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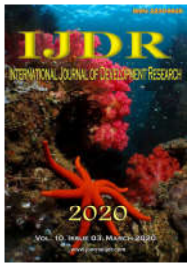

RESEARCH ARTICLE **OPEN ACCESS**

FINGER JOINTING OF EUCALYPTUS HYBRID USING TWO COMMON ADHESIVES

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ABSTRACT

In this paper, an attempt was made to assess the effectiveness of utilising short sections of Eucalyptus hybrid through finger jointing using two common adhesives. The study was based on the estimation of Modulus of elasticity (MoE) and Modulus of Rupture (MoR) of jointed sections under static bending and comparing them with the values measured for clear wood sections from the same wood. For joining the sections, the Poly Vinyl Acetate (PVAc) and Urea Formaldehyde (UF) adhesives were used. It was found that the MoE of the sections joined by either adhesive remain unaffected compared to that of unjointed clear wood sections. The MoR values of jointed sections were lesser than that of controls. Sections jointed through PVAc adhesive exhibited lower MoR. But both the adhesives were able to retain the bending strength by 52 % to 65 %. The study demonstrates the utility of finger jointing of Eucalyptus wood sections for structural purposes especially with the UF adhesive.

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INTRODUCTION

Appreciable savings in wood wastage at the workshop and saw mill level can be achieved through utilization of the short pieces effectively. In this direction, finger jointing has caught the imagination of solid wood industry worldwide. The strength of the finger joint depends to a large extent on the adhesive used to join the fingers. Adhesives can effectively transfer and distribute stresses thereby increasing the strength and stiffness of a joined wood section. It is, therefore, important to arrive at a suitable adhesive to make jointed sections of Indian hardwoods for structural uses. In most of the works the effectiveness of various adhesives in finger jointing of different wood species were studied with a biased thinking that the role of adhesives is more crucial for strength enhancement of the jointed sections (Barboutis and Vasileiou 2013; Danawade *et al*. 2014). Bardak *et al* (2018) reported that the bonding strength of Urea Formaldehyde (UF) enhanced when nano-SiO_2 was added to the adhesives but nano-TiO_2 added UF did not exhibit this phenomenon. Thus, this is also an area worth exploring in finger jointing. The efficiency of finger jointing in replacing precious solid wood sections has been well illustrated the world over. However, the use of finger jointed sections in structural members of furniture is less investigated. MoR efficiencies between 50 % and 100 % in finger jointed sections of Eucalyptus and mango wood depending on the quality of the original material using the common Urea formaldehyde and the carpenters' favourite Poly Vinyl Acetate (PVAc) adhesives have been reported using different finger profiles (Kishan Kumar *et al*. 2011; 2013; 2015). The type of adhesive, curing time and the pressure of application influence the strength of the assembled joints. The bonding properties of cell components in wood depend upon a number of parameters relating to the physiochemical characteristics of the adhesives, the bonding method, the geometric shape and size of pieces apart from the conditions to which the bonded pieces would be exposed to while in use (Marra 1992). A polymer is a very large molecule which is comprised of repeating units and those units connected with each other to form long chains which can be linear, branching or cross-linked. There are two main types of polymers used in wood composite industry: thermoplastics and thermosetting resins Thermoplastics are usually linear polymers which may change in structure as temperature changes, such as glass transition, crystallization and melting. Polylactic acid (PLA) and Polyvinyl chloride (PVC) are the most commonly used thermoplastic resins for fabricating wood plastic composites (Pavlidou and Papaspyrides, 2008). Thermosetting resins are three-dimensional cross-linked networks which are hard, infusible and insoluble after curing. Thermosetting resin is more difficult to characterize than a thermoplastic resin because it remains stable after curing. Urea formaldehyde (UF), Melamine formaldehyde (MF) and Phenol formaldehyde (PF) resins are the predominant thermosetting resins used as wood adhesives in the production of hot pressed wood composites. Thermosetting resins are usually a mixture of low molecular weight condensates or intermediates generated by primary addition reactions, and monomers which are all soluble in water. These low molecular weight condensates will further react at higher temperatures and form the final cross-linked, rigid network (Pizzi and Mittal 1994).

