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Bending and Compressive Strengths of Laminated Short Beams of Bamboo using Two Adhesives

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Abstract
Bamboo is a rapidly renewable material that has many structural applications. The main objective of this study is to make beams of standard size from non structural bamboos such as Dendrocalamus giganteus by gluing them using two different adhesives namely, Urea Formaldehyde (UF) and Poly Vinyl Acetate (PVA) and make a comparative study on bending strength and maximum crushing strength and comparing the same with some well known solid woods. The strength properties of laminated beams that were made with different adhesives were then compared with some known solid wood species which are generally been used in furniture and cabinet making industry

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I. Introduction:

Bamboo has always been known as an enduring, versatile and renewable resource, biodegradable and sequestering carbon from the atmosphere. There are more than 125 species of bamboos in India where they grow in about 9.60 M ha of forestland. Adding to that, other resources of bamboos are homestead land and private plantations. Since the availability of solid wood is becoming limited with time and new technologies are being emerged, we need to look at alternatives like Bamboo based composites, Wood Plastic Composites, Agro-waste based panels etc. For this, green raw bamboo needs to be used it in flattened form. Moreover, bamboo in round form does not provide adequate strength in permanent construction. Hence, laminated bamboo lumber (LBL) came into the frame to resolve these deficiencies in the natural shape of bamboo because it is formed in rectangular sections that are more suitable for use in permanent structural applications. LBL has been introduced in research studies by using adhesives to join strands or flattened surfaces taken from the Culm.

In hilly areas or earthquake prone areas, the buildings must be light weight but with good shock resisting ability. In this direction, Glulam or glue laminated bamboo has emerged up as potential replacement of solid timber, traditionally used for structural purposes. It has been observed that Panel Composites made from bamboo has better strength, stiffness, dimensional stability and strength to weight ratio than many fast-growing timber species. In a study carried out by Lugt et al. (2006), an environmental life cycle analysis (LCA) of bamboo was analyzed in an effort to quantify the environmental effects of using bamboo as a construction material. The results of this study showed that, in some special applications, bamboo has even achieved “factor 20” environmental impact, which indicates that it has 20 times less load on the environment than currently used alternatives. Although the processing cost for bamboo laminates is sometimes higher, if we adopt efficient waste management techniques, processing cost can be minimized.

II. Materials and Methods

Three mature culms (4-5 years) of *Dendrocalamus giganteus* were cross cut to obtain pieces with inter nodal lengths of 35 – 40 cm. Such round sections were converted to strips using a bamboo splitting machine. After splitting, the outer and inner skin of the strips was removed using hand knives. Hand knives were also used to obtain slivers of roughly 5 mm thickness and 25 mm width from the splits. These slivers were then dried to suitable moisture content in a dryer so that they can be glued properly.

For the preparation of laminated samples, about five to six slivers were glued one above the other so that the thickness was about 25 mm.Two different adhesives, Polyvinyl Acetate (PVAc) and Urea Formaldehyde (UF) were used for gluing. The adhesive was applied using a brush and as soon as the adhesive was applied, the laminated beams were placed in a cold press for at least 24 hours with minimum contact pressure so that glue is cured. After the cold pressing, the glued laminates were sized to 20 mm x 20 mm x 300 mm by using hand saws and planer machine. Thirteen such beams were made with each of the glue for bending studies.

In a similar way, fifteen samples with each adhesive of size 20 mm x 20 mm x 80 mm were made for compression studies.

Static Bending measurements were carried out on a Universal testing machine (UTE-10) following IS-1708 (BIS, 1986). The span used was 280 mm. The specimen was placed such that the load was applied at right angle to the specimen at its centre. The load was applied continuously throughout the test such that the movable head of the testing machine moved at 2.5 mm/min. Deflections corresponding to progressively applied loads were noted at regular load intervals till the specimen broke. The load at which the specimen broke was recorded as the maximum load (P'). The load deflection graph was then plotted on a spreadsheet with the deflections in mm on the abscissa and corresponding loads in Newton (N) on the ordinate. Load (P) and deflection (D) at the limit of proportionality were noted. For finding out D, a line parallel to the linear portion of the load-deflection graph was drawn from the origin.
The parameters of modulus of Rupture (MOR) a Modulus of Elasticity (MOE) were calculated for each sample using the following formulae:

Modulus of Rupture (MOR) (N/mm^2) = $3P'L/2bh^2$ (1)

Modulus of Elasticity (MOE) (N/mm^2) = $PL^3/4Dbh^3$ (2)

Where,
P = Load at the limit of proportionality in N
P' = Load at failure or Maximum load in N
L= Span of the specimen in mm
b = Breadth of the specimen in mm
h = Height or thickness of the specimen in mm
D = Deflection or slip of the midpoint of the beam at the limit of proportionality in mm.
To determine the strength of beams under compression, Compression parallel to grain test was conducted according to IS: 1708 (BIS, 1986). The tests were carried out on a suitable testing machine (RIEHLE). The specimens were placed in a way, that, the centre of the movable head of the machine is vertically just above the centre of the cross section of the specimen. The rate of loading was 0.6mm per minute.
The formula used for Maximum Crushing Strength (MCS) at Compression parallel to grain is $\frac{P'}{A}$(N/mm^2).
Where,
P' = Maximum Crushing load in N
A = Cross sectional Area in mm^2

III. Results and Discussion

The static bending parameters of laminated bamboo joined with PVAc and UF were computed by calculating the modulus of rupture (MOR) and Modulus of elasticity (MOE)as discussed in the previous section. The calculated MOR and MOE are given in Table 1.

Table 1: MOR values with the two adhesives

Sample No.	**MOR (N/mm^2)**	
	PVAc	**UF**
1	58	90.9
2	44.9	89.2
3	37.7	95.1
4	46.3	55.7
5	65.7	76.4
6	61.1	106.2
7	82.0	94.6
8	52.2	55.7
9	51.0	122.2
10	66.3	115.7
11	51.0	75.1
12	69.1	97.1
13	69.5	74.7
Mean	**58.06**	**88.35**
St. Dev	**10.57**	**12.82**

CV (%)	**18.20**	**14.51**

From table 1, it can be seen that the average values of MOR for both the adhesive differ a lot. The beams glued with UF have resulted in a much higher MOR by about 30 N/mm^2. To investigate the statistical significance of the difference, one-way ANOVA was carried out and results are given in Table 2.

Table 2: ANOVA of MOR due to Adhesive

Source of Variation	**df**	**MS**	**F**	**P-value**	**F crit**
Adhesive	1	5964.56	20.9312	**<0.001**	4.2597
Error	24	284.96			
Total	25				

The ANOVA suggests that the p-value obtained is much lesser than 0.001 indicating that one can say with more than 99% confidence that the difference between MOR values is statistically highly significant for the beams made with the two adhesives.
The average values of MOR obtained for the two adhesives are compared with the help of bar diagram in fig. 1.

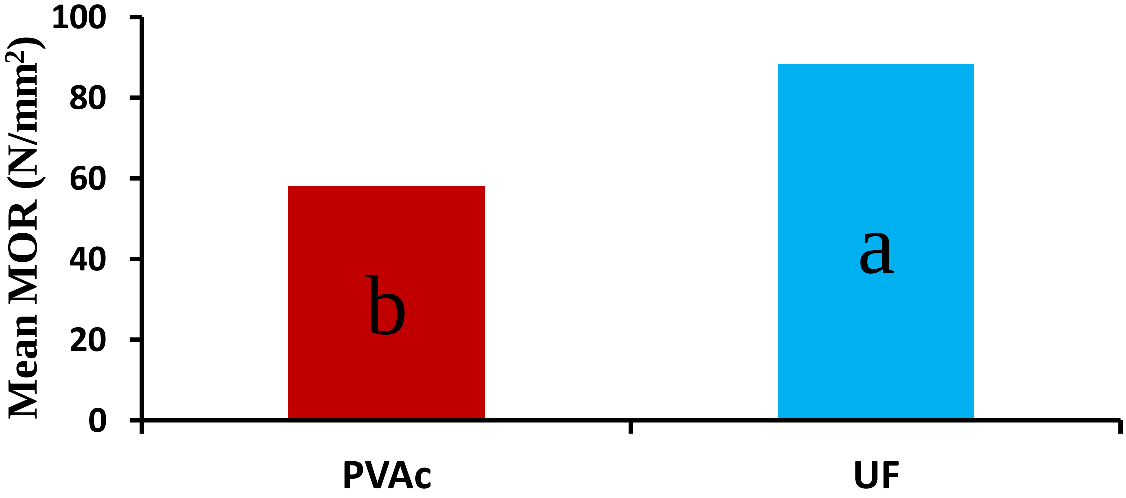

Figure 1: Comparison of Mean MOR values due to two different Adhesives
Note: Different alphabets (a and b) in the above Figure indicate different significance levels

