Impact of sapwood and the properties and market utilisation of plantation and young hardwoods: Determination of minimum radius of bending curvature of heartwood and sapwood from plantation and young hardwood species using microwave wood bending technology (PART B)
Impact of sapwood and the properties and market utilisation of plantation and young hardwoods: Determination of minimum radius of bending curvature of heartwood and sapwood from plantation and young hardwood species using microwave wood bending technology (PART B)

Prepared for
Forest & Wood Products Australia

by
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Publication: Impact of sapwood and the properties and market utilisation of plantation and young hardwoods

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Executive Summary

This project studied the bending characteristics of the heartwood and sapwood material of nine hardwood species from young regrowth forests or grown on managed plantations for sawlog regimes in Australia. Bending experiments were performed using microwave wood bending technology developed by the University of Melbourne within the Cooperative Research Centre for Wood Innovations.

The bending assessment procedure involved two steps: general assessment of bending and determination of minimum radius of bending curvature. Descriptive statistical tools such as the frequency distribution method were used for the final analysis of the collected data.

The outcomes of the study indicate that when subject to the microwave softening process, the general bending performance of the studied wood species shows the following results:

Plantation resources:
- E. cloeziana: no ability to bend at a radius range of 400-260 mm. Very large failures occurred for the majority of tested specimens.
- E. saligna: good and satisfactory bending for heartwood (machining needed to remove large or fairly large failures) but very severe failures for the majority of sapwood samples.
- E. globulus: very good to moderate bending ability, with some machining of bends required.
- E. nitens and E. dunnii: perfect bending characteristics for heartwood, with no final preparation or little sanding needed and satisfactory bending for sapwood.

Young regrowth resources:
- E. pilularis and Corymbia maculata: no ability to bend at a radius range of 400-260 mm. Very large failures occurred for the majority of tested specimens.
- E. obliqua: satisfactory to no ability to bend. Machining needed to remove fairly large failures.
- E. diversicolor: very good to moderate bending ability, with some machining of bends required.

The minimum radius of curvature for the studied wood species, where no failure occurs or a small amount of machining is needed, falls within the following range:
- E. pilularis, Corymbia maculata and E. cloeziana: 400-340 mm or even lower (up to 310 mm)
- E. obliqua and E. saligna: 400-280 mm
- E. diversicolor and E. dunnii (sapwood): 370/340 mm to 260 mm
- E. globulus: 340-260 mm
- E. nitens and E. dunnii (heartwood): 280-260 mm.
The above results suggest that with better ability to bend, the lower curvature radius is likely to be achieved.

For the wood species with modest bending abilities (E. diversicolor, E. saligna, E. obliqua), the bending quality level of heartwood and sapwood may differ. Notable are E. saligna and E. dunnii, which have relatively good and respectively excellent bending characteristics for heartwood but very poor for sapwood. In general, the heartwood for all investigated wood species showed the ability to bend at slightly smaller radii than the sapwood. A larger difference in the minimum bending radius was found for the heartwood and sapwood of E. dunnii (heartwood bent at 100 mm lower radii than the sapwood) and E. diversicolor (sapwood bent at 60 mm lower radii than the heartwood).

Overall, the results of the study on the bending performance capabilities of plantation and young hardwood Australian timbers showed several differences compared with the literature data relating to the bending abilities of the relevant old growth timbers. For the majority of species evaluated in this study, the values of the minimum radii of curvature obtained during the bending experiments were lower than the values reported in the literature and anecdotal statements made by experienced Australian wood benders. Based on this study and previous research undertaken at the University of Melbourne on bending performance of plantation timbers the conclusion can be made that wood resources from regrowth and plantation forests give better bending performances than old growth timbers.
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Project Outline

This project is the result of work coordinated by the University of Tasmania (UTAS), in collaboration with the Department of Primary Industries & Fisheries – Queensland (DPI-Q), University of Melbourne (UMEL) and the Forest Products Commission (FPC) in Western Australia. The objectives of the project are to:

(i) Determine and compare the physical and visual properties of the heartwood and sapwood of commercially important hardwood species grown in plantation and young regrowth regimes in Australia with accepted public data for native forest material of those species.
(ii) Determine the likely net value of retaining the sapwood in the tested species given these properties. The project outcomes are reported in six parts as listed in Table 1.

Table 1: Overview of project reporting structure.

<table>
<thead>
<tr>
<th>REPORT NUMBER</th>
<th>NAME</th>
<th>AUTHOR/S</th>
</tr>
</thead>
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<tr>
<td>Part 1</td>
<td>Project executive summary</td>
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<td>Part 5</td>
<td>Mechanical testing of southern &amp; northern species</td>
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<td>Part 6</td>
<td>Visual properties assessment</td>
<td>UTAS</td>
</tr>
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</table>
Project Background

The hardwood processing industry in Australia is in transition from milling predominantly native forest logs to milling a combination of plantation and native forest logs of different age and diameter. Increases to Australia's native forest reserves and a reduction in productivity of the remaining resource have reduced the supply of native forest sawlogs (for both solid wood and veneer production) from public forests. Smaller diameter native forest regrowth, and plantation sawlogs are being substituted to make up this shortfall (Nolan et al 2005). Mechanical properties of the Australian timber species (both hardwoods and softwoods) considered at the time to have most commercial potential are given in the standard 1960s references. These reports were prepared by CSIRO Division of Forest Products in the 1960s (Kingston and Risdon (1961) for shrinkage and density, and Bolza and Kloot (1963) for mechanical properties). The data were nearly all based on samples from mature trees. The continually changing availability of forest resources to the Australian timber industry means that it is essential to assess the properties of regrowth species from native forest and those of plantation-grown timbers.

