Determining an Optimum Model for the Bending of *Eucalyptus regnans* Wood Heated by Microwave Energy

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Abstract

Microwave wood bending involves softening wood using microwave energy and then bending it into a required shape. An experimental framework was developed that included two sets of experiments: microwave mechanical property experiments (MMPE) and microwave wood-bending experiments (MWBE).

This article reports on an investigation into the effect of the salient wood-bending variables on important mechanical and bending characteristics of *Eucalyptus regnans* wood, using a full factorial experimental framework and associated statistical analysis. Variables investigated were moisture content in the range of 18 to 20 percent and above 35 percent; wood temperature in the ranges of 80°C to 85°C, 100°C to 105°C, and 120°C to 125°C; MMPE for three wood strain rates of 0.1, 0.2, and 0.6 mm/s; and MWBE for three strain rates of 13°/s, 27°/s, and 81°/s.

This article reports on two objectives: (1) the development of a full factorial experimental design framework for wood-bending research, and (2) the application of this framework to efficiently determine salient mechanical properties of *E. regnans* during microwave bending and to determine the bending parameters required for optimum microwave bending of this species. Bending strains for compression parallel-to-grain, shear parallel-to-grain, and tension parallel-to-grain were investigated.

The study revealed the following optimum microwave bending variables for *E. regnans*: moisture content above 70 percent, temperature in the range of 100°C to 105°C, and strain rates in the region of 0.1 mm/s or 13°/s.

The study authenticated an optimum set of bending variables for the microwave heating of *E. regnans* that enabled minimum wood failure during bending operation.

Traditionally, the wood-bending process includes a steam-softening stage prior to the bending stage, but this essentially manual process is time-consuming, labor-intensive, and technologically dormant. An alternative softening process using microwave energy has gained attention due to distinct advantages over steam softening. These include significantly faster heating rates, more efficient use of energy, and the capacity for automated mass-production processing. An extensive research study has been undertaken at the University of Melbourne to investigate the application of microwave technology to soften timber for the manufacture of bent components from regrowth and plantation timber resources (Torgovnikov 1995, Juniper 2007, Ozarska and Daian 2010, Burvill et al. 2013, Ozarska et al. 2013).

Steam softening uses an external heating source, while microwave irradiation heats the wood by activating the water molecules in the wood itself and does not require additional water in the form of steam. The microwave heating process is very rapid. For example, a 25-mm-thick piece of wood can be heated within 1 to 3 minutes (Juniper 2007), while the usual heating time for steaming is 40 to 60 minutes. In addition, the wood temperature can be precisely controlled during microwave heating, and consequentially the desired wood temperature can be quickly achieved. As

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such, microwave heating is very attractive for mass production.

Table 1 lists the wood properties important for bending and identifies the values required for maximizing bending performance, as found in the published literature. Although these previous bending studies successfully investigated various properties required for optimum bending performance, they did not follow rigorous structured experimental methods and did not consider interaction effects between properties. The studies are also not always comparable because methods varied between them. The lack of published optimum bending parameter data and associated documented experimental guideline needed to determine these parameters subsequently required a new approach. As such, the first objective of this research was to develop a research methodology that incorporates a full factorial experimental design framework, investigating both main effects and interaction effects between the variables. A full factorial experimental design measures the response of every possible combination of variables and variable levels (Moore and McCabe 1993). Full factorial experimental design provides a comprehensive analysis of all treatments and their levels and interactions (Frigon and Mathews 1997). The following issues must be considered: the main effect of an independent variable is the effect of the variable averaged over all levels of other variables in the associated experiment; an interaction variable is formed when two independent variables are multiplied together; and an interaction effect exists when differences for one independent variable depends on the level of another. An understanding of interaction effects is important for research activities to determine the extent of required experimental and analytical effort.