A report by Biswas et al. (2017) on laminated panels made of *Bambusa vulgaris* and *Bambusa balcooa*, where UF and PVAc were used as binders indicated that the shear strength of the UF Panel was greater than PVAc Panel. It is a well-known fact that with many solid woods, UF gives a better bond with the wood than PVAc. Penetration of a liquid adhesive into a porous substrate either occurs on the micro- or the nano- scales depending on its ability to penetrate into cell lumens or cell walls respectively (Follrich et al. 2010). Long PVAc adhesive chains have lower mobility resulting in lower penetration ability due to the long fibrous molecules present in the resin (Frihart 2005).
In a similar way, the MOE values also were compared. The values are given in Table 3.

Comparison of MOE:

Table 3: MOE values with the two adhesives

	MOE (N/mm^2)	
Sample	PVAc	UF
1	6894	7133
2	2972	8903
3	2413	7713
4	4055	4477
5	6378	8053

6	4516	10191
7	6668	9374
8	2859	7954
9	4804	11043
10	5167	8397
11	5652	5864
12	5755	9193
13	**4938**	**6798**
Mean	**4851.62**	**8084.08**
St. Dev	**444.95**	**1717.10**
CV	**9.17**	**21.24**

From the above table, we see that the average MOE values of the beams made of UF adhesive is almost double that of beams made with PVAc. To find out the statistical significance of the difference, one-way ANOVA was carried out and results are given in Table 4

Table 4: ANOVA of MOR due to Adhesive

Source of Variation	**df**	**MS**	**F**	**P-value**	**F crit**
Adhesive	1	67917249.38	25.843	**<0.001**	4.26
Error	24	2628095.5			
Total	25				

The ANOVA clearly shows that, the p-value is much lesser than 0.001. Hence, we can infer with nearly 100% confidence that the MOE values differ significantly due to the change in adhesive while manufacturing bamboo beams. UF performs much better as glue for laminating *D. giganteus* strips for making elastic beams. The average values of MOE obtained by using two types of adhesive while manufacturing beams are compared using bar diagram in Fig 2

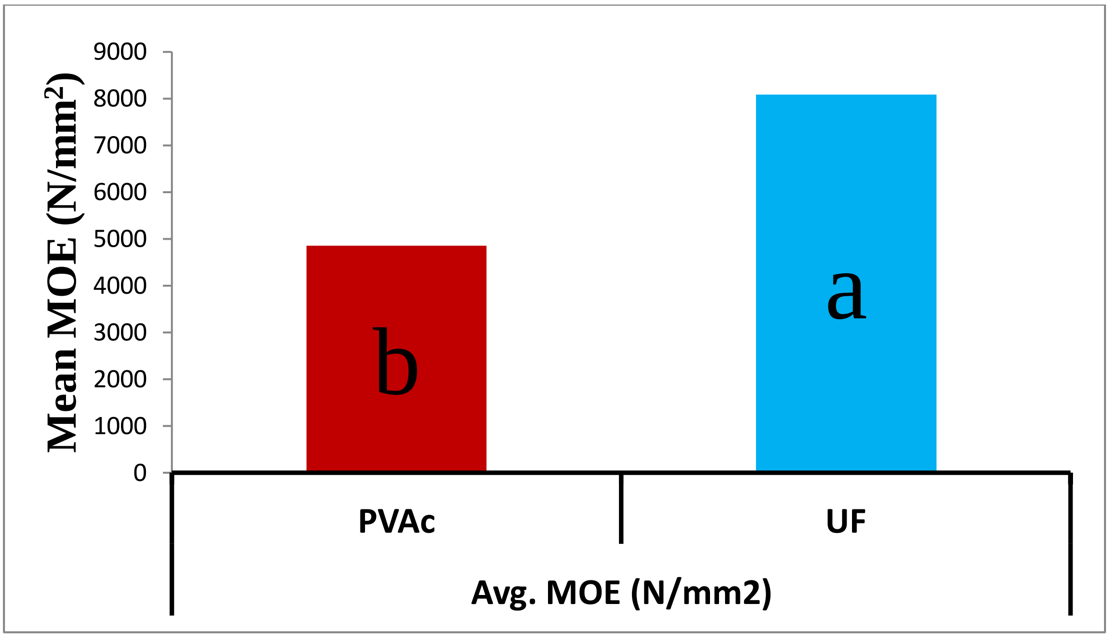

Figure 2: Comparison of Mean MOE values due to the two different Adhesives

Note: Different alphabets (a and b) in the above Figure indicate different significance levels.

