Assessment of Microwave Bending Capabilities for Australian Wood Species

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Abstract

An innovative wood bending technology has been developed by the University of Melbourne, within the Cooperative Research Centre for Wood Innovations, which involves the microwave softening of wood components to make them pliable for bending, the use of an automated bending machine, and microwave drying of bent furniture components. This article presents the results of a study that assessed bending quality and that determined the minimum radius of bending curvature of eight plantation and regrowth Australian timbers using the microwave wood bending process: *Eucalyptus nitens, Eucalyptus saligna, Eucalyptus marginata, Eucalyptus diversicolor, Pinus radiata, Nothofagus cunninghamii, Atherosperma moschatum,* and *Acacia melanoxylon*.

Based on the results of the study, the microwave bending performance of the wood species was rated as follows: (1) *E. diversicolor,* very good (sanding or small amount of machining was required); (2) *P. radiata, Atherosperma moschatum,* and *E. nitens,* decent (machining was needed); (3) *Acacia melanoxylon* and *N. cunninghamii,* satisfactory (fairly large failures occurred but these were removed by machining); and (4) *E. saligna* and *E. marginata,* very bad (large failures which could not be removed by machining).

Overall, the results of the study on the bending performance capabilities of plantation and regrowth Australian timbers showed several differences compared with the literature data relating to the bending abilities of the relevant old growth timbers.

Wood bending as a means of producing curved components in timber construction has many advantages over other methods of manufacture, but the main advantage is increased strength and recovery of timber. Up to 100 percent higher yield can be gained by bending wood components compared with the traditional techniques such as sawing for shaping wood. This higher yield, combined with the remarkably higher quality and durability of the finished product, leads to lower production costs and an improved cost benefit to the industry.

In Australia, bent-wood components have only been used to a limited extent by craft producers, individual designer makers, and a few manufacturers. Research data on the bending properties of Australian timbers, based on studies from the 1940s to 1970s, are applicable only to steam bending of old growth timbers (Kingston 1939, CSIRO 1948, Stevens and Turner 1970).

Although in the past mainly old growth timbers were used for the production of furniture and other appearance products, a global trend to promote a sustainable use of timber resources has stimulated the industry to adapt to the changes by using plantation and regrowth timbers and by using more efficient production techniques. Therefore, researchers and postgraduate students at the Cooperative Research Centre (CRC) for Wood Innovations within the University of Melbourne have been studying various aspects of wood bending with the objective to develop innovative techniques, based on microwave (MW) technology, for the design and manufacture of bent-wood components from young timber resources because these are the current and future timber resources for the furniture industry in Australia.

This article presents the results of a study aimed at assessing bending quality and determining the minimum radius of bending curvature of selected plantation and regrowth Australian timbers.

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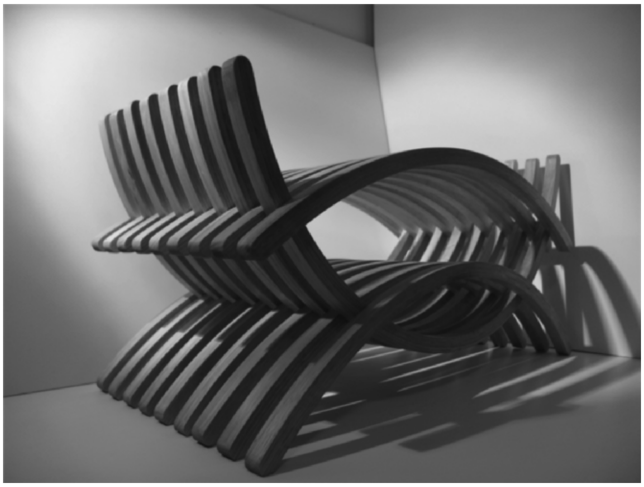

Figure 1.—Wine rack made from microwave bent components of E. regnans *(designer: Lotars Ginters, Swinburne University of Technology).*

Microwave Wood Bending Technology

The MW wood bending process consists of three stages:

1. microwave heating of timber to soften and make it ready for bending,
2. bending of softened timber to the required shape and restraining the bent components before drying and conditioning, and
3. accelerated drying and stabilization of bent components using MW technology.

Prior to the study discussed in this article, extensive research was conducted at CRC Wood Innovations on various aspects of MW wood bending. A short summary of this research is presented below.