Barboutis and Vassiliou (2008) found that the bending strength (MoR) of European Chestnut (*Castanea sativa*) wood finger-joints ranged from 55.3 N/mm^2 to 83.5 N/mm^2 using short and long fingers in the range of 4 mm to 20 mm when joined with PVAc. They concluded that there is strong relationship existing between the tensile shear strength and bending strength (MoR) of the finger-jointed Chestnut wood. Studies by Murphy and Rishel (1972) revealed that the finger length of 3.2 mm showed highest strength (MoR) property of 30.5 N/mm^2 on White pine and 55.8 N/mm^2 with finger length of 9.5 mm on Yellow poplar when joined with PVAc. In *Pinus* spp., an MoR retention in the range of 75 % was reported when the fingers were joined using Resorcinol-Formaldehyde (Vrazel and Sellers Jr. 2004). The lesser moisture uptake, melting point, dry time and higher tensile strength of a UF based blend with natural rubber have demonstrated the UF resin's utility as a joiner and good binder to even paint coatings (Osemeahon *et al*, 2007). On three African hardwoods, efficiencies ranging from 72-94% have been achieved with much thinner finger tips using melamine formaldehyde adhesive (Ayarkawa *et al*. 2000b). However, with Recorcinol formaldehyde adhesive, these hardwoods showed efficiencies in the range of 43-94 % depending on the finger parameters and the end pressure used during joint mating (Ayarkawa *et al*. 2000a). Bustos *et al*. (2003) reported that the finger-joint of high flexural and tensile performance can be produced by using an Isocyanate type of adhesive.

The PVAc adhesive is reported to give better MoR for *Eucalyptus benthamii* sections compared to PU when samples were joined with 10 mm fingers, while the modulus of elasticity was not affected by the adhesive used (Martins *et al*. 2013). Kaboorani and Riedl (2011) reported that the shear strength of wood joints increased by adding nano-clay to PVAc. Urea formaldehyde (UF) resins are the most important type of adhesive resins for the production of wood products, wood joineries and panel boards. They are very useful due to their high reactivity and good performance in the production and by their low price; however, they lack in water resistance of the hardened resin owing to the reversibility of the aminomethylene link leading to susceptibility to hydrolysis. This can be overcome by introducing other components like melamine to the UF resin molecules (Dunky, 1998). Various useful properties like relatively low cost, ease of use under a wide variety of curing conditions, low curing temperatures, resistance to microorganisms and to abrasion, good thermal properties, and absence of colour of the cured resin make the use of urea-formaldehyde resins as a major adhesive by the wood based industry popular. However, UF resin has a disadvantage of poor resistance to moisture and water at higher temperatures making it not very useful for exterior applications (Connor 1996). The question of effect of gluing areas on the strength of finger joints has been addressed by various workers (Selbo, 1963; Kishan Kumar *et al*. 2010, 2013). A most suitable profile for getting maximum flexural MoR for finger jointed Eucalyptus using UF adhesive was reported recently by Singh *et al*. (2018). It is in this context that two most widely used wood adhesives were compared in the finger jointing of Eucalyptus hybrid sections. One is the aliphatic rubbery synthetic polymer (poly venyl acetate) which is manufactured by polymerizing vinyl acetate monomer and stabilizers with other polymers or co-polymers (Kim and Kim 2006). The second one is the urea formaldehyde which is the most prominent in the class of thermosetting resins usually referred to as amino resins in wood processing industry and particularly in wood-based panel production (Gadhave *et al* 2017).

