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Investigating the use of defect-containing timber from young *Eucalyptus* plantations for manufacturing engineered products

Bruno Monteiro Balboni

Thesis presented to obtain the degree of Doctor in Science, Area: Forest Resources. Option in: Forest Products Technology

Piracicaba
2022

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Investigating the use of defect-containing timber from young *Eucalyptus* plantations for manufacturing engineered products

versão revisada de acordo com a Resolução CoPGr 6018 de 2011

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Àqueles que sempre me deram apoio incondicional,
que me estimularam a buscar o meu melhor, sempre.
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O menino dos dinossauros cresceu. Experimentou. Viveu. Voou.

“Descobri como é bom chegar quando se tem paciência. E para se chegar, onde quer que seja, aprendi que não é preciso dominar a força, mas a razão. É preciso, antes de mais nada, querer”.

Amyr Klink

SUMÁRIO

RESUMO

Investigação do uso de madeira com defeitos de florestas jovens de *Eucalyptus* para fabricação de produtos engenheirados

A crescente demanda por madeira no mundo tem levado a buscas por fontes sustentáveis desta matéria prima. Florestas jovens de *Eucalyptus* são uma potencial fonte de madeira, devido a seu rápido crescimento e alta adaptabilidade a diversas condições climáticas. Árvores jovens normalmente apresentam características indesejáveis, como nós, empenamentos e altas porcentagens de madeira juvenil, além de gerar madeira serrada de seção transversal de dimensões limitadas, o que pode ser superado pela fabricação de produtos engenheirados. Nosso objetivo foi avaliar alguns pontos chaves, do ponto de vista da qualidade e propriedades mecânicas, para adoção de madeira de plantações de ciclo curto de *Eucalyptus* na fabricação de produtos engenheirados de madeira. Dentre os clones de *Eucalyptus* altamente produtivos já utilizados na indústria de bioenergia brasileira, foram identificados alguns com propriedades da madeira desejáveis mesmo em idades precoces (sete anos). Um índice de arqueamento e encurvamento foi desenvolvido com madeira adulta e jovem de *E. grandis*, que nos permite identificar e segregar porções de madeira cuja distorção localizada é muito severa, auxiliando o uso das seções pouco empenadas na composição de lamelas emendadas para produtos engenheirados de madeira. Ao avaliar a resistência de adesão em madeira com nós de *E. grandis* jovens em relação à madeira sem defeitos, foi encontrado que a presença de nós afeta a resistência da adesão da madeira em densidades acima de 0.65 g cm^{-3}, reforçando os benefícios da estratificação de lamelas em vigas laminadas. Lamelas de alta densidade são posicionadas em zonas que demandam maiores tensões de compressão e tração, mas onde a tensão de cisalhamento é menor. Este fato, junto à baixa proporção de nós na superfície das lamelas, torna a influência dos nós na adesão da madeira de *Eucalyptus* jovens, pouco significante. Foram construídas e ensaiadas vigas laminadas coladas de madeira de *E. grandis* jovens com diferentes níveis de encurvamento, adicionando pré-tensão às vigas. A pré-tensão não influenciou a capacidade de carga das vigas como hipotetizado. Porém, as vigas retornaram propriedades mecânicas adequadas para uso estrutural, ainda que 80% das lamelas não atendessem os requisitos mínimos estabelecidos em norma. Enquanto nós na zona de compressão não influenciaram o comportamento das vigas, os nós presentes na porção tracionada foram pontos onde a ruptura teve início. No entanto, apenas em uma das vigas o comportamento e a resistência na flexão foram afetados pelo nó, ainda que não suficiente para alterar a média e variação dos dados. Por sua vez, os nós não influenciaram o módulo de elasticidade na flexão, independente da posição. Os resultados demonstram que a madeira de eucaliptos jovens apresenta potencial para a fabricação de produtos engenheirados, especialmente em países onde o *Eucalyptus* já é uma cultura florestal bem estabelecida, como Brasil, África do Sul e Chile. Existem diversos benefícios em utilizar esta fonte de madeira serrada, desde produção e processamento rápidos, menores riscos, entrada financeira antecipada, até a possibilidade de se estabelecer plantios próximos ao mercado consumidor. Há, no entanto, a necessidade de se avaliar o rendimento de cada etapa de processamento e a viabilidade econômica da fabricação de produtos engenheirados de madeira provinda de plantações jovens de *Eucalyptus*.

