 could know, under each level load, the beam mid-span strain along section height direction was basically follow linear distribution. When load closed to its ultimate value, there were individual curves did not conform this law, which had stress mutation. The reason was that big beam deformation led strain gage broken, while there was no influence on whole linear trend, besides, the curves of other groups were similar to Figure.13, which expressed that the beam section stress distribution was accord with plane section assumption.

4.2 Bending capacity calculation formula

According to above analysis, the pre-stress had little influence on beam bearing capacity. When the steel plate reached to its able-yield max thickness, the beam bearing capacity could be improved [12]. Therefore, the bending capacity calculation formula was inferred by OB.

In inference process, the following assumptions were used: first, under bending state, the beam section stress distribution accord with plane section assumption; second, for glue-lumber, its elasticity modulus under tension and compression was same; third, the influence of steel plate and glue thickness on total beam height was ignored, and the influence of steel plate shear slip was ignored, too; fourth, for glue-lumber compression area, the elastic-plastic stress-strain relation curve was used, as shown in Figure.14; fifth, for glue-lumber tension area, the elastic stress-strain relation curve was used, as shown in Figure.14.

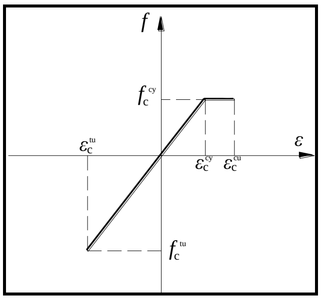

Figure 14.*The stress-strain relation curve of glue-lumber*

A. Tension failure

For tension failure, the beam section stress-strain relation curve was shown in Figure.15.

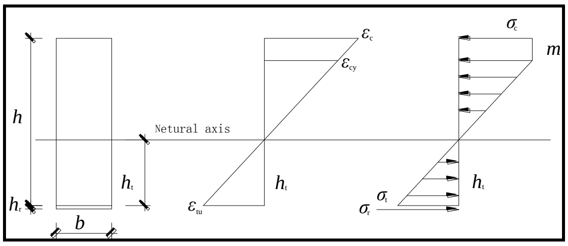

Figure 15.*The section stress-strain relation curve for tension failure*

Under tension failure, the tension stress reached to its ultimate value ($\sigma_t=f_{tu}$); when steel plate yield ($\sigma_r=f_y$), there was plastic deformation in compression area, while it did not reached to its ultimate stress value, that was to say, $\varepsilon_{cu}>\varepsilon_c>\varepsilon_{cy}$, and there was a plastic area whose height was m.

From Figure.15, the equilibrium relation formula of force and moment was obtained:

$$\sigma_c m b+\frac{1}{2}\sigma_c b(h-h_t-m)=\sigma_r h_r b+\frac{1}{2}h_t\sigma_t b \quad (1)$$

$$M=\sigma_c mb\times(h-\frac{m}{2})+ \frac{1}{2}\sigma_c\times(h-h_t-m)\times b\times\left[\frac{2}{3}(h-h_t-m)+h_t\right]-\frac{1}{6}h_t^2\sigma_t b \quad (2)$$

In which:

h——beam section height;
h_t——beam section tension height;
h_r——steel plate thickness;
b——beam section width;
m——beam section plastic area height;
σ_c——beam top surface compression stress;
σ_t——beam bottom surface tension stress;
σ_r——steel plate tension stress;
M——beam section moment design value.

In formula (1), there were two unknown number m and h_t, which need similar triangles relation in FIG.15 ($\frac{\sigma_t}{\sigma_c}=\frac{h_t}{h-h_t-m}$) to solve.

B. Compression failure

For compression failure, the beam section stress-strain relation curve was shown in Figure.16.

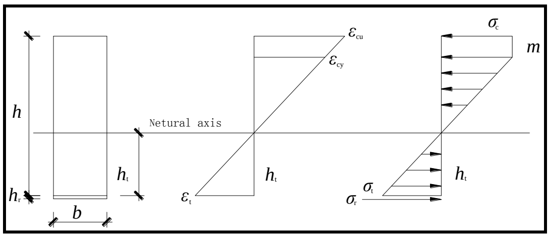

Figure 16.*The section stress-strain relation curve for compression failure*

Under compression failure, the beam bottom surface did not reach to its ultimate value ($\varepsilon_t<\varepsilon_{tu}$, $\sigma_t<f_{tu}$); the steel plate yield ($\sigma_r=f_y$); beam bottom surface reached to its ultimate value ε_{cu}, so through $\alpha=\frac{\varepsilon_{cy}}{\varepsilon_{cu}}=\frac{h-h_t-m}{h-h_t}$, $m=(1-\alpha)(h-h_t)$ could be obtained. And then, according to the stress-strain relationship obtained from material experiment, calculated that α=0.5. Eventually, in consideration of the steel plate potentiation, α=0.65.

From FIG.16, the equilibrium relation formula of force and moment was obtained:

$$\sigma_c m b + \frac{1}{2}\sigma_c (h - h_t - m) b = \frac{1}{2} h_t \sigma_t b \quad (3)$$

$$M = \sigma_c m b \times (h - \frac{m}{2}) + \quad (4)$$
$$\frac{1}{2}\sigma_c \times (h - h_t - m) \times b \times \left[\frac{2}{3}(h - h_t - m) + h_t\right] - \frac{1}{6} h_t^2 \sigma_t b$$

The formula (3) was similar with formula (1), while under compression failure, the σ_t did not reach to its ultimate f_{cu}. That was to say, in formula (3),there were two unknown number σ_t and h_t, which need similar triangles relation ($\frac{\sigma_t}{\sigma_c} = \frac{h_t}{h - h_t - m}$) to solve.

For pre-stress beams whose steel plate was fixed by both glue and screws, there was a consideration of anchorage effect caused by screws, and beam tension strength was valued 1.1 times of f_{tu}. There was no tackless between steel plates and glue-lumber, therefore, the following formula could also be used for pre-stress beams whose steel plate was firmly fixed by glue.

According to the above formulas, for beam bearing capacity, the comparison between experimental value and theoretical value was shown in Table.4.

Table 4.*The bearing capacity comparison between experimental value and theoretical value*

Group	Mid-span moment / kN·m		Error %
	Theoretical value	Experimental value	
PBgd-2	10.42	9.55	8.35
PBgd-3	11.25	11.93	6.04
PBgd-4	11.77	12.43	5.60
PBsd-2	10.99	11.06	0.64
PBsd-3	11.62	11.86	2.07
PBsd-4	12.13	13.17	8.57
Average			4.85

For pre-stress steel plate strengthened glue-lumber beams, form Table.4 could know, the error was no more than 10%, therefore, the above formulas could be used in its actual design and calculation.

5. Conclusions

(1) Compared with OB, when 2 mm or 3 mm thick steel plate was glued, the bearing capacity was similar, while when 4 mm thick steel plate was glued, there were no separation between glue-lumber and steel plate, and its bearing capacity improved by 19.5%; When the same thick steel plate was glued and fixed it by screws, the bearing capacity had no much difference, while the probability of out-of-plane stability increased.

(2) With increase of steel plate thickness, the beam deformability increased, and compared it with OB, the deflection decreased obviously, and the pre-stress had no influence on beam stiffness.

(3) Beam section strain was accorded with plane section assumption, and for this kind of member, its bending capacity calculation formula was proposed, and compared it with experimental results, the average error between theoretical value and experimental value was no more than 10%.

6. Acknowledgment

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