MATERIALS AND METHODS

Urea Formaldehyde (UF) adhesive was prepared from 100% UF resin available in powder form. 100 gm of the powder resin and 2 gm of ammonium chloride (NH_4Cl) hardener which assists in room temperature curing were mixed in 75 ml of water to get a viscous solution with a solid content of 57.6 %. A commercial Poly Vinyl Acetate (PVAc) adhesive (Fevicol SH grade) was the other adhesive used. Fingers of 20 mm length, 5 mm pitch and 0.8 mm tip thickness were profiled using a commercial finger shaping machine. The adhesives were applied on all fingers using a brush. Immediately after adhesive application, the sections were mated and pressed on a pneumatic pressing vice at a constant end - pressure of about 6 N/mm^2. The jointed sections were made in such a way that the joints occupied the central position of the section. Twenty five samples were prepared with each of the adhesive and both sets were cured at room temperature for at least 48 hours. The static bending tests on the clear and jointed samples were carried out on Universal testing machines. Tests were done by placing the specimen in such a way that it was at right angle to the load. The span of the test was kept at 700 mm irrespective of the thickness of the samples. Since the maximum thickness of any sample was ~ 50 mm, a span of 14 times the thickness was thus was ensured. The continuous load was applied statically throughout the test such that the movable head of the testing machine moved at 2.5 mm per minute. The readings of deflections corresponding to progressively applied loads were recorded by the automatic UTM. This process was continued until the samples broke at the joints and the loads at which the breaking took place also were recorded for each sample. The load deflection graphs were then plotted using spreadsheet. From the load-deflection graphs on a spread sheet, the load and deflection at the limit of proportionality were recorded. From the load-deflection graphs on a spread sheet, the load and deflection at the limit of proportionality were recorded using standard procedure (Kishan Kumar *et al*. 2013).

Calculation of bending parameters

The bending strength (Modulus of Rupture - MoR) and bending stiffness (Modulus of Elasticity - MoE) were calculated for each sample using the following formulae:

$$MOR = \frac{3P'l}{2bh^2} \quad \text{N/mm}^2 \qquad (1)$$

$$MOE = \frac{Pl^3}{4Dbh^3} \quad \text{N/mm}^2 \qquad (2)$$

Where

P = Load at limit of proportionality (N)
P' = Maximum load (N) at which the sample/joint failed
l = Span of sample (mm)
b = Breadth of sample (mm)
h = Height (thickness) of sample (mm)
D = Deflection (mm) at limit of proportionality

Efficiencies of strength

The efficiency of each strength parameter was calculated using the following formula:

$$Efficiency\ (\%) = \frac{\text{Mean of Parameter determined for jointed section}}{\text{Mean of Parameter determined for unjointed clear section}} * 100$$

For this purpose, a set of (25 numbers) unjointed clear samples was also prepared and were used as controls.

Statistical analyses of the data were carried out using the SPSS package.

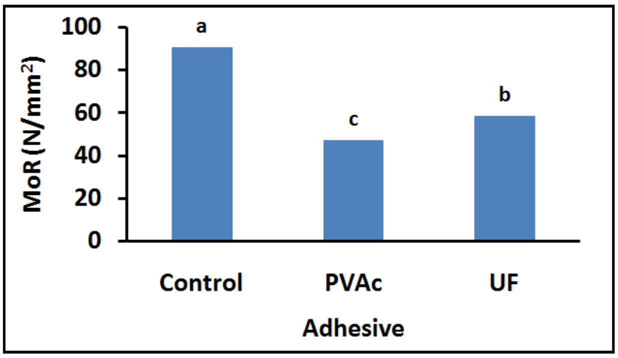
RESULTS AND DISCUSSION

Table 1 presents the mean values of MoR and MoE of the 75 samples used in the study.