The properties in Table 1 that can be practically controlled and optimized are included as variables in the experimental optimization study, which is the second objective of this research. These variables are moisture content (MC) of wood during bending, temperature of wood (T) during bending, and the rate that the wood specimen is deformed during bending (i.e., strain rate [SR]). Using the full factorial experimental design, these variables were explored in relation to their effect on wood strength and bending performance to determine the combination of variables that maximizes bending performance.

The proposed method can be used to investigate the effect of a range of bending variables on the mechanical and bending properties of wood using the full factorial experimental design. It involves completing a series of experiments that directly relate to the mechanical and bending performance of a particular wood species. For each experiment, an associated response is measured and recorded, and following this, an appropriate statistical analysis of the response is conducted to identify the combination of variables that produces the most favorable mechanical and bending performance. In doing so, the set of optimum bending parameters for a particular species is obtained.

The approach offers a more comprehensive and focused investigation of the mechanical behavior of a wood species by examining, in isolation, the individual deformation responses of the wood. It involves completing mechanical property experiments (MPE) and wood-bending experiments (WBE) using the full factorial experimental framework (Table 2). Three values are normally selected for each of the three wood-bending variables: (1) moisture content—prior knowledge of optimum steam-softening moisture content of above fiber saturation point (30% to 35%) and then selecting an appropriate value either side of this midpoint, based on preliminary trials; (2) wood temperature—prior knowledge of optimum steam-softening temperature (100°C) and then selecting an appropriate value either side of this midpoint, based on preliminary trials; and (3) wood strain rates—an appropriate range of strain rates for the MPE and WBE is required.

The proposed full factorial experimental design framework has been successfully implemented in a detailed study of the mechanical behavior of *Eucalyptus regnans* during bending for industrial applications (Fig. 1). Findings are reported in the remainder of this article and in the published literature (Burvill et al. 2013, Ozarska et al. 2013). The number of experiments completed in this study was minimized through ongoing reviews of interaction effects between moisture content, temperature, and strain rate, i.e., MC × T, MC × SR, T × SR, MC × T × SR.

The deformation behavior of any material depends on a series of parameters, including material properties, external environmental factors, and loading conditions. For a microwave bending operation, the important mechanical parameters are those that affect the response of the

Table 1.—Salient wood properties for wood bending.

Wood property	Optimum steam performance conditions found in literature	Summary of findings from previous experimental studies	Consider as a variable in experimental study
Wood moisture content	Around fiber saturation point	Acknowledged as having strong influence on strength and bending performance	Yes
Wood temperature	100°C	Acknowledged as having strong influence on strength and bending performance	Yes
Strain rate of wood	Not found	Only strength performance data found, no bending performance	Yes
Direction of wood deformation	Not found	Investigate during bending method experiments	No
Grain angle	Straight grain	Precedent is that wood strength and bending best when straight grain used	No
Density	Not found	Not a directly controllable variable during testing; density variation has lower priority than other wood properties; minor density variations unlikely to affect bending	No

Table 2.—Full-factorial experimental framework applied during microwave mechanical property experiments (MMPE) and microwave wood-bending experiments (MWBE).[a]

Wood-bending variable	Combinations of bending variables implemented in the experiments																	
Moisture content (%)	15–25									30+ (above fiber saturation point)								
Wood temp. (°C)	80–85			100–105			120–125			80–85			100–105			120–125		
MMPE wood strain rate (mm/s)	0.1	0.2	0.6	0.1	0.2	0.6	0.1	0.2	0.6	0.1	0.2	0.6	0.1	0.2	0.6	0.1	0.2	0.6
MWBE wood strain rate (°/s)	13	27	81	13	27	81	13	27	81	13	27	81	13	27	81	13	27	81

[a] Three sets of MMPE and one set of MWBE were conducted. Twenty-five samples were tested for each of the mechanical properties within the framework. Total bending experiments = 1,800 experiments = 2 moisture contents × 3 wood temperatures × {[3 × MMPE] × [3 × strain rates (mm/s)] + [1 × MWBE] × [3 × strain rates (°/s)]} × 25 samples.