Palavras-chave: Silvicultura de ciclos curtos, Madeira juvenil, Nós, Empenamentos

ABSTRACT

Investigating the use of defect-containing timber from young *Eucalyptus* plantations for manufacturing engineered products

The increasing demand for timber globally has led to a search for sustainable wood sources. Young *Eucalyptus* plantations are a potential source of timber, taking advantage of their fast growth and high adaptability to a wide range of climatic conditions. Young trees usually contain undesirable features, such as knots, warping, and high contents of juvenile wood, apart from providing timber of limited cross-sectional dimensions, what can be overcome by the manufacture of engineered products. We aimed to address some key points, from the wood quality and mechanical properties point of view, for the adoption of short-rotation *Eucalyptus* plantations to manufacture engineered wood products. Among the high-productive clones already in use in the Brazilian bioenergy industry, we have identified some with desirable wood mechanical properties even at early ages (seven years-old). We developed and tested a bow and spring index in young and mature *E. grandis* timber boards which allows us to identify and segregate timber portions whose localized distortion is too high, helping to use the low warping sections to compose finger-jointed lamellas for engineered wood products. When testing the adhesion strength on knot-containing timber from young *E. grandis* in relation to clear wood, we found that knots reduce wood adhesion strength only when density is above 0.65 g cm^{-3}, reinforcing the benefits of stratifying lamellas on glued laminated beams. High-density lamellas are positioned on zones with higher compression and tensile stress demand, but where shear stress is low. This fact, together with the low proportion of knots on lamellas' surfaces, makes the influence of knots on the adhesion of wood of young *Eucalyptus* less significant. We build an tested glued laminated beams using timber from young *E. grandis* with different levels of bow, adding presstress to the beams. Prestress did not influence the beams' load capacity as hypothesized. However, laminated beams returned mechanical properties adequate for structural applications, even though 80% of lamellas did not meet the minimum requirements of national timber standards. While knots in the compression zone did not influence the beams' behavior, knots on the tension side were the points where rupture started. However, only one beam had the bending behavior and strength affected by the knot, although not enough to affect the average and the variation of the data. In turn, knots did not influence beams' bending stiffness independently of their position. The results showed young *Eucalyptus* timber has a high potential for manufacturing engineered products, especially in countries where *Eucalyptus* is already well established as a forest culture, such as Brazil, South Africa, and Chile. There are several benefits of using this timber source, from the fast-growing raw material production and processing, lower risks, and earlier payout, to the possibility of establishing plantations close to the consumer market. There is, however, the need for assessing the yield of each processing step and the economic viability of manufacturing engineered wood products from young *Eucalyptus* forests.

Keywords: Short rotation forestry, Juvenile wood, Knots, Warping

1. INTRODUCTION

The construction industry was responsible alone for more than 40% of the global carbon emission related to energy production and consumption in 2015 (Abergel et al., 2017). This fact led to a significant increase in the energy efficiency of buildings, which, together with many buildings having no occupation (bridges, roads, tunnels, etc), the focus of investigations turned to embodied emissions instead of operational emissions (Huang et al., 2018). Embodied emissions can be defined as the carbon emitted during the manufacture of the materials used in the building and the construction process itself, including renewals (Cabeza et al., 2014). The replacement of steel and concrete for timber is one of the most efficient strategies to reduce CO_2 emissions (Oliver et al., 2014). However, some studies point out that stocking carbon in a standing forest is even more efficient for decreasing carbon emissions (Harmon et al., 1990; Nunery & Keeton, 2010). An alternative for stocking carbon in the forests and, at the same time, adopting timber on buildings is to use plantations forests as a wood source instead of native forests.