A study conducted by Blanchet et al., (2003) found that while manufacturing engineered wood parquet flooring using different binders, the strength properties and moisture resisting ability of PVAc were lesser than those of UF.

Effect of Adhesive on the compression properties

To compare the maximum crushing strength (MCS) of the laminated beams glued with two different types of adhesives, a comparative study on 15 laminated bamboo sample for each adhesive were conducted. The maximum crushing stress values with two different adhesives is shown in Table 5.

Table 5: MCS values with the two adhesives

Maximum Crushing Strength (N/mm^2)		
Sample	**PVAc**	**UF**
1	31.57	59.05
2	34.57	64.28
3	43.71	66.95
4	55.00	49.91
5	59.68	47.09
6	44.23	49.65
7	54.39	44.36
8	47.46	45.78
9	54.09	49.12
10	46.74	53.60
11	48.67	57.84
12	52.68	55.05
13	41.86	57.77
14	28.16	49.80
15	49.30	56.48
Mean	**46.14**	**53.78**
St. Dev	**9.07**	**6.65**
CV	**19.65**	**12.37**

From the above table it is evident that, the values of average MCS vary considerably due to difference in adhesive. The average MCS value of the beams made with UF is clearly higher than those of made with PVAc. The bar diagram of average MOR values is shown below in Figure 3

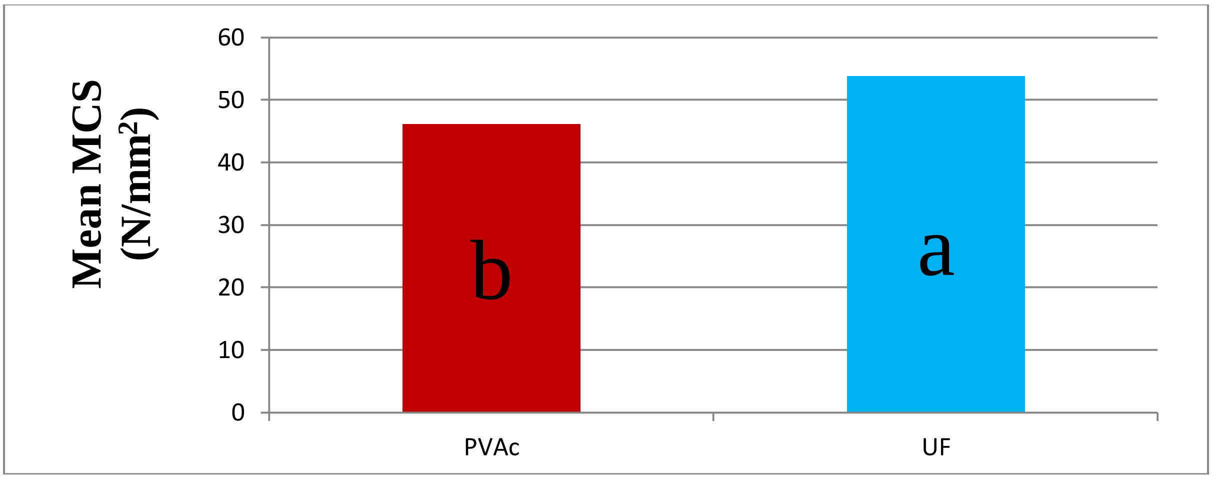

Figure 3: Comparison of Mean MCS values due to two different Adhesives

Note: Different alphabets (a and b) in the above Figure indicate different significance levels.
It is seen that as in the case of bending, the maximum crushing stress is also higher for UF glued beams as compared to that of PVAc.

From the above Table 5, we see that the average MCS values of the beams made of UF adhesive is considerably higher than that of beams made with PVAc. To find out the statistical significance of the difference, one-way ANOVA was carried out and results are given in Table 6.