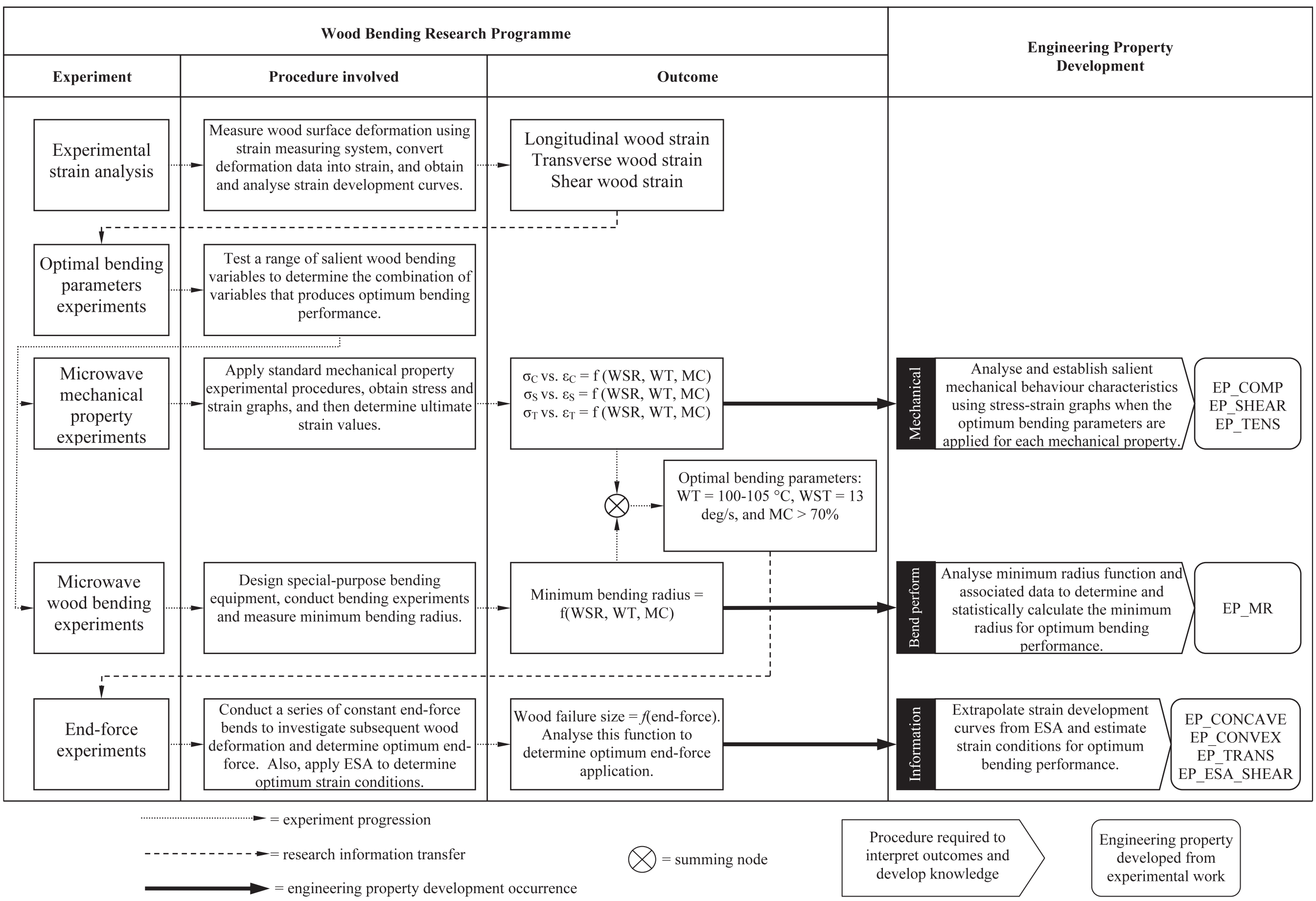

Figure 1.—Information development, transfer, and interrelationship associated with engineering properties. WSR = wood strain rate; WT = wood temperature; MC = moisture content; σ_C = compressive parallel-to-grain stress; ε_C = compressive parallel-to-grain strain; σ_S = shear parallel-to-grain stress; ε_S = shear parallel-to-grain strain; σ_T = tensile parallel-to-grain stress; ε_T = tensile parallel-to-grain strain; EP_COMP = compression parallel-to-grain; EP_SHEAR = shear parallel-to-grain; EP_TENS = tension parallel-to-grain; MR = Minimum bending radius at optimum bending performance.