Although planted forests usually need long rotations for timber production, some species can provide the raw material for the timber industry at earlier ages, such as *Populus* sp. (Casado et al., 2012; Castro & Paganini, 2003), *Schizolobium parahyba* (Rosa et al., 2019), *Tectona grandis* e *Gmelina arborea* (Montero & Moya, 2015). Nevertheless, species from the genus *Eucalyptus* stand out at that point. Besides being the most planted hardwood in the world (Myburg et al., 2014) and one of the fastest-growing trees (Japarudin et al., 2020), eucalypts adapt to a wide variety of environments (Gonçalves et al., 2013).

However, *Eucalyptus* wood is mainly destined for low-value products, such as paper, reconstituted panels, or bioenergy, and the reason is the generation of several quality problems after processing or drying (Wessels et al., 2020). Brazil has almost 7.5 million hectares covered with *Eucalyptus* plantations (IBGE, 2020), and it could provide timber in replacement of those coming from natural forests or long rotation pine plantations. Derikvand et al. (2017) argue that the best destination for low-grade eucalyptus timber in Australia is through the manufacture of mass timber products, such as glued laminated timber and cross-laminated timber. The motivation for the mentioned authors to look for another timber source in Australia is the same as in other countries: wood demand is increasing, but forest plantation area does not follow the same trend and natural forests are not able to rationally supply the market with timber.

The basic concept behind engineered wood products is that timber pieces are connected to form a single element. Timber can be joined with glue, nails, screws, or dowels, and their main advantage is to produce a large element from timber with small dimensions (Abbott & Whale, 1987). Besides generating only timber with small sizes, young trees are mostly unpruned and constituted by juvenile wood only. Knots resulting from the unpruned branches usually harm wood mechanical properties, reaching decrease values of 50% or more (Abbott & Whale, 1987). Juvenile wood, in turn, has lower density and mechanical properties and is usually avoided for the manufacture of solid wood products, especially for structural purposes (Missanjo & Matsumura, 2016).

However, studies with wood from young *Eucalyptus* plantations have brought encouraging results. Fideles (2017) reported branch diameters from 7 to 9.9 mm in *Eucalyptus urophylla* at 18 months, the age when natural pruning starts to occur and branches stop growing. These values are considerably lower than those reported for *Pinus sylvestris*, with diameters ranging from 10 to 45 mm (Moberg, 2000). Knots with small diameters were also reported by Crafford and Wessels (2016), and it is the probable reason why knots in young *Eucalyptus* trees did not have major impacts on the mechanical properties of timber of structural sizes (Nocetti et al., 2017; Pagel et al., 2020).

Juvenile wood, in turn, is a minor problem in hardwoods compared to softwoods, the usual raw material for engineered wood products (Zobel & Sprague, 1998). Balboni et al. (2020) confirmed juvenile wood has lower strength than mature wood, but they share the same strength-to-density relationship. Products manufactured with juvenile wood from *Eucalyptus* plantations had returned adequate properties (Liao et al., 2017; Pagel et al., 2020), with a special reference to the roof trusses made with young *E. grandis* wood, which is already well established in the South African market (Wessels et al., 2020).

The high growth rates of *Eucalyptus* allow the establishment of short-rotation forests to provide raw material to the timber industry. These plantations harvested at young stages have some advantages over the classic forests managed for timber, whether planted or natural. Besides prompt availability of wood in some regions and countries, these forests can be planted close to the main consumer markets, avoiding extra costs with transport or importation. Shorter rotations have lower risks of fire, pests, wind damage (Griess et al., 2016), and do not require thinning or pruning. An earlier cash inflow also turns plantation forests into a more attractive investment opportunity. Young trees generate logs of small diameters, allowing the adoption of linear sawmills, which increases speed and reduces the costs of primary processing (Washusen, 2013).