With the transition of the log supply many challenges face the industry regarding the economics of processing the future resource and the ability of the future resource to substitute for declining native sawlog supply (Cameron & Willersdorf 2006). The industry is in different stages of this transition in different regions. Tasmania will experience this transition before others with Forestry Tasmania estimating that hardwood plantations will account for 50% of the (high quality) hardwood sawlog supply by 2020 (currently providing less than 1%). By 2010, the total national supply of hardwood plantation sawlogs will be about 358,000 cubic metres per year. Tasmania will produce about 53% of the total and Central Gippsland and North Coast New South Wales about 20% each. Hardwood plantation sawlog supply is forecast to exceed 1 million cubic metres per year after about 2020 and to peak at around 1.8 million cubic meters per year in 2030 (Parsons et al 2007).

A successful transition from native forest logging to intensively managed hardwood plantations will require not only the development of new processing techniques, but also improved knowledge of the properties of the young, fast grown wood resource. Among the attributes most critical to the successful utilisation of plantation hardwoods are the physical and mechanical properties of the wood. Studies on the utilisation properties of Australia plantation hardwoods have recently been conducted by Muneri et al. (1998), Muneri and Leggate (2000), Muneri et al. (2003), McGavin et al. (2007) and McGavin et al. (2006), who have reported on a range of physical and mechanical properties.

However these studies, and most others reported in the literature, have omitted sapwood from their investigations. Among the reasons for this are:
• sapwood has been regarded of such low value due to its low durability and susceptibility to *Lyctus* spp. (lyctid or powder post beetle) infestation in most species, that it has been regarded as a waste product;

• sapwood made up only a small part of hardwood logs traditionally extracted from native forests, and little was recovered during traditional milling operations.

Hardwood producers in all states are recognizing that adjustment to the changed resource is essential. Fundamental questions raised by this adjustment include defining the properties of this new resource and comparing them to the species properties currently recognised in the marketplace. Furthermore, the sapwood of lyctid susceptible eucalypts is removed from the sawn board and veneer as standard practice. With large diameter logs sourced from mature native forests the yield losses through removal of sapwood are relatively minor. However, the recovery losses by removing sapwood become increasingly significant as log diameter decreases and the relative proportion of sapwood increases. Thus potential gains may be made by retaining the sapwood and treating the susceptible material to prevent lyctid attack.

As the sapwood is likely to differ in properties from the heartwood this project will determine and compare the physical and appearance properties of the heartwood and sapwood of commercially important hardwood species grown in plantation and young regrowth regimes with the accepted public data for native forest material of those species. For non-susceptible species and in states where sapwood is currently retained and treated, there is still significant value in clarifying the properties of the future resource. The characteristics of interest in the marketplace include mechanical properties, such as stiffness, strength, density, stability, screw holding and hardness. Appearance properties are also assessed with particular reference to colour, finishing quality and the ability to take a stain and coating.

**Report introduction and objectives**

This report provides Part 3 “Determination of minimum radius of bending curvature using microwave wood bending technology” of the large collaborative research project described above.

The aim of this study was to assess the bending characteristics of the heartwood and sapwood material of nine hardwood species from young regrowth forests or grown on managed plantations for sawlog regimes in Australia.

Minimum radius of curvature, which can be achieved through bending, has been determined using microwave wood bending technology developed by the Cooperative Research Centre for Wood Innovations.

The application of microwave technology to soften wood before bending has the following advantages over other softening methods:
The heating process is completed very quickly and thick pieces of wood can be heated within seconds, while it would take significantly longer (hours) with steaming.

- It is an online process and the temperature can be controlled to the required levels at specific positions in the timber.
- With no additional water (as occurs with steaming), the setting process can be achieved faster.
- Both softening and drying (setting) can be achieved using the same technology.

Studies undertaken within the CRC Wood Innovations (Juniper 2008; Reis and Siemon 2006) showed that the application of microwave technology for bending selected Australian timbers enables to achieve lower values of radii of curvature of bent components in comparison with the steam bending method.

Taking into account the innovative aspects of the microwave bending method and its future availability to the Australian timber and furniture industries, this method was selected to be used in the assessment of bending characteristics of sapwood and heartwood timbers included in this project.

**Hardwood species tested and samples preparation**

Nine hardwood species originating from either plantations or regrowth forests from Australia were assigned for the bending test (Table 2). Two different sites (named throughout the report as Site 1 or Site 2) were sampled in supplying the wood material for each species, except for Dunn’s white gum\(^1\).

The site details for any particular wood species indicated similarities with regard to forests age and silviculture practices.