microwave-softened wood, and in doing so, can be adjusted to establish their optimum values. This study aimed to improve the current understanding of the mechanical properties associated with the bending of *E. regnans* heated by microwave energy.

Materials and Methods

The wood used in this study was mountain ash (*E. regnans*) from a natural regrowth stand. *E. regnans* is widely used in furniture manufacturing in Australia and has been found to produce good quality bent components using steam bending (e.g., Forest Products Research Laboratory 1967, Stevens and Turner 1970).

A series of wood-bending experiments were designed to investigate the influence of the three salient wood-bending variables of moisture content, temperature, and strain rate in the context of microwave heating. The study consisted of two sets of experiments: microwave mechanical property experiments (MMPE) and microwave wood-bending experiments (MWBE).

MMPE determined ultimate wood strains of microwave-softened specimens using the clear-wood testing standards developed by Mack (1979) and examined the specific deformation responses of specimens in isolation. MWBE investigated the minimum bending radius before wood failure for a series of material property settings. A novel, experimental wood-bending machine that accommodates a single-plane, decreasing radius bent-wood shape (Juniper 2007) was designed and built for the study (Fig. 2).

Three bending variables were included in this study:

Moisture content: Two ranges of 15 to 25 percent and 30+ percent were used. Previous studies using steam bending demonstrated that a moisture content around 30 percent was optimal for bending (Stevens and Turner 1970). This study investigated two achievable moisture content ranges, one on each side of the cited 30 percent optimum value. Timber with high moisture content (over 70%) was not used because it was found to be extremely difficult to source suitable specimens.

Wood temperature: Three ranges were used, specifically 80°C to 85°C, 100°C to 105°C, and 120°C to 125°C. Selection of these ranges was based on prior knowledge of the optimum steam-softening temperature being around 100°C (Stevens and Turner 1970). The middle range corresponds to prior experience, and the two ranges on each side of 100°C were chosen based on preliminary trials. Microwave heating facilitates precise control of wood temperature.

Wood strain rates: The rates for MMPE were 0.1, 0.2, and 0.6 mm/s, and for MWBE, they were 13°/s, 27°/s, and 81°/s. Preliminary trials were completed to establish these wood strain rates because prior data were not found in the available literature.

The study investigated the effect of a range of each of the salient wood-bending variables on mechanical and bending characteristics of wood. Due to unknown interactions between the variables, these experiments used a ''full-factorial experimental design framework'' to test each combination of the variables. By using an appropriate statistical analysis, the combination of variables that produced the most favorable mechanical and bending performance determined the optimum bending parameters for the microwave-softened wood. Figure 3 shows the microwave-softening system used in this study. Different wood temperatures were obtained by varying the microwave power while maintaining constant conveyor speed. Wood temperatures were measured during microwave softening using fiber optic probes.

Experimental strain analysis outcomes (Ozarska et al. 2013) demonstrated the occurrence of longitudinal compression and tension, shear, and transverse compression strains during the bending of microwave-softened *E. regnans*. Although transverse compression was also measured during the strain analysis, compression perpendicular-to-grain experiments were not included because bending specimens never failed in this direction.

Based on these outcomes, the mechanical property experiments conducted in this study were compression parallel-to-grain, shear parallel-to-grain, and tension parallel-to-grain.

The study tested 25 samples for each of these mechanical properties within the experimental framework (Table 2).