There are still some challenges before adopting young *Eucalyptus* as a timber source, and we have identified some of them considering previous studies as well as the Brazilian scenario. The paper and the bioenergy industries in Brazil have several *Eucalyptus* clones and varieties with high growth rates and adapted to the environment. Although they were developed for reconstituted products or for providing energy, some of these clones or varieties may provide wood with adequate quality for solid products. Identifying them can reduce costs and time for developing a variety specifically for timber production. Knots have not shown impacts on wood mechanical properties, but they are zones that may reduce wood adhesion strength due to different grain angles and higher extractive contents (Davis, 1997). Their effect on adhesion is an important subject to be assessed since a weak adhesion may cause a structural failure. Timber warping is another point of relevance, because, as stated by Derikvand et al. (2017), timber standards are too severe and do not take into consideration low grade timber can be used to compose engineered products. We have also found some standards have an imprecise calculation of timber bow and crook that should be fixed to improve the use of warped timber.

In the present series of studies, we aim to address some key points, from the wood quality and mechanical properties point of view, to turn feasible the use of timber from young *Eucalyptus* plantations to manufacture engineered wood products.

References

Abbott, A. R., & Whale, L. R. J. (1987). An overview of the use of glued laminated timber (glulam) in the UK. Construction & Building Materials, 1(2), 104–110.

Abergel, T., Dean, B., & Dulac, J. (2017). Towards a zero-emission, efficient, and resilient buildings and construction sector. www.globalabc.org

Balboni, B. M., Batista, A. S., Rodrigues, R. de A., & Garcia, J. N. (2020). Relationship between strength and density in juvenile and mature Eucalyptus sp. wood. Brazilian Journal of Animal and Environmental Research, 3(3), 983–991. https://doi.org/10.34188/bjaerv3n3-019

Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. Renewable and Sustainable Energy Reviews, 29, 394–416. https://doi.org/https://doi.org/10.1016/j.rser.2013.08.037

Casado, M., Acuña, L., Basterra, L.-A., Ramón-Cueto, G., & Vecilla, D. (2012). Grading of structural timber of Populus × euramericana clone I-214. Holzforschung, 66(5), 633–638. https://doi.org/doi:10.1515/hf-2011-0153

Castro, G., & Paganini, F. (2003). Mixed glued laminated timber of poplar and Eucalyptus grandis clones. Holz Als Roh- Und Werkstoff, 61(4), 291–298. https://doi.org/10.1007/s00107-003-0393-6

Crafford, P. L., & Wessels, C. B. (2016). The potential of young, green finger-jointed Eucalyptus grandis lumber for roof truss manufacturing. Southern Forests, 78(1), 61–71. https://doi.org/10.2989/20702620.2015.1108618

Davis, G. (1997). The performance of adhesive systems for structural timbers. International Journal of Adhesion and Ahesives, 17(3), 247–255.

Derikvand, M., Nolan, G., Jiao, H., & Kotlarewski, N. (2017). What to Do with Structurally Low-Grade Wood from Australia ' s Plantation Eucalyptus ; Building Application ? BioResources, 12(1), 4–7.

Fideles, J. C. A. (2017). Oclusão da casca indica o início da formação de clear em árvores desramadas.

Gonçalves, J. L. D. M., Gonçalves, D. M., Alcarde, C., Rioyei, A., Duque, L., Couto, A., Stahl, J., Frosini, S., Ferraz, D. B., Paula, W. de, Henrique, P., Brancalion, S., Hubner, A., Bouillet, J. D., Laclau, J., Nouvellon, Y., & Epron, D. (2013). Integrating genetic and silvicultural strategies to minimize abiotic and biotic constraints in Brazilian eucalypt plantations. Forest Ecology and Management, 301, 6–27. https://doi.org/10.1016/j.foreco.2012.12.030

Griess, V. C., Uhde, B., Ham, C., & Seifert, T. (2016). Product diversification in South Africa ' s commercial timber plantations : a way to mitigate investment risk. Southern Forests, 78(2), 145–150. https://doi.org/10.2989/20702620.2015.1136508

Harmon, M. E., Ferrell, W. K., & Franklin, J. F. (1990). Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests. Science, 247(4943), 699–702. https://doi.org/10.1126/science.247.4943.699