1. An investigation of the application of MW technology for softening timber in order to make it plastic for bending (Studhalter 2005, Studhalter at al. 2008) was designed to determine temperature distribution and transmission in cross sections of wood (*Eucalyptus regnans*) during and after the heating process, and to determine moisture distribution variations in the cross section before and after the heating process. In addition, the MW heating process was investigated to determine optimal heating parameters for softening wood using MW irradiation.
2. A study of the mechanical behavior of wood during bending (Juniper 2008) offers original contributions to the improved understanding of the mechanical behavior of wood (*E. regnans*) during MW bending (mechanical properties of MW and steam-heated wood, optimal bending parameters, strain analysis during the bending process, the effect of end-force on bending performance). A theoretical model of the wood bending operation was developed using computer-based, nonlinear finite element methods. The outcomes of this study have been instrumental in designing and constructing prototype wood bending equipment for industrial applications.
3. A study of the use of MW irradiation for drying and stabilization of bent components (Harris et al. 2007) aimed to determine the feasibility of utilizing MW heating to dry bend timber components 25 by 25 by 1,000 mm, to reduce the drying time compared with the conventional method, without increasing degrade. The studies showed that the rapid drying of wood components of *E. regnans* from an initial moisture content (MC) of 45 to 50 percent, is feasible using MW heating. This can be achieved in a matter of hours with minimal degrade compared with the conventional method of drying, which could take 5 months to dry similar components of this species.
4. Development of technical parameters for heating, bending, and drying of components for selected commercial species (Daian and Ozarska 2007). Bending performance of various commercial species was evaluated using MW wood bending equipment.
5. Development of technical specifications and requirements for commercialization of the technology. A Design Brief for the construction of the prototype industrial equipment for commercialization of the MW wood bending technology was developed (Ozarska and Juniper 2006).
6. Modeling of business processes in the adaptation of MW wood bending technology in the furniture industry (Moe et al. 2007). The key objective of the project was to develop a business model, to evaluate the implications of the MW wood bending technology to a specific business environment of furniture manufacturers and shaped component manufacturers.
7. Parallel design investigation of a comprehensive range of applications (Hyams 2007). A wide range of products has been designed and made by the team from the National Faculty of Design at Swinburne University of Technology (an example is provided in Fig. 1).

The outcomes of the extensive research program summarized above have significant scientific and commercial values due to their novel and innovative approaches.

Table 1.—Frequency distribution by visual ranking.

Wood species	Visual ranking (%)					Total no. of samples
	1	2	3	4	5	
Nothofagus cunninghamii	53	15	11	16	5	19
Pinus radiata	47	37	16	0	0	19
Acacia melanoxylon	6	47	29	18	0	17
Atherosperma moschatum	44	25	31	0	0	16
Eucalyptus saligna	5	32	37	11	15	19
E. nitens	60	25	10	0	5	20
E. marginata	61	22	0	0	17	18
E. diversicolor	40	60	0	0	0	10

Table 2.—Average moisture content and ovendry density of the assessed samples.

Wood species	Average MC (%)[a]	Average ρ_0 (kg/m^3)
Nothofagus cunninghamii	76	715
Pinus radiata	92	491
Acacia melanoxylon	98	615
Atherosperma moschatum	80	563
Eucalyptus saligna	78	791
E. nitens	69	733
E. marginata	62	713
E. diversicolor	56	852

[a] The moisture content of the samples was determined using the ovendry method according to AS/NZS 1080.1:1997 (Standards Australia/Standards New Zealand 1997).

The studies provided a set of scientific data on optimal material and technical parameters in the bending process that proved that this technology is suitable for ''mass production'' of bent components in an industrial application.

The technology has created a great interest within the timber and furniture industries as it is seen as having great potential for new designs and future product development (BFG Consulting Group 2004).

Fundamental research studies just described provided a set of scientific data on the optimal parameters for *E. regnans,* which is a species in high demand by furniture manufacturers in Australia.

This article describes the assessment of the bending performance capability (bending quality and the minimum radius of curvature) of eight other Australian species suitable for furniture manufacture.

Materials and Methods

Samples from eight wood species, originating from plantations (*Eucalyptus nitens, Eucalyptus saligna, Pinus radiata*) and regrowth forests (*Eucalyptus marginata, Eucalyptus diversicolor, Nothofagus cunninghamii, Atherosperma moschatum, Acacia melanoxylon*) were collected for assessing the bending performance capability of Australian timbers.