Experimental procedure used in study

Microwave mechanical property experiments.—A standard Instron Universal material testing machine was used for MMPE tests. The preparation of samples and test methods for mechanical properties determination were conducted according to Mack (1979). To avoid loss of softening due to temperature drop, specimens were immediately installed in the material testing machine and tests were performed. The pre– and post–microwave-softened moisture content of the specimen was calculated, following Australian/New Zealand Standard (AS/NZS) 1080.1 (AS/NZS 1997).

Ultimate strain was chosen as the measured response variable because an increase in ultimate strain corresponds to an improvement in bending performance, with the highest ultimate strain associated with the salient bending variables (Table 2), resulting in a measure of optimum bending performance.

Microwave wood-bending experiments.—A novel, experimental wood-bending machine, based on a variable-curve

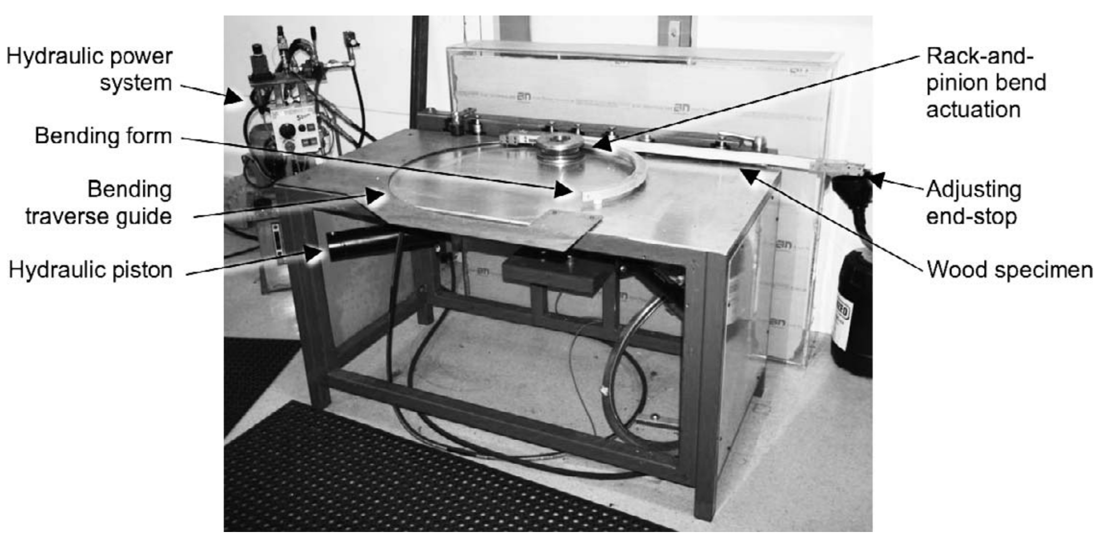

Figure 2.—Custom-designed, decreasing radius wood rotation-bending machine that uses rack-and-pinion bending actuation. Performance specifications: specimens with nominal cross section 25 by 25 mm^2, bends at deformation speeds in the range 13°/s to 81°/s with a constant wood deformation rate, and bends wood specimens using two distinct bending forms (a continuous decreasing radius from 400 to 200 mm, and a constant radius of 300 mm).