Huang, L., Krigsvoll, G., Johansen, F., Liu, Y., & Zhang, X. (2018). Carbon emission of global construction sector. Renewable and Sustainable Energy Reviews, 81, 1906–1916. https://doi.org/https://doi.org/10.1016/j.rser.2017.06.001

IBGE. (2020). Produção da Extração Vegetal e da Silvicultura—PEVS. In https://www.ibge.gov.br/estatisticas-novoportal/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html . https://www.ibge.gov.br/estatisticas-novoportal/economicas/agricultura-e-pecuaria/9105-producao-da-extracao-vegetal-e-da-silvicultura.html

Japarudin, Y., Lapammu, M., Alwi, A., Warburton, P., Macdonell, P., Boden, D., Brawner, J., Brown, M., & Meder, R. (2020). Growth performance of selected taxa as candidate species for productive tree plantations in Borneo. Australian Forestry, 83(1), 29–38. https://doi.org/10.1080/00049158.2020.1727181

Liao, Y., Tu, D., Zhou, J., Zhou, H., Yun, H., Gu, J., & Hu, C. (2017). Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers. Construction and Building Materials, 132, 508–515. https://doi.org/10.1016/j.conbuildmat.2016.12.027

Missanjo, E., & Matsumura, J. (2016). Wood Density and Mechanical Properties of Pinus kesiya Royle ex Gordon in Malawi. Forests, 7(7). https://doi.org/10.3390/f7070135

Moberg, L. (2000). Models of Internal Knot Diameter for Pinus sylvestris. Scandinavian Journal of Forest Research, 15(2), 177–187. https://doi.org/10.1080/028275800750014984

Montero, R. S., & Moya, R. (2015). Reducing Warp and Checking in 4 by 4 Beams from Small-Diameter Tropical Species (Tectona grandis, Gmelina arborea, and Cordia alliodora) Obtained by Turning the Pith Inside Out. Forest Products Journal, 65(5–6), 285–291. https://doi.org/10.13073/FPJ-D-14-00089

Myburg, A. A., Grattapaglia, D., Tuskan, G. A., Hellsten, U., Hayes, R. D., Grimwood, J., Jenkins, J., Lindquist, E., Tice, H., Bauer, D., Goodstein, D. M., Dubchak, I., Poliakov, A., Mizrachi, E., Kullan, A. R. K., Hussey, S. G., Pinard, D., van der Merwe, K., Singh, P., … Schmutz, J. (2014). The genome of Eucalyptus grandis. Nature, 510(7505), 356–362. https://doi.org/10.1038/nature13308

Nocetti, M., Pröller, M., Brunetti, M., Dowse, G. P., & Wessels, C. B. (2017). Investigating the potential of strength grading green Eucalyptus grandis lumber using multi-sensor technology. BioResources, 12(4), 9273–9286. https://doi.org/10.15376/biores.12.4.9273-9286

Nunery, J. S., & Keeton, W. S. (2010). Forest carbon storage in the northeastern United States: Net effects of harvesting frequency, post-harvest retention, and wood products. Forest Ecology and Management, 259(8), 1363–1375. https://doi.org/https://doi.org/10.1016/j.foreco.2009.12.029

Oliver, C. D., Nassar, N. T., Lippke, B. R., & McCarter, J. B. (2014). Carbon, Fossil Fuel, and Biodiversity Mitigation With Wood and Forests. Journal of Sustainable Forestry, 33(3), 248–275. https://doi.org/10.1080/10549811.2013.839386

Pagel, C. L., Lenner, R., & Wessels, C. B. (2020). Investigation into material resistance factors and properties of young, engineered Eucalyptus grandis timber. Construction and Building Materials, 230, 117059. https://doi.org/10.1016/j.conbuildmat.2019.117059

Rosa, T. O., Terezo, R. F., Rios, P. D., Sampietro, J. A., & Rosa, G. O. (2019). Schizolobium Parahyba var. Amazonicum Glulam Classified by Non-destructive Tests. In Floresta e Ambiente: Vol. v. vol.26 num.2. Instituto de Florestas da Universidade Federal Rural do Rio de Janeiro.