Table 6: ANOVA of MCS due to Adhesive

Source of Variation	*df*	*MS*	*F*	*P-value*	*F crit*
Adhesive	1	438.00	6.925	**0.0137**	4.196
Error	28	63.25			
Total	29				

From the ANOVA we can infer that, the p-value obtained is 0.0137, which is less than 0.05. Thus, the variation in MCS due to change in adhesive while manufacturing laminated bamboo beam is statistically significant. It is once again the UF adhesive which is performing better under compression also.

Comparison of strength properties with solid wood:

Another important aspect of this study was to check whether the beams produced by laminating bamboo strips together with either of PVAc or UF adhesive can be used as Furniture components or not. In other word it is to be examined whether these beams are suitable replacement for furniture components like chair legs, chair front rails etc.

According to a report by Anokye et al. (2016), since bamboo has a very high strength to weight ratio, laminated bamboo has great potential to substitute wood for the purpose of furniture manufacturing.

An effort was made to compare the mechanical strength properties of the beams studied with some well known furniture wood species, namely, Acacia, Sissoo, Mango, Chir Pine, Teak etc. For this purpose, we compared the average MOR and MCS parallel to the grain values of the bamboo beams, manufactured with PVAc and UF with the reported values of some furniture wood species (Rajput et al. 1996). Comparison of strength parameters of bamboo beams and few furniture woods is shown in Table 7.

Table 7: Comparison of strength parameters of bamboo beams and few Furniture wood

Wood/Bamboo beam	Avg. MOR (N/mm^2)	Average Maximum Crushing Strength (N/mm^2)
Bamboo beam by PVAc	**58.06**	**46.14**
Bamboo beam by UF	**88.35**	**53.78**
Teak (Thane)	76.8	38.2
Mango (Puri)	61.2	29.4
Acacia (Saharanpur)	77.6	35.4
Chir Pine (Uttarakhand)	49.4	25.0
Sissoo (Dehradun)	71.8	35.2

From the above table, it is to note that the average MOR value of the Bamboo beam manufactured with PVAc is greater than that of Chir Pine and almost comparable with Mango wood. But the average MOR value of the bamboo beam manufactured with UF is greater than that of all the furniture wood species, discussed here. The bar diagram (Fig 4.4) shows the variation of MOR of the bamboo beams with solid woods like Teak, Pine, Acacia, Mango, Sissoo etc.