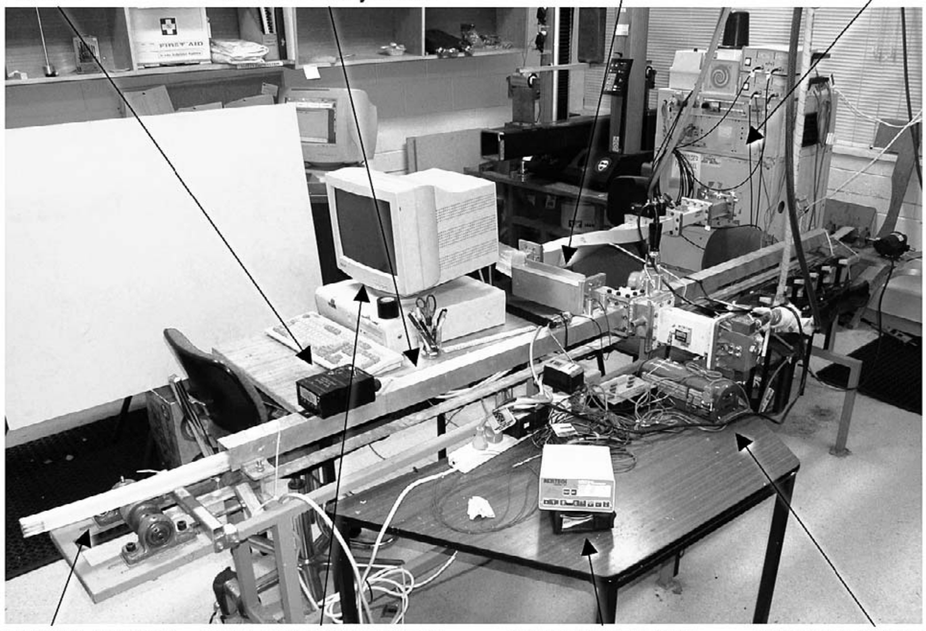

Figure 3.—Microwave-softening system used in the study. The microwave generator produces variable power output in the range of 300 to 5,000 W at a frequency of 2.45 GHz. Wood softening occurs at the intersection of the microwave guide and conveyor belt as the wood specimen moves through the microwave energy field. Microwave power sensors are fitted to the microwave-softening system to measure generated power and are connected to a data acquisition system.

rack-and-pinion, was designed and built for this study (Juniper 2007). The machine accommodates a single-plane, decreasing radius bent-wood shape. The machine reduced the number of experiments required to determine the minimum bending radius before failure due to its varying curvature bending form (Fig. 2).

A fiber optic probe was installed in each specimen to record wood temperature during microwave softening to the required temperature. To avoid loss of softening due to temperature drop, specimens were immediately installed in the wood-bending machine. During bending, the end-stop position of a support strap was adjusted (as per standard bending practice) to prevent large compressive end-forces from occurring. The location of wood failure (i.e., minimum bending radius), failure type, and abnormal results were recorded for each specimen. The moisture content in the vicinity of the failed region of the specimen was determined.

The assessment procedure for identifying initial wood failure was based on ranking systems reported in prior wood-bending studies (Wangaard 1952, Sattar 1981, Sharma et al. 1982, So and Chai 1995). However, these were modified to accommodate the amount of postbend wood preparation (e.g., sanding or machining) required to remove the failure zone and therefore enable production of high-quality furniture products.

Statistical analysis of experimental data

Response variables for the MMPE and MWBE (i.e., ultimate strains from the MMPE and minimum bending radii from the MWBE) and their corresponding combination of bending variables were subjected to an analysis of variance (ANOVA) statistical analysis (Nelson et al. 2003). This type of analysis is a common statistical approach for full factorial experimental frameworks and allows investigation into the influence of each bending variable (i.e., main effect) and combination of each variable (i.e., interaction effect) on the mechanical and bending performance of microwave-softened wood. This facilitated identification of the bending variables that generated optimum bending performance. Robustness of the experimental data used in the ANOVA was verified for each series of MMPE (i.e., for each of parallel-to-grain compression, shear, and tension) and also for MWBE. The analytical sequence was performed as follows.

- Model the response variable against all main and interaction effects of each bending variable (i.e., moisture content, temperature, and strain rate). The main interaction effects were MC × T, MC × SR, T × SR, and MC × T × SR.
- Examine the *P* values of the main and interaction effects to assess their statistical significance.
- For significant effects, complete Bonferroni multiple comparison tests[1] (Walpole 2002) on the significant bending variable groups to examine in greater detail significant differences within each group.

[1] Bonferroni comparison test: a conservative multiple comparison assessment that allows examination of which means are different and offers an estimation of how much they differ.