Washusen, R. (2013). Processing methods for production of solid wood products from plantation- grown Eucalyptus species of importance to Australia (Issue April).

Wessels, C. B., Nocetti, M., Brunetti, M., Crafford, P. L., Pröller, M., Dugmore, M. K., Pagel, C., Lenner, R., & Naghizadeh, Z. (2020). Green-glued engineered products from fast growing Eucalyptus trees: a review. European Journal of Wood and Wood Products, 78(5), 933–940. https://doi.org/10.1007/s00107-020-01553-6

Zobel, B. J., & Sprague, J. R. (1998). Juvenile Wood in Forest Trees. Springer.

2. CONCLUSIONS

The topics assessed in the present study, usually considered impeditive for the use of wood from young trees, are an obstacle possible to overcome through the use of technology. We believe as happens in other areas of science, that the knowledge acquired by the developed countries has an influence on studies conducted in other regions, sometimes creating a general rule that may not be true for all situations. In our opinion, such is the case of the impacts of juvenile wood and knots on mechanical properties. Both features reduce the wood quality in softwoods more than in hardwoods. Although some authors have pointed that out previously, studies about softwood created an idea that it is not possible to use wood containing such features for solid products or structures. In Brazilian Pine, for example, the juvenile core of logs is large and has low quality, resulting in the timber from that zone to be often discarded. The brittle behavior usually seen in Pine timber from the log cores was not observed in the *Eucalyptus* we used. The fragile rupture in young *Eucalyptus* may be restricted to timber from the first two rings around the pith, so lamellas returned the same mechanical behavior usually observed in mature wood.

The knots showed a similar result. In young *Eucalyptus*, knots are smaller than those in Pine and are not distributed in clusters. These characteristics have a relevant influence on the mechanical behavior of wood with knots from these two types of wood. We did find decreases in adhesion and tensile strength (on beams) caused by knots, while on compression (on beams), knots did not show any qualitative or quantitative impact. We consider these reductions still allow the use of timber from young *Eucalyptus* for structural purposes, especially when considering the good adhesion results we observed.

Timber bow, even above the limits established, was not harmful to the manufacture of glued laminated beams, on the contrary, it seems to be beneficial. The other types of warping, on the other hand, are harder to handle and should be avoided. The developed index for timber bow and spring can be useful to improve yield on the conversion of timber to lamellas, especially finger jointed ones.

Our studies were conducted on a laboratory scale, so the positive results observed in our beams are strongly related to the careful selection and stratification of lamellas. On a commercial scale, the classification of lamellas by stiffness and bow levels must be faster and, consequently, may be less precise. However, we believe it is feasible to obtain results close to what we reported here if a production line is designed specifically for manufacturing glued laminated beams using timber from young *Eucalyptus*.

We also had the opportunity to manufacture a piece of furniture using wood from young *Eucalyptus grandis* (Appendix). We applied different techniques such as edge gluing, biscuit and dowel connections, resin filling and the material behaved normally. This is a positive result and indicate young *Eucalyptus* may also supply the furniture industry with timber, besides the already stablished reconstituted panel based furniture.

There are several benefits of using young forests as a timber source, from the fast raw material production and optimized processing, earlier payout, to the possibility of establishing plantations close to the consumer market. However, there is still relevant information about young *Eucalyptus* timber for structural application. From the material science perspective, the assessment of the behavior of knots under tension and the effect of a thin layer of clear wood on top of the knots under tension. From the industrial side, it might be interesting to develop a production line specifically for young *Eucalyptus* products, assess the losses of timber due to splitting and warping together with the economic viability.

APPENDIX

Item manufactured at the wood workshop course during the doctoral internship at Stellenbosh University: a bedside table made with young *Eucalyptus grandis* timber.

Figure 1. Raw material: finger-jointed boards of young *Eucalyptus grandis* timber.

Figure 2. Pieces of the bedside table before assembling.

Figure 3. Detail of the connections used: biscuit joints at the top and dowel connections at the bottom on both sides.

Figure 4. Final product presented as requirement for the wood workshop course.