The samples for testing were supplied by various sawmills from different parts of Australia. The sawmillers were provided with detailed specification on the dimensions, wood quality, and quality of machining of the samples. Although some sawmillers accurately followed the requirements listed in the specification, unfortunately the others did not and supplied samples that were not suitable for bending. For this reason, the number of assessed wood samples varied for each species (Table 1).

In general, clear, well-machined, straight-grained, and wet samples, cut at 25 by 25 by 885 mm, were selected to perform the MW bending trials.

Wood properties such as MC and ovendry density (ρ_0) were measured for each sample (Table 2). The average values of MC of the samples were above 60 percent. According to previous studies (Juniper 2008), MC higher than 60 percent is required to achieve optimal results during MW bending.

The bending trials were performed using the bending equipment set-up at the Melbourne University laboratory. The equipment consisted of a 5-kW, 2.45-GHz microwave unit used for the wood softening process (Studhalter 2005) and a purpose built ''spiral'' bending machine equipped with the spiral form in which radius decreases progressively from a maximum value of 400 mm to a minimum value of 260 mm (Juniper 2008). The optimum operating parameters established in the previous bending research (Studhalter 2005, Juniper 2008) were used during the trials: MW power, 1.5 kW; conveyor speed, 34 mm/s; and bending strain rate, 13°/s.

As a critical parameter in successful bending, the temperature of wood developed during the softening process was continuously monitored for each sample, using a fiber optic probe temperature measuring device and recorded by a data acquisition system, until it reached 100°C. To achieve this temperature, the wood sample was passed through the conveyor tunnel from four to six times, depending on the species and its MC.

Based on the ranking systems developed in previous MW wood bending studies (Juniper 2008), the assessment procedure involved two stages: general assessment of bending quality and minimum radius determination. The failure assessment procedure was implemented for each bend.

The general assessment consisted of a visual examination of each bent-wood specimen, a description of the general level of wood failure, and ranking of the specimens according to the following levels: 1 = perfect bend, no final preparation or little sanding needed; 2 = very good bend, sanding needed or small amount of machining; 3 = decent bend, machining needed; 4 = just satisfactory bend, fairly large failure, but can be mostly removed by machining; and 5 = failed bend, very large failure with no chance of recovery.

The first failure location on the length of the bent specimen was used to determine the minimum radius of bending for each sample. The type of failure (fracture or wrinkle) and the reason for the failure (e.g., tension, compression, knot, gum vein) for each sample were

Table 3.—Frequency distribution by minimum radius.

Wood species	% frequency distribution by minimum radius (mm)					Total no. of samples
	260–280	281–310	311–340	341–370	371–400	
Nothofagus cunninghamii	42	11	5	16	26	19
Pinus radiata	68	11	5	11	5	19
Acacia melanoxylon	53	12	18	0	17	17
Atherosperma moschatum	81	0	0	19	0	16
Eucalyptus saligna	0	21	32	26	21	19
E. nitens	70	5	10	10	5	20
E. marginata	72	17	5	0	6	18
E. diversicolor	100	0	0	0	0	10

Table 4.—Cumulative frequency distribution by visual ranking.

Wood species	% cumulative frequency by visual ranking				
	1	1+2	1+2+3	1+2+3+4	1+2+3+4+5
Nothofagus cunninghamii	53	68	79	95	100
Pinus radiata	47	84	100	—	—
Acacia melanoxylon	6	53	82	100	—
Atherosperma moschatum	44	69	100	—	—
Eucalyptus saligna	5	37	74	85	100
E. nitens	60	85	95	95	100
E. marginata	61	83	83	83	100
E. diversicolor	40	100	—	—	—

recorded on a spread sheet developed for the experiments. In addition, a photo of each sample was taken to document the type of failure.

Data Analysis and Discussion

A descriptive statistic (i.e., the frequency distribution method) was used for the final analysis of the collected data. Due to the inconsistent number of samples relevant for assessment within each species, the frequency distribution of both visual ranking and minimum radius was expressed as percentages of samples in different ranking and radii groups (Tables 1 and 3).

The literature shows that various studies (Forest Products Research Laboratory 1967, Kollmann and Cote 1968, Stevens and Turner 1970) use a 95 percent confident level to indicate a safe radius of curvature to which timbers may be bent, so that no more than 5 percent of the total number of bent pieces will fracture during the process. Likewise, a particular ranking level is assigned within this study to the wood components so that 95 percent of the bent pieces pass the criteria described for this level.