\(^1\) All Dunn’s white gum material was received only from one site due to supply constraints.
<table>
<thead>
<tr>
<th>Species</th>
<th>Site Details</th>
<th>Planting Date</th>
<th>Age</th>
<th>Silviculture Details</th>
<th>Site Owner</th>
<th>Processing Details</th>
<th>Date collected</th>
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<tr>
<td>Blackbutt (Eucalyptus pilularis)</td>
<td>Compartment 53, Wild Cattle Creek State Forest</td>
<td>1990</td>
<td>18</td>
<td>Natural regeneration</td>
<td>State Forests NSW</td>
<td>Salisbury Research Centre</td>
<td>Oct-07 &amp; Nov-07</td>
</tr>
<tr>
<td></td>
<td>Nr. Grafton, NSW</td>
<td></td>
<td></td>
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<td>State Forests NSW</td>
<td>Salisbury Research Centre</td>
<td>Oct-07 &amp; Nov-07</td>
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<td>Gympie messmate (Eucalyptus cloeziana)</td>
<td>Cpt 5C, Ringtail S.F., Tewantin, Qld</td>
<td>Dec-59</td>
<td>48</td>
<td>Plantation</td>
<td>NRW Qld</td>
<td>Salisbury Research Centre</td>
<td>Sep-07</td>
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<tr>
<td></td>
<td>Cpt 12B, Yurol S.F., Tewantin, Qld</td>
<td>Dec-49</td>
<td>58</td>
<td>Plantation</td>
<td>NRW Qld</td>
<td>Salisbury Research Centre</td>
<td>Feb-08</td>
</tr>
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<td>Dunn’s white gum (Eucalyptus dunnii)</td>
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<td>Plantation</td>
<td>State Forests NSW</td>
<td>Salisbury Research Centre</td>
<td>Feb-08</td>
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<tr>
<td></td>
<td>Moonpar S.F., nr. Dorrigo, NSW</td>
<td>1996</td>
<td>12</td>
<td>Plantation</td>
<td>State Forests NSW</td>
<td>Salisbury Research Centre</td>
<td>Feb-08</td>
</tr>
<tr>
<td>Karri (Eucalyptus diversicolor)</td>
<td>Iffley Block</td>
<td>Regen-1979</td>
<td>29</td>
<td>Natural regeneration</td>
<td>State Forests WA</td>
<td>Rockbridge Milling SE</td>
<td>Nov-07</td>
</tr>
<tr>
<td></td>
<td>Brockman Block</td>
<td>Regen-1980</td>
<td>28</td>
<td>Natural regeneration</td>
<td>State Forests WA</td>
<td>Rockbridge Milling SE</td>
<td>Jan-08</td>
</tr>
<tr>
<td>Messmate (Eucalyptus oblique)</td>
<td>Dip River Forest Block</td>
<td>Regen-1950</td>
<td>50/60</td>
<td>Natural regeneration</td>
<td>Brittons</td>
<td>Brittons Timber</td>
<td>Sep-07</td>
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<td>Arve Loop Rd, Tahune</td>
<td>Regen-1920</td>
<td>80</td>
<td>Natural regeneration</td>
<td>ITC</td>
<td>ITC</td>
<td>Nov-07</td>
</tr>
<tr>
<td>Tasmanian blue gum (Eucalyptus globulus)</td>
<td>Mt Direction</td>
<td>1990</td>
<td>18</td>
<td>Unpruned</td>
<td>Private</td>
<td>FEA</td>
<td>Sep-07</td>
</tr>
<tr>
<td></td>
<td>Meunna</td>
<td>Aug-88</td>
<td>20</td>
<td>Pruned Winter 93, Autumn 94, Winter 95</td>
<td>Forestry TAS</td>
<td>Gunns Deloraine</td>
<td>Feb-08</td>
</tr>
<tr>
<td>Shining gum (Eucalyptus nitens)</td>
<td>Meunna</td>
<td>Aug-88</td>
<td>20</td>
<td>Pruned Winter 93, Autumn 94, Winter 95</td>
<td>Forestry TAS</td>
<td>Gunns Deloraine</td>
<td>Feb-08</td>
</tr>
<tr>
<td></td>
<td>St Georges Rd, Ridgley</td>
<td>1981</td>
<td>27</td>
<td>Thinned and pruned</td>
<td>Gunns</td>
<td>Gunns Deloraine</td>
<td>Apr-08</td>
</tr>
</tbody>
</table>
Heartwood and sapwood boards for each wood species were sourced from the nominated sites. Examples of the boards delivered for testing are shown on Figure 1. Their identification was confirmed by the supplier (sawmills), except for Sydney blue gum where the boards were received mixed and unlabeled. Therefore the heartwood and sapwood boards for the Sydney blue gum were visually identified in the testing laboratory.

According to the information provided by the project manager, the boards provided for this project were selected from 15 logs for each species and for each site.

The boards were cut and planed to a specific dimension of 25 x 25 x 885 mm or 23 x 23 x 885 mm, depending on the initial thickness. In general, samples free of knots and well machined were selected to perform the microwave bending trials. Due to the high variability of the wood properties, 25 samples from each species and from different log locations (heartwood and softwood) were used for the test.

The moisture content (MC) was measured for each sample, which showed a considerable variation within each species (Table 3).
Blackbutt, spotted gum and Gympie messmate presented relatively low values of the moisture content for bending considerations. According to previous research findings (Juniper 2008), the optimal moisture content of timber required for bending is about 50-80%, to prevent bending failures caused by too low moisture content.