Table 1. Mean bending parameters of samples used in the study

Adhesive		No. of Samples	Bending parameter	
			MoR	MoE
Control (Unjointed)	Mean value (N/mm^2)	25	91.1	10404
	Std. Dev. (N/mm^2)		8.2	2033
	CV (%)		9.0	19.5
PVAc	Mean value (N/mm^2)	25	47.6	10318
	Std. Dev. (N/mm^2)		11.7	2285
	CV (%)		24.6	22.1
UF	Mean value (N/mm^2)	25	58.9	11195
	Std. Dev. (N/mm^2)		7.6	883
	CV (%)		13.0	7.9

Table 1 reveals that samples joined with UF result in nearly 59 N/mm^2 of MoR whereas those joined with PVAc yield less than 48 N/mm^2 of MoR. Thus, numerically, UF seems to be yielding better bending strength for the joints. All the 75 MoR values were subjected to One-way ANOVA which indicated significant differences between the obtained MoR values ($p < 0.001$). Hence, Duncan's homogeneity test was conducted on the 75 MoR values obtained and the results obtained grouped the values into three distinct subsets in the order PVAc < UF < Control. These results are illustrated in Fig. 1.



Note: Different alphabets on the bars indicate different significance levels

Fig. 1. Behaviour of the MoR values

The gluing behaviour of different Eucalyptus species may vary due to the fact that their anatomical characteristics are reported to differ widely. For example, the average apparent density of *E. nitens* increased with the ring width and cell wall area but decreased with the vessel area (Salvo *et al*. 2017). Despite presenting high growth rates, *E. globulus* was found to have relatively narrow vessels resulting in small-sized fibers compared to *E. grandis* and *E. viminalis* (Barotto *et al*. 2017). It is seen that in general, UF results in stronger finger joints than PVAc with any profile (Kishan Kumar *et al*. 2013). Penetration of a liquid adhesive into a porous wood 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). PVAc adhesives have lower mobility resulting in lower penetration ability due to the long fibrous molecules present in the resin (Frihart 2005). Because of this, this adhesive can penetrate only into the cell lumens and not into the cell walls resulting in only micro scale stiffening effects. Due to this fact, though this is a widely used adhesive by small scale artisans, it is seldom used in structural applications. The value of 47.6 N/mm^2 obtained with PVAc is in good agreement with values reported for this species (Ranjan *et al*. 2019). However, a very high MoR of 68 N/mm^2 has been reported for *E. benthamii* by Martins *et al*. (2013) by using shorter fingers end-glued at a very low end pressure of 1.5 N/mm^2. This illustrates the dependence of finger profile, end pressure and wood species on the joint strength.

On the other hand, the UF adhesive has given a much higher value of MoR. With another weaker profile, the MoR reported for *E. tereticornins* is only 37.4 N/mm^2 (Kishan Kumar *et al*. 2013). A value of 56 N/mm^2 was reported for Eucalyptus hybrid with a profile similar to the one used in the present study which also used UF adhesive (Singh *et al* 2018). Thermosetting resins like UF are usually a mixture of low molecular weight condensates or intermediates generated by primary addition reactions, and monomers which are all soluble in water. These low molecular weight condensates will further react at higher temperatures and form the final cross-linked, rigid network (Pizzi and Mittal, 1994). Moreover, as explained earlier, low molecular weight glues like UF are capable of diffusing into the cell walls where their curing leads to an increased hardness of the cell wall resulting in higher joint strength (Follrich *et al.* 2010). The MoR value of control samples (with no joints) is in agreement with the ones reported in literature. Kishan Kumar *et al*. (2013) reported a value of 89 N/mm^2. The mechanical properties of different Eucalyptus species have a bearing on their individual structural characteristics. For instance, the high density *Eucalyptus globulus* trees were reported to possess thicker fibre cell walls and lower fibre lumen width compared to those of low density ones (Carrillo *et al*. 2015). *E. globulus* is reported to have a higher bending strength of 115.4 N/mm^2 (Franke and Marto 2014) than that of 91.6 N/mm^2 reported for *Eucalyptus saligna* (Nogueira *et al*. 2019). *E. camaldulensis* is reported to possess a bending MoR of 102.6 N/mm^2 (Awan *et al*, 2012). The MoR values reported for Eucalyptus hybrid from various parts of India varies between 65.1 N/mm^2 to 118.9 N/mm^2 (Kothiyal 2014).