Results

Microwave mechanical property experiments

Compression parallel-to-grain.—Observation of the ANOVA statistical output for the compression parallel-to-grain experiments (Table 3) yielded the following results. Both of the main effects, strain rate and temperature, had a significant influence on ultimate compressive strain at a 5 percent significance level, as $P_{SR} = 0.014$ and $P_T = 0.01$. No interaction effect between strain rate and temperature (i.e., SR × T) was observed because its associated P value was far greater than a 10 percent significance level. The covariate moisture content was strongly significant and had the strongest influence on ultimate compressive strain because it had the largest F-stat value[2] (Moore and McCabe 1993) of all the terms (i.e., F-stat = 17.82). Finally, the coefficient for moisture content in the regression model was positive (i.e., moisture content covariate was $+1.9 \times 10^{-3}$), which indicates that the higher the moisture content, the greater the value of ultimate compressive strain in the microwave-softened *E. regnans* compressive sample.

A similar approach was completed for shear parallel-to-grain (Table 4) and tension parallel-to-grain (Table 5) experiments.

Due to the significant influence of both strain rate and temperature, these main effects were further examined using a Bonferroni multiple comparison test (Table 6; Fig. 4) to identify the salient characteristics of wood temperature and wood strain rate associated with mean ultimate compression strain.

Salient characteristics for wood temperature.—The lowest wood temperature (i.e., 80°C to 85°C) produced the lowest mean value of ultimate compressive strain (Fig. 4). These results indicate that the associated Bonferroni ''difference in means'' between 80°C to 85°C and 100°C to 105°C are significant at the 1 percent level, and 80°C to 85°C and 120°C to 125°C are significant at the 10 percent level (Table 6). The difference in means between 100°C to 105°C and 120°C to 125°C for compression parallel-to-grain indicates an insignificant difference on ultimate compressive strain between these two temperature ranges because its associated adjusted P value = 1.0. Wood temperature ranges of 100°C to 105°C and 120°C to 125°C had the same statistical influence on, and caused the highest value of, ultimate compressive strain.

Salient characteristics for wood strain rate.—The fastest strain rate (i.e., 0.6 mm/s) produced the lowest mean value of ultimate compressive strain and compression parallel-to-grain (Table 6). This indicates that the associated difference in means between 0.1 and 0.6 mm/s and 0.2 and 0.6 mm/s strain rates were both significant at the 5 percent level. Both 0.1 and 0.2 mm/s strain rates have ultimate mean compressive strain values above the overall sample mean. Table 6 indicates that the associated difference in means between 0.1 and 0.2 mm/s are insignificant because the adjusted P value = 1.0. These characteristics indicate that the wood strain rates of 0.1 and 0.2 mm/s had the same statistical influence on, and caused the highest mean value of, ultimate compressive strain.

[2] An F-stat value is statistical output associated with an ANOVA regression model and indicates the statistical strength of a factor. The larger the F-stat, the stronger the statistical significance of the factor under examination.

Table 3.—Summary of analysis of variance for compression parallel-to-grain experiments.[a]

Main and interaction effects	F-stat	P value
Moisture content	17.82	0.000
Strain rate	4.32	0.014
Temp.	4.72	0.010
Strain rate × temp.	0.43	0.788
Individual regression terms	**Coefficient**	**P value**
Constant	0.3141	0.000
Moisture content (covariate)	0.0019	0.000
Strain rate: 0.1	0.0183	0.100
Strain rate: 0.2	0.0154	0.169
Strain rate: 0.6	—	—
Temp.: 82.5	−0.0339	0.003
Temp.: 102.5	0.0241	0.031
Strain rate × temp.: 0.1 × 82.5	0.0115	0.464
Strain rate × temp.: 0.1 × 102.5	−0.0041	0.791
Strain rate × temp.: 0.2 × 82.5	−0.0138	0.385
Strain rate × temp.: 0.2 × 102.5	0.0168	0.285

[a] Model factors: strain rate at three levels: 0.1, 0.2, and 0.6 mm/s; temperature at three (mean) levels: 82.5°C, 102.5°C, and 122.5°C. Model covariant: moisture content (%). Response variable: ultimate compressive strain (%). Dashes = insignificant.