Looking at the frequency distribution figures from Table 1, the bending quality level is difficult to determine due to the inconsistent values. Therefore, the cumulative frequency distribution was used to establish the lowest level at which the bend of a wood species could fail (Table 4).

Based on the results presented in Table 4, the MW bending performance of the studied wood species has been rated as follows:

- *E. diversicolor*—very good bend (wood failure level 2).
- *P. radiata, Atherosperma moschatum,* and *E. nitens*—decent bend (wood failure level 3).
- *Acacia melanoxylon* and *N. cunninghamii*—just satisfactory bend (wood failure level 4).
- *E. saligna* and *E. marginata*—very bad bending quality (wood failure level 5).

The minimum bending radius for each wood species was established on the same principle: grouping the radii in classes of radii and then applying the frequency and cumulative frequency distributions (Tables 3 and 5) to estimate the probable minimum failure point. Each wood species was assigned a particular minimum radius of curvature to which it could bend if 95 percent of the components bent with a decent bend at radii lower or equal to the assigned radius (refer to radii grouping in Table 5).

The radius range between 260 and 400 mm was derived from the technical parameters of the spiral bending machine used for the trials.

According to the data shown in Table 5, a low probability (5%) of obtaining failure points is expected if the bending of the studied wood species is performed at radii greater than 280 mm for *E. diversicolor*; 370 mm for *P. radiata, Atherosperma moschatum,* and *E. nitens*; and 400 mm for *N. cunninghamii, Acacia melanoxylon, E. saligna,* and *E. marginata*.

The unexpected high-quality bending for some of the tested wood species (i.e., *E. diversicolor, P. radiata, Atherosperma moschatum,* and *E. nitens*) and the fact that the wood specimens originated from young trees, may imply that wood resources from regrowth and plantation forests give better bending performances than mature wood. However, it should be pointed out that the data on the bending performance of old growth timbers were obtained using the conventional steam bending method, whereas this study investigated young timbers (plantation and regrowth) using the MW bending method. Therefore, to compare the bending performance of old growth and plantation/regrowth timbers, a research study needs to be undertaken using the MW bending method for both timber resources. This study is due to be undertaken in the near future.

Table 5.—Cumulative frequency distribution by minimum radius.

Wood species	% cumulative frequency by minimum radius (mm)				
	260–280	260–310	260–340	260–370	260–400
Nothofagus cunninghamii	42	53	58	74	100
Pinus radiata	68	79	84	95	100
Acacia melanoxylon	53	65	83	83	100
Atherosperma moschatum	81	81	81	100	—
Eucalyptus saligna	0	21	53	79	100
E. nitens	70	75	85	95	100
E. marginata	72	89	94	94	100
E. diversicolor	100		—	—	—

Table 6.—Summary of the bending performance (bending quality and minimum radius of curvature) for tested plantation and regrowth Australian timbers.

Species included in the study	Bending quality	Minimum radius of curvature in bending (mm)
Eucalyptus diversicolor	Very good	280
Pinus radiata	Decent	370
Atherosperma moschatum	Decent	370
E. nitens	Decent	370
Acacia melanoxylon	Satisfactory	400
Nothofagus cunninghamii	Satisfactory	400
E. saligna	Very bad	400
E. marginata	Very bad	400

Conclusions

Overall, the results of the study on the bending performance capabilities of plantation and regrowth Australian timbers showed several differences compared with the literature data relating to the bending abilities of the relevant old growth timbers (Kingston 1939, CSIRO 1948, Diehm 1989, Leaversuch 2002). For instance, according to the literature, *E. marginata* has moderate bending qualities and *N. cunninghamii* is difficult to bend, while the bending qualities of *Acacia melanoxylon* are generally very good.

The summary of the bending quality and minimum radii of curvature for the wood species subjected to the MW softening process is presented in Table 6.

The high quality bending results for some of the tested wood species (i.e., *E. diversicolor, P. radiata, Atherosperma moschatum,* and *E. nitens*) demonstrate that the timbers from regrowth and plantation resources can be satisfactorily used for the production of bent components. The intention is to extend the research by undertaking more trials on Australian timbers, especially from New South Wales, Queensland, and Victoria, in order to provide a mapping of the capabilities of Australian species to bend for potential commercial applications of the MW bending technology.

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