It is seen from table 1 that the MoE values of jointed and control samples are in the range of 10318 N/mm^2 for PVAc samples to 11195 N/mm^2 for UF samples. The one-way ANOVA revealed no significant differences between the 75 individual MoE values ($p = 0.184$). The elastic behaviour is reported to be more a property of the wood rather than the adhesive bond (Frihart, 2005). In many studies, the MoE of finger jointed sections usually do not vary much from the values of even unjointed sections. In the case of *Eucalyptus benthamii*, similar MoE for two different (PVAc and polyurethane-based) adhesives has been reported for finger jointed sections (Martins *et al*., 2013). Singh *et al* (2018) reported a value of 11731 N/mm^2 for finger jointed samples of Eucalyptus hybrid.

Joint Efficiency

Having looked at the performance of the individual adhesives, it would be interesting to have a glance at the efficiencies of the joints prepared with them. The efficiencies are estimated with respect to the bending parameters of the unjointed clear wood sections of the species under investigation. The calculated efficiencies are shown in Fig. 2.

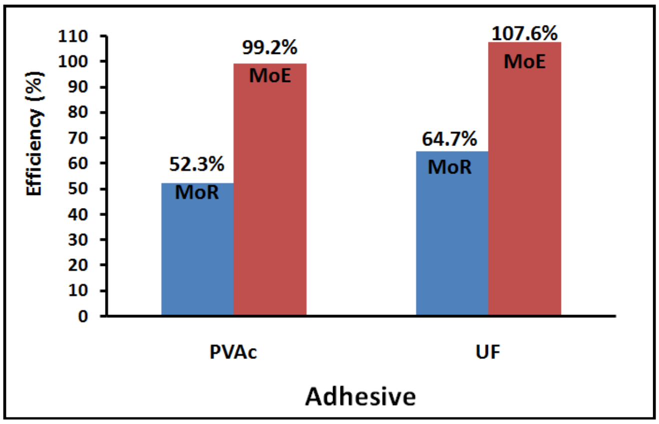


Fig. 2. Efficiency of flexural parameters of the finger joints

It can be seen from fig. 2 that the efficiencies of MoR for the two adhesives are 52.3 % for PVAc and 64.7 % for UF. The relatively lower retention of bending strength by PVAc joined wood sections also have been reported in many species. MoR efficiency of less than 30 % was reported for mango wood with PVAc adhesive with another finger profile (Kishan Kumar *et al.* 2011). In *Eucalyptus tereticornis*, this glue yielded only 23 % to 35.2 % MoR efficiency with two other finger profiles (Kishan Kumar *et al*. 2013). However, it is to be noted that the present value of 54.2 % is higher than these values which is a result of the better finger profile used which was attributed to the role of available gluing areas and lower tip areas (Singh *et al*. 2018). Only 34% to 42.2 % MoR efficiencies were reported for *E. tereticornis* with UF but using two other finger profiles (Kishan Kumar *et al*. 2013). The use of a more suitable profile has helped to achieve an efficiency of nearly 65 % with UF in the present study. Higher performance by UF adhesive over PVAc in dowel joints under cyclic bending tests also has been reported (Chou and Lee 2000). A similar pattern of UF performing better than PVAc was reported for mango wood also with a different finger profile earlier (Kishan Kumar *et al*. 2011). Martins *et al*. (2013) reported an efficiency of 59.5 % for MoR of finger jointed *E. benthamii* wherein they obtained an MoR of 46.5 N/mm^2 with Poly Urethane (PU) adhesive against a reported clear wood MoR of 78.3 N/mm^2. This value is slightly lesser to the 64.7 % obtained in the present study. Urethane wood adhesives are well known for its ability to provide strength to the joints due to the fact that urethane bonds are formed with the wood material. A study using patented polyurethane glue showed that the adhesive penetrates several cells deep into the wood at the joint and also indicated formation of covalent bonds with the wood substrate (Pommier and Elbez 2006). The study also illustrated the role of hydroxyl ions in the wood in helping the bonding through the fact that joint strengths were higher in sections that were joined in green condition than those which were joined in dry condition. It would be interesting to note that Obucina *et al*. (2014) claim that the MoR of finger jointed fir/spruce can be made 100 % or more efficient by controlling the glue spread on the fingers. However, the dependence on species, finger profile, glue spread etc. would strongly influence the joint strength. A reported interesting example is that of PVAc resulting in better bonding performance and reliability than Polyurethane adhesive for black locust (*Robinia pseudoacacia* L.) and Beech wood (*Fagus sylvatica* L.) the reasons for which were unexplained (Vasiliki and Ioannis 2017). However, another study on beech wood which has similar MoR (108.71 N/mm^2) as that of Eucalyptus had also reported better MoR efficiency of 43.6 % for PVAc than for PU (32.7 %) adhesive when joined with small fingers of 9 mm length (Barboutis and Vasileiou 2013).