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Min. MC (%)</th>
<th>Max. MC (%)</th>
<th>Average MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackbutt (Eucalyptus pilularis)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 35</td>
<td>Site 2: 61</td>
<td>Site 1: 43 (6)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 26</td>
<td>Site 2: 41</td>
<td>Site 1: 32 (5)</td>
</tr>
<tr>
<td>Spotted gum (Corymbia maculata)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 27</td>
<td>Site 2: 41</td>
<td>Site 1: 33 (4)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 35</td>
<td>Site 2: 59</td>
<td>Site 1: 47 (8)</td>
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<td>Gympie messmate (Eucalyptus cloeziana)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 26</td>
<td>Site 2: 38</td>
<td>Site 1: 31 (4)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 22</td>
<td>Site 2: 54</td>
<td>Site 1: 38 (9)</td>
</tr>
<tr>
<td>Dunns white gum (Eucalyptus dunnii)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 98</td>
<td>Site 2: 195</td>
<td>Site 1: 129 (19)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 53</td>
<td>Site 2: 89</td>
<td>Site 1: 71 (11)</td>
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<tr>
<td>Karri (Eucalyptus diversicolor)</td>
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<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 42</td>
<td>Site 2: 109</td>
<td>Site 1: 77 (19)</td>
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<tr>
<td>sapwood</td>
<td>Site 1: 38</td>
<td>Site 2: 90</td>
<td>Site 1: 59 (15)</td>
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<td>Sydney blue gum (Eucalyptus saligna)</td>
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<td>heartwood</td>
<td>Site 1: 30</td>
<td>Site 2: 93</td>
<td>Site 1: 62 (17)</td>
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<tr>
<td>sapwood</td>
<td>Site 1: 26</td>
<td>Site 2: 71</td>
<td>Site 1: 53 (10)</td>
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<tr>
<td>Messamte (Eucalyptus obliqua)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 68</td>
<td>Site 2: 157</td>
<td>Site 1: 105 (20)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 50</td>
<td>Site 2: 111</td>
<td>Site 1: 86 (16)</td>
</tr>
<tr>
<td>Tasmanian blue gum (Eucalyptus globulus)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 67</td>
<td>Site 2: 145</td>
<td>Site 1: 90 (17)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 65</td>
<td>Site 2: 113</td>
<td>Site 1: 95 (14)</td>
</tr>
<tr>
<td>Shining gum (Eucalyptus nitens)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>heartwood</td>
<td>Site 1: 105</td>
<td>Site 2: 173</td>
<td>Site 1: 140 (21)</td>
</tr>
<tr>
<td>sapwood</td>
<td>Site 1: 87</td>
<td>Site 2: 138</td>
<td>Site 1: 114 (14)</td>
</tr>
</tbody>
</table>

Note:
- Values are a representation of 25 specimens (tested samples).
- There was no sampling for Dunns white gum, Site 2.
- Heartwood and sapwood boards of Blackbutt and Spotted gum were mixed in-house during machining for dimensions required for testing. The tests were performed for the mixed Site 1 and 2 material.
- Tasmanian blue gum from Site 2 was misplaced at the storage site.

**Microwave wood bending equipment set-up**

The bending tests were performed at the University of Melbourne, using the microwave wood bending equipment set up in the Wood Testing Laboratory.
The equipment consists of a 5kW, 2.45 GHz microwave heating unit used for the wood softening process (Figure 2) and a rack-and-pinion rotation wood bending machine (Figure 3) used for the effective bending.

During the softening process in the microwave heating unit, the following optimum operating parameters, which were established in the previous bending research, were used:

- Microwave power: 1.5 kW
- Conveyor speed: 34 mm/sec
- Spiral machine rig speed\(^2\): 1.9

As a critical parameter, the wood temperature developed during softening process was continuously monitored for each sample by means of optical temperature probes. When the sample reached 100°C, the bending could be considered. In order to get the optimal temperature, the number of wood passes through the conveyor tunnel varied (from four to six passes) throughout the wood samples (even within the same species).

\(^2\) According to the speed indicator scale.
After heating, the wood specimens were installed on the bending machine between the leading and trailing end-stops of the supporting strap and always with the annual rings concave towards the bending form. As the bending process progresses slowly due to the rotational speed of the driving gear pinion, the bending form radius decreases progressively from a maximum value of 400 mm to a minimum value of 260 mm. The procedure for determining the bending radius values along the bending form was established by Juniper (2008) and these were followed accordingly.

Clamps were applied during bending operation to avoid bending failures due to the lack of contact between wood specimens and bending form (Figure 4). Clamping of timber introduces additional transverse forces which help support the timber in the form and act to improve its shear capacity, thus improving the bending performance. Otherwise the component will be pushed away from the form and will fail.
Microwave wood bending assessment procedure

Based on the quality ranking systems used in the previous microwave wood bending studies, the bending assessment procedure involved two steps:

• general assessment of bending, and
• determination of minimum radius of bending curvature.

The bending assessment procedure was implemented for each bent specimen.

The general assessment consisted of visual examination of each wood specimen bent and the description of general level of wood failure. The specimens ranking was performed 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 – Good bend; machining needed.
4 – Satisfactory bend; fairly large failure, but can be mostly removed by decent amount of machining.
5 – Failed bend; very large failure with no chance of recovery.

When a piece of wood is bent, the wood fibers on the side next to the form are put in compression and those on the opposite side in tension. The compression is accompanied by shortening and the tension by lengthening or stretching, thus generating failures (Wilson 1929; Taylor 2001; Schleining 2002). Tension and compression occurring during a bending process are illustrated in Figure 5:

![Figure 5: Tension and compression effects on wood bent to radius R](image)

The minimum radius of each wood specimen was taken at the first failure location (failure point) with a ranking level of minimum 3. If no failure points of level 3 occurred up to a radius of 330 mm, the sample was assessed with visual ranking 1 or 2.