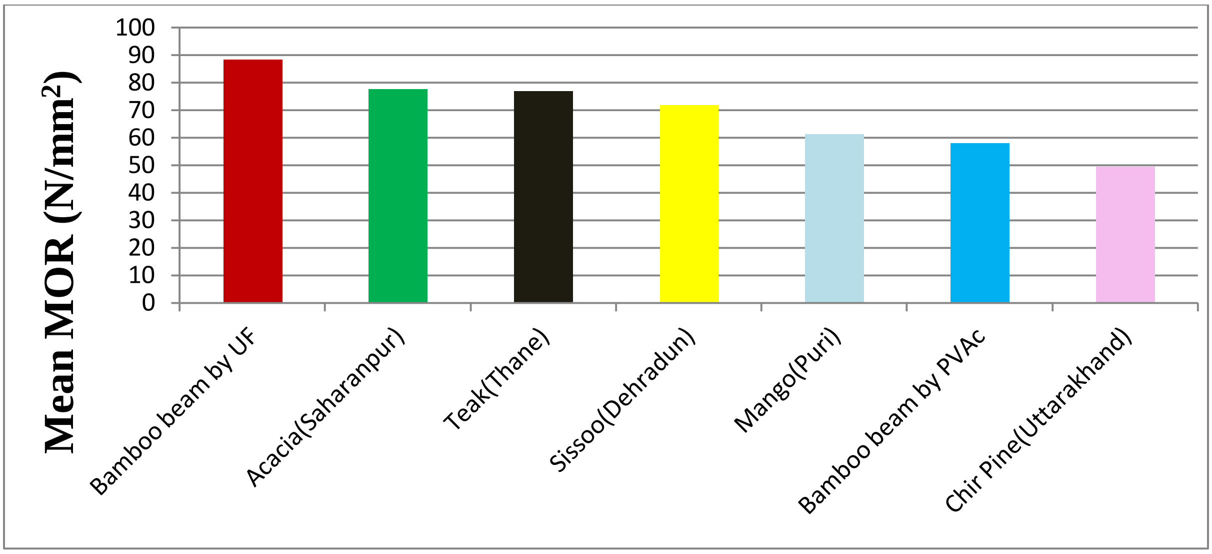

Figure 4: Comparison of Mean MOR values of Bamboo beams with Furniture woods

Comparing the compressive strength Parallel to the grain of Bamboo beams with other solid woods shows that, bamboo beams manufactured with both PVAc and UF provides better strength than the Solid woods, when compressed parallel to grain. The bar diagram (Fig. 5) shows the variation of Maximum crushing strengths between bamboo beams and solid wood species.

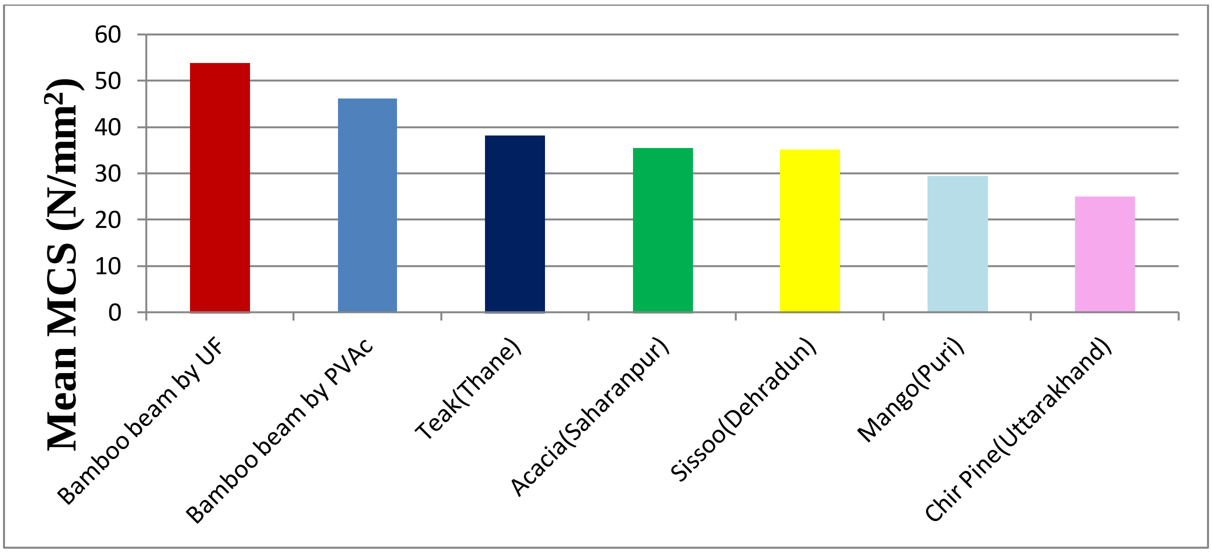

Figure 5: Comparison of Mean MCS values of Bamboo beams with Furniture woods

From the above figure, it can be seen that the average MCS value of the Bamboo beam manufactured with PVAc is greater than that of even Teak. But the average MCS value of the bamboo beam manufactured with UF is greater than that of all the furniture wood species. This clearly illustrates the use of laminated bamboo beams as furniture parts where they can tolerate both bending (eg. Front seat rail of a chair) and compression (eg. legs of a chair) equally well as many known furniture wood species.

IV. CONCLUSIONS:

Results indicate that laminated bamboo is a versatile material and it can be used not only for furniture making, but also for construction and other major applications. The UF glued beams perform better than those of glued with PVAc in both Static bending and Compression parallel to grain tests. The difference in MOR, MOE and MCS values are statistically significant as well. The Rigidity of bamboo beams glued with UF is even better than Teak, Acacia, Shisham, Mango, Pine etc. furniture woods. Even mean MOR value of PVAc glued beam is higher than that of Chir Pine and almost comparable with Mango wood. Bamboo beams made with both UF and PVAc show more resistance in Compression parallel to grain than Teak, Acacia, Shisham, Mango, Chir Pine etc. However, the MCS values of UF glued beams are better compared to PVAc glued beams. Thus the laminated beams of *Dendrocalamus giganteus* can be considered as alternatives of solid wood components in furniture industry.

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