Fig. 2 reveals that with either adhesive, the MoE efficiency is above 99 % and in the case of UF, the value actually exceeds 100 %. Very high (> 80 %) MoE efficiencies have been reported for finger joints glued with different adhesives for many wood species in literature. The scarf portions of the joint help in minimizing wood material discontinuities (River, 2003). This is expected to help the mechanical properties of the jointed sections to be not dependent on the adhesive used to very high extents. In mango wood, higher MoE value was reported with UF adhesive than that of clear wood specimens when sections were joined with another finger profile (Kishan Kumar *et al.* 2011). Good retention of MoE of finger jointed African hardwood sections using resorcinol-formaldehyde adhesive up to about 83-98 % of the individual clear sections depending on the wood density and with a finger length of 18 mm also has also been reported (Ayarkwa *et al.* 2000a). They attributed this to the fact that stiffness being a more global phenomenon is not very sensitive to joint properties. Ayarkwa *et al.* (2000b) reported no significant effect of glue type on the modulus of elasticity in bending of finger jointed African hardwoods. Very high MoE efficiencies in the range of 114-129 % were reported for mango wood with UF and PVAc adhesives but with a very different finger profile (Kishan Kumar *et al.* 2015). MoE of finger jointed samples of Beech wood joined using 10 mm long fingers and PVAc was found to be unaffected compared to clear samples (Vassiliou *et al.* 2007). In an interesting study on commercially available finger jointed wood of Burma teak (adhesive unknown), it was found that the elasticity retention was about 98.4 % with respect to solid wood (Danawade et al. 2014). This shows the lesser influence of adhesive on the elasticity of finger joints. In a study on *Populus alba*, it was found that even giving a slope did not affect the elasticity of the jointed sections whereas, the MoR was affected (Habipi and Ajdinaj 2013). Barboutis and Vasileiou (2013) had reported 86.9 % and 88.6 % MoE efficiency for beech wood when a profile of short fingers was use for finger jointing.

Conclusions

It is clear from the present study that, with a suitable finger profile, the urea formaldehyde adhesive which cure at room temperature give higher bending strength than with PVAc in the case of Eucalyptus hybrid. The efficiencies achieved are near 65 % with UF. Even the lesser performing carpenter's favourite adhesive, Polyvinyl Acetate's performance in finger joints can be improved by optimising the finger parameters. In the present case, the MoR efficiency for this glue was around 52 %. The elastic behaviour of the joints remained unaffected by the adhesives studied. Both PVAc and UF resulted in efficiencies exceeding 99 % in the case of MoE of finger jointed samples.

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