Various visual ranking levels and minimum radius values assessed during this research are exemplified in Figure 6.
a) *E. globulus* - sapwood, Tasmania, Site 1; visual ranking 1, full length bending without failure.

b) *Corymbia maculata* - sapwood, Qld. Site 1&2; visual ranking 5, min radius 400 mm - tension failure going forward throughout the sample.

c) *E. pilularis* - heartwood, Qld., Site 1&2; visual ranking 2, min radius 330mm – severe compression failure.

**Figure 6: Examples of wood bending quality classification (visual ranking and minimum radius)**

This assessment method relates to an industrial bending procedure where the ranking of 1 or 2 constitutes an excellent bending result even though at the microstructural level the wood fibers have undergone some minor failure. Level 3 represents a bent wood component which is still usable as a furniture component but some major wood failure has occurred.

**Data analysis and results**

Descriptive statistical tools such as the frequency distribution method were used for the final analysis of the collected data. The frequency distributions of both visual ranking and minimum radius observations were expressed as percentages for each wood species.
examined (Table 4 and 6). However, the frequency distribution values shown in Tables 4 and 6 are not very indicative, causing difficulties in the determination of bending quality levels or minimum radius permissible for each species for bending.

From practical considerations, it is recognized that if at least 70% of the observations for a wood species falls within one category (quality level or minimum radius range), the bending performances of that wood species can be defined accordingly. To make use of this principle, the cumulative frequency distribution was used in order to be able to establish the lowest bendability level of a wood species (Table 5). Similarly, by grouping the obtained values of radii in classes of radii and then making use of cumulative frequency distributions, the probable minimum bending failure point could be estimated (Table 7). It has to be noted that for the evaluation of minimum bending curvature radius, the wood species were first classified according to data from Table 5 in species with satisfactory or no bending capabilities and species with good and very good bending abilities. Then the cumulative frequency distribution was computed starting from the larger to smaller radii for the first class of species and from smaller to larger radii for the second mentioned class.
<table>
<thead>
<tr>
<th>Wood species</th>
<th>Site 1&amp;2</th>
<th>Visual ranking - Frequency distribution (%)</th>
<th>Site 2</th>
<th>Visual ranking - Frequency distribution (%)</th>
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</thead>
<tbody>
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<td></td>
<td>heartwood 8% 12% 0% 16% 64%</td>
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</tr>
<tr>
<td></td>
<td></td>
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<td>sapwood - - - - -</td>
</tr>
<tr>
<td>Spotted gum (Corymbia maculata)</td>
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<td></td>
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<td></td>
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<tr>
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<td></td>
<td>heartwood 12% 0% 4% 0% 96%</td>
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<td></td>
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<td></td>
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<td>heartwood 84% 4% 0% 8% 4%</td>
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<td>sapwood 52% 8% 8% 0% 32%</td>
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<td>heartwood 68% 16% 0% 0% 16%</td>
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<td>sapwood 48% 20% 8% 4% 20%</td>
</tr>
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<td>Sydney blue gum (Eucalyptus saligna)</td>
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<td></td>
<td>heartwood 20% 24% 40% 8% 8%</td>
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<td></td>
<td>sapwood 16% 12% 20% 16% 36%</td>
</tr>
<tr>
<td>Messmate (Eucalyptus obliqua)</td>
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<td>heartwood 24% 24% 8% 12% 32%</td>
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<td>sapwood 24% 28% 8% 12% 28%</td>
</tr>
<tr>
<td>Tasmanian blue gum (Eucalyptus globulus)</td>
<td></td>
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<td></td>
<td>heartwood 48% 24% 12% 8% 8%</td>
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<td></td>
<td>sapwood 52% 28% 8% 0% 12%</td>
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### Table 5: Visual ranking - Cumulative frequency distribution (%)

<table>
<thead>
<tr>
<th>Wood species</th>
<th>Site 1 &amp; 2</th>
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<th>1+2</th>
<th>1+2+3</th>
<th>1+2+3+4</th>
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<td>Spotted gum (Corymbia maculata)</td>
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</tr>
<tr>
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<td>Gympie messmate (Eucalyptus cloeziana)</td>
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<td>36%</td>
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<td>88%</td>
<td>88%</td>
<td>96%</td>
</tr>
<tr>
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<td>60%</td>
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<td>68%</td>
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<td>Site 2</td>
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<td>Site 2</td>
<td>Site 2</td>
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<td>56%</td>
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<td>52%</td>
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<td>Site 2</td>
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Table 6: Minimum bending curvature radius - Frequency distribution (%)
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<th>Sapwood (%)</th>
<th>Heartwood (%)</th>
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</tr>
<tr>
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<td>4%</td>
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<td>24%</td>
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</tr>
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<td>12%</td>
<td>16%</td>
</tr>
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<td>8%</td>
<td>4%</td>
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<td>Wood species with satisfactory or no bending capabilities</td>
<td>Minimum radius - Cumulative frequency distribution (%)</td>
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<td>400-280 mm</td>
<td>400-260 mm</td>
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</tr>
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<td>80%</td>
<td>84%</td>
<td>96%</td>
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<td>72%</td>
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<td>88%</td>
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<tr>
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<td>65%</td>
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<td>Spotted gum (Corymbia maculata)</td>
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<td>64%</td>
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<td>-</td>
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<tr>
<td>Gympie messmate (Eucalyptus cloeziana)</td>
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<td>68%</td>
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<td>96%</td>
<td>100%</td>
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<td>96%</td>
<td>100%</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>Site 1</td>
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<td>48%</td>
<td>76%</td>
<td>84%</td>
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<td>44%</td>
<td>68%</td>
<td>88%</td>
<td>92%</td>
</tr>
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<td>260-310 mm</td>
<td>260-340 mm</td>
<td>260-370 mm</td>
<td>260-400 mm</td>
</tr>
<tr>
<td>------------------------------------------------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>Dunn’s white gum (Eucalyptus dunnii)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 1</td>
<td>heartwood</td>
<td>84%</td>
<td>88%</td>
<td>96%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>40%</td>
<td>52%</td>
<td>60%</td>
<td>96%</td>
</tr>
<tr>
<td>Site 2</td>
<td>heartwood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Karri (Eucalyptus diversicolor)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 1</td>
<td>heartwood</td>
<td>48%</td>
<td>64%</td>
<td>68%</td>
<td>92%</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>48%</td>
<td>56%</td>
<td>64%</td>
<td>76%</td>
</tr>
<tr>
<td>Site 2</td>
<td>heartwood</td>
<td>44%</td>
<td>56%</td>
<td>76%</td>
<td>88%</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>84%</td>
<td>84%</td>
<td>88%</td>
<td>92%</td>
</tr>
<tr>
<td>Tasmanian blue gum (Eucalyptus globulus)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 1</td>
<td>heartwood</td>
<td>32%</td>
<td>60%</td>
<td>80%</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>64%</td>
<td>68%</td>
<td>88%</td>
<td>100%</td>
</tr>
<tr>
<td>Site 2</td>
<td>heartwood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shining gum (Eucalyptus nitens)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site 1</td>
<td>heartwood</td>
<td>96%</td>
<td>96%</td>
<td>96%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>72%</td>
<td>84%</td>
<td>84%</td>
<td>96%</td>
</tr>
<tr>
<td>Site 2</td>
<td>heartwood</td>
<td>84%</td>
<td>92%</td>
<td>92%</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td>sapwood</td>
<td>72%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
</tbody>
</table>

Sydney blue gum (Eucalyptus saligna)
The highlighted percentages from Table 5 indicate the lowest quality level of bending performed by a wood species, which was considerably detected within at least 70% of tested samples.

When subject to the microwave softening process, the general bending performance of the wood species studied shows the following results:

- *E. pilularis*, *Corymbia maculata* and *E. cloeziana*: no ability to bend at a radius range of 400-260 mm. Very large failures occurred for the majority of tested specimens.
- *E. obliqua*: satisfactory to no ability to bend. Machining needed to remove fairly large failures.
- *E. saligna*: good and satisfactory bending for heartwood (machining needed to remove large or fairly large failures) but very severe failures for the majority of sapwood samples.
- *E. globulus* and *E. diversicolor*: very good to moderate bending ability, with some machining of bends required.
- *E. nitens* and *E. dunnii* (except sapwood – satisfactory bending): perfect bending characteristics, with no final preparation or little sanding needed.

The type of failures observed to occur frequently at the wood species which were tested is described by:

- *E. pilularis*, *Corymbia maculata*: predominantly compression and tension together with compression failures.
- *E. cloeziana*: predominantly tension failure.
- *E. obliqua*: predominantly tension but compression failure as well for heartwood, and tension failure for sapwood.
- *E. saligna*: both tension and compression failures.
- *E. globulus*: tension failure.
- *E. diversicolor*: tension failure for heartwood and both tension and compression failures for sapwood.
- *E. nitens* and *E. dunnii*: tension failure.

Similarly, the highlighted percentages from Table 7 indicate the lowest bending curvature permissible by a wood species (in the tested radius range of 400-260 mm), which was found within at least 70% of tested samples. As a result, the minimum bending radius recorded for the studied wood species, where no failure occurs or a small amount of machining is needed, falls within the following range:

- *E. pilularis*, *Corymbia maculata* and *E. cloeziana*: 400-340 mm or even lower (up to 310 mm).
- *E. obliqua* and *E. saligna*: 400-280 mm.
- *E. diversicolor* and *E. dunnii* (sapwood): 370/340 mm to 260 mm.
- *E. globulus*: 340-260 mm.
- *E. nitens* and *E. dunnii* (heartwood): 280-260 mm.
The above observations and figures represent the overall bending characteristics of the studied species. However, this study demonstrates that the bending characteristics of a wood species may slightly vary with the log’s harvesting location. In addition, heartwood and sapwood can have diverse bending properties in some wood species.

Figure 7 shows that in the case of wood species with modest bending abilities (E. diversicolor, E. saligna, E. obliqua), the bending quality levels of heartwood and sapwood differ. The results obtained from two different sites, demonstrate that E. saligna sapwood has no ability to bend at a radius lower than 400 mm while the heartwood bends relatively well. The highest bending quality level of E. diversicolor and E. obliqua sapwood and heartwood is uncertain as the two sites gave contradictory results. It was interesting to note that E. dunnii has excellent bending characteristics for heartwood but very poor for sapwood.

In addition, the heartwood of the species with modest bending abilities (E. diversicolor, E. saligna, E. obliqua) shows different quality level of bending when regarded as supplied from two distinct sites (Figure 8). The sites details (Table 2) indicate that in the case of E. diversicolor and E. saligna, the forest age and silvicultural practices of these sites could not be an influential factor for bending quality as they are similar. The slightly better bending performances of the heartwood samples sourced from Site 1 could be associated with the moisture content which was about 10% higher (in average) – (Table 3). Similar explanations could be given for the sapwood samples of E. diversicolor from Site 2. This is contrary for the E. obliqua, as although the E. obliqua heartwood from Site 1 possessed 10% higher moisture content than the samples from Site 2, the bending results were much poorer. Both sites were characterised by natural regrowth forests of 50/60 and 80 years old, respectively.

The past studies (Daian and Ozarska 2006) indicated that the bending characteristics of young plantation timbers are better than the old growth timbers. However, as this study does not provide sufficient data to prove the contrary, the 20 years difference in age could not be considered a main factor influencing the bending performances. A reasonable explanation of the different results could be the thickness of the tested samples: 25 x 25 mm for the heartwood samples from Site 1 and 23 x 23 mm for the heartwood samples from Site 2 were provided for testing. The thinner the sample, the better are the bending abilities. The length interval of minimum bending curvature (radius) found to be permitted by the heartwood and sapwood of each wood species is, in most cases, similar or very close (at most 30 mm difference) - Figure 9. In general, the heartwood showed the ability to bend at slightly sharper radii than the sapwood. A larger difference in the minimum bending radius was found for the heartwood and sapwood of E. dunnii (heartwood bent at 100 mm lower radii than the sapwood) and E. diversicolor (sapwood bent at 60 mm lower radii than the heartwood - observed only at Site 2). The better bending curvature of E. diversicolor sapwood in relation with the heartwood, which was obtained only for the sample at Site 2, could be explained by the higher moisture content of the sapwood samples (about 20% difference in average – Table 3). Similarly, Figure 10 shows that the length intervals of minimum bending curvature (radius) for the distinct heartwood/sapwood samples of a particular wood species sourced.
Figure 7: Lowest level of bendability for the studied wood species: comparison between heartwood and sapwood.

Figure 8: Lowest level of bendability for the studied wood species: comparison between Site 1 and Site 2.
Figure 9: Minimum bending curvature for the studied wood species: comparison between heartwood and sapwood

Figure 10: Minimum bending curvature for the studied wood species: comparison between Site 1 and Site 2
from two different sites (Site 1 and Site 2) are comparable (at most 30 mm difference). One exception was the sapwood of *E. diversicolor*, where the results indicate that the sapwood from Site 2 bent at 60 mm lower radii than the sapwood from Site 1. Again, it is considered that this behavior occurred due to the significant difference in moisture content (about 26% in average).

**Conclusions**

The ability of wood to bend is mostly related to the wood structure and, at some extent, to the employed bending method as well. Knowledge of the bending behavior of commercially available wood species, which usually bear specific characteristics given by the nature of the origin at forest and sawmilling practices, represents an important issue for the timber industry.

Nine hardwood species originating from Australian plantations or regrowth forests were investigated within this research. Each species was supplied in heartwood and sapwood boards from two distinct sites. The sites for any particular wood species were reasonably similar in regard to forests age and silviculture practices. The moisture content of the tested samples varied considerably within the species and generally was about 10-20% different in average for the same species but from different sites and location within log (sapwood and heartwood).

The current study indicated that when subject to the microwave softening process, the general bending performance of the studied wood species shows the following results:

**Plantation resources:**
- *E. cloeziana*: no ability to bend at a radius range of 400-260 mm. Very large failures occurred for the majority of tested specimens.
- *E. saligna*: good and satisfactory bending for heartwood (machining needed to remove large or fairly large failures) but very severe failures for the majority of sapwood samples.
- *E. globulus*: very good to moderate bending ability, with some machining of bends required.
- *E. nitens* and *E. dunnii*: perfect bending characteristics for heartwood, with no final preparation or little sanding needed and satisfactory bending for sapwood.

**Young regrowth resources:**
- *E. pilularis* and *Corymbia maculata*: no ability to bend at a radius range of 400-260 mm. Very large failures occurred for the majority of tested specimens.
- *E. obliqua*: satisfactory to no ability to bend. Machining needed to remove fairly large failures.
- *E. diversicolor*: very good to moderate bending ability, with some machining of bends required.
The minimum radius of curvature for the studied wood species, where no failure occurs or a small amount of machining is needed, falls within the following range:

- *E. pilularis*, *Corymbia maculata* and *E. cloeziana*: 400-340 mm or even lower (up to 310 mm)
- *E. obliqua* and *E. saligna*: 400-280 mm
- *E. diversicolor* and *E. dunnii* (sapwood): 370/340 mm to 260 mm
- *E. globulus*: 340-260 mm
- *E. nitens* and *E. dunnii* (heartwood): 280-260 mm.

The above results suggest that with better ability to bend, the lower curvature radius is likely to be achieved.

For the wood species with modest bending abilities (*E. diversicolor*, *E. saligna*, *E. obliqua*), the bending quality level of heartwood and sapwood may differ. Notable are *E. saligna* and *E. dunnii*, which have relatively good and respectively excellent bending characteristics for heartwood but very poor for sapwood.

In general, the heartwood for all investigated wood species showed the ability to bend at slightly smaller radii than the sapwood. The length interval of minimum radius curvature found in the heartwood and sapwood of each wood species was similar or very close (at most 30 mm difference). However, it was noticed that for some species (e.g. *E. diversicolor*), higher moisture content is likely to improve the minimum bending radius of sapwood.

This study could not make any inference about the influence of the log’s harvesting location on the bending characteristics of a wood species, as the sourcing forest sites for any of the studied wood species had comparable age and silvicultural practices. The slightly better bending performances of the heartwood samples of *E. diversicolor* and *E. saligna* sourced from Site 1 and sapwood samples of *E. diversicolor* from Site 2 could be associated with the higher moisture content. The length intervals of minimum radius curvature of heartwoods and sapwoods were comparable when evaluating the samples from the two different sites.

The above results underline a strong relationship between wood structure, physical and mechanical characteristics and the wood’s ability to bend. Therefore, timber used for bending needs to be carefully selected by the production company personnel to take into account the suitability of the species for bending, quality of timber, moisture content and machining. The wood selection requirements for bending are attached as Appendix 1.

Overall, the results of the study on the bending performance capabilities of plantation and young hardwood Australian timbers showed several differences compared with the literature data relating to the bending abilities of the relevant old growth timbers (Table 8).
Table 8: Comparison of minimum radius of curvature for tested plantation timbers and old growth timbers.

<table>
<thead>
<tr>
<th>Species included in the study</th>
<th>Minimum radius of curvature in bending (mm)</th>
<th>Test results for plantation and regrowth timbers</th>
<th>Data for old growth timbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. pilularis</td>
<td>400-340</td>
<td>610 (Stevens and Turner 1970)</td>
<td></td>
</tr>
<tr>
<td>Corymbia maculata</td>
<td>400-340</td>
<td>&gt; 5600 (data from wood benders)</td>
<td></td>
</tr>
<tr>
<td>E. cloeziana</td>
<td>400-340</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>E. obliqua</td>
<td>400-280</td>
<td>410 (Stevens and Turner 1970)</td>
<td></td>
</tr>
<tr>
<td>E. saligna</td>
<td>400-280</td>
<td>&gt; 600 (data from wood benders)</td>
<td></td>
</tr>
<tr>
<td>E. diversicolor</td>
<td>370/340-260</td>
<td>500 (Siemon 2002)</td>
<td></td>
</tr>
<tr>
<td>E. dunnii (sapwood)</td>
<td>370/340-260</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>E. globulus</td>
<td>340-260</td>
<td>&gt; 450 (data from wood benders)</td>
<td></td>
</tr>
<tr>
<td>E. nitens</td>
<td>280-260</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>E. dunnii (heartwood)</td>
<td>280-260</td>
<td>n/a</td>
<td></td>
</tr>
</tbody>
</table>

For the majority of species evaluated in this study, the values of the minimum radius of curvature obtained during the bending experiments were lower than the values reported in the literature. As no published data is available on the minimum radius of curvature of old growth timbers for many of the tested species, information provided by well experienced Australian wood benders on the bendability of Corymbia maculata, E. saligna and E. globulus have been included in the table.

The unexpected high-quality bending performance for some of the tested wood species (i.e. E. nitens, E. dunnii, E. globulus and E. pilularis) and the fact that the wood specimens originated from young trees, led us to the conclusion that wood resources from regrowth and plantation forests give better bending performances than old growth timbers.
References


APPENDIX 1: Requirements for selection of wood used for wood bending

Quality of Timber Used for Bending

Timber for bending must be carefully selected in order to minimise the percentage of failures. Generally, bending timber is specified to be free from defects. In particular, large knots, gum veins and pin knots and pin holes must be excluded. It is also very important that timber is free from drying defects such as internal and surface checking.

Ideally, straight grained material should be selected. Sloping grain and localised grain irregularities will increase the probability of failures during bending. As high stresses occur during the bending process any faults which are likely to cause severe stress concentrations and weaken the timber must be avoided.

The above requirements are particularly important if the wood is going to be bent to small radius of curvature (severe bends). For short, moderate bends, such as chair back slats, the quality of timber may be slightly lower, but it still should be selected with care. Some defects are permitted as they can be placed on the tension side of the bent component.

Moisture in the Wood before Bending

Moisture in the wood not only affects the plasticity of wood after heating but also has an important effect on retaining useful biological compound in the material to retain its shape after bending.

The raw wood material for bending must be kept in a humidity controlled environment in order to be protected against drying which results in surface checking.

Research study revealed that the best bending results using microwave technology are achieved when green wood with the moisture content of about 40% is used for bending. However, if wood is going to be bent to a large radius of curvature, the lower moisture content of wood (about 20%) can be used. Therefore, the moisture content level of timber can be selected according to the severity of bends required. However, in the industrial conditions, the selection of different levels of timber moisture content for various shapes may not be practical. This decision needs to be made by an individual company producing bent components.

It should be pointed out that the higher the moisture content, the greater is the difficulty in drying the wood after bending which may result in collapse and internal checking.

Machining of Wood prior to Bending
Timber components should be over-sized compared to the final dimensions of the finished bent components to allow for machining before bending and after drying as well as the shrinkage of timber during drying. However, as the success of bending is highly related to the thickness of wood and the radius of curvature, the allowances for final shrinkage and final dressing should be kept to minimum.

It is critical that timber is dressed before being used for bending, preferably on all four sides. Even minor irregularities on the surface of timber, such as saw marks, broken fibres, cracks or surface checks, will set up “weak spots” during bending, where failure is likely to take place. The timber specimen should be cut to length with as close to as possible perfectly square ends.