Shear parallel-to-grain.—Shear parallel-to-grain experiments were completed for only 80°C to 85°C and 100°C to 105°C temperature ranges because, in preliminary testing, the acquisition and maintentance of the 120°C to 125°C temperature range was found to be difficult for the standard wood specimen size.

Observation of the ANOVA statistical output for the shear parallel-to-grain experiments (Table 4) indicated that strain rate was statistically significant at a 1 percent level because $P_{SR} = 0.005$; the moisture content covariate was statistically significant at a 5 percent level because $P_{MC} = 0.027$; the interaction effect between wood strain rate and wood temperature (i.e., SR × T; $P = 0.437$) and wood temperature ($P = 0.892$) were statistically insignificant because their associated P values were far greater than a

Table 4.—Summary of analysis of variance for shear parallel-to-grain experiments.[a]

Main and interaction effects	F-stat	P value
Moisture content	4.98	0.027
Strain rate	5.39	0.005
Temp.	0.02	0.892
Strain rate × temp.	0.83	0.437
Individual regression terms	**Coefficient**	**P value**
Constant	6.028	0.000
Moisture content (covariate)	0.0095	0.027
Strain rate: 0.1	0.0054	0.971
Strain rate: 0.2	0.3979	0.006
Strain rate: 0.6	—	—
Temp.: 82.5	0.0138	0.892
Strain rate × temp.: 0.1 × 82.5	0.1825	0.217
Strain rate × temp.: 0.2 × 82.5	−0.1345	0.346

[a] Model factors: strain rate at three levels: 0.1, 0.2, and 0.6 mm/s; temperature at two (mean) levels: 82.5°C and 102.5°C. Model covariant: moisture content (%). Response variable: ultimate shear strain (%). Dashes = insignificant.

Table 5.—Summary of analysis of variance for tension parallel-to-grain experiments.[a]

Main and interaction effects	F-stat	P value
Moisture content	7.9	0.005
Strain rate	1.65	0.194
Temp.	4.31	0.039
Strain rate × temp.	1.58	0.208
Individual regression terms	Coefficient	P value
Constant	0.792	0.000
Moisture content (covariate)	0.0022	0.005
Strain rate: 0.1	−0.021	0.167
Strain rate: 0.2	−0.0052	0.729
Strain rate: 0.6	—	—
Temp.: 82.5	0.0225	0.039
Strain rate × temp.: 0.1 × 82.5	0.0155	0.316
Strain rate × temp.: 0.2 × 82.5	−0.0263	0.077

[a] Model factors: strain rate at three levels: 0.1, 0.2, and 0.6 mm/s; temperature at two levels: 82.5°C and 102.5°C. Model covariant: moisture content (%). Response variable: ultimate tensile strain (%). Dashes = insignificant.

10 percent significance level; and the coefficient for moisture content in the regression model was positive (i.e., moisture content covariate $= +9.5 \times 10^{-3}$), which indicated that the higher the moisture content, the greater the ultimate shear strain in the microwave-softened *E. regnans* shear sample.

Because of the significant influence of wood strain rate, this main effect was further analyzed by using a Bonferroni multiple comparison test (Fig. 4; Table 6) to identify the salient characteristics of wood strain rate associated with mean ultimate shear strain.

Salient characteristics for wood strain rate—All strain rates (i.e., 0.1, 0.2, and 0.6 mm/s) produced statistically similar ultimate shear parallel-to-grain strain values because the difference in means between strain rates (i.e., 0.1 and 0.2 mm/s, and 0.1 and 0.6 mm/s) were insignificant; their adjusted *P* values were far greater than a 10 percent significance level (Table 6).

The 0.2 mm/s strain rate caused the highest ultimate shear strain (Fig. 4). Shear parallel-to-grain results indicate that the difference in means between strain rates of 0.2 and 0.6 mm/s was significant at a 1 percent level (i.e., adjusted *P* value = 0.0037). The wood strain rates of 0.1 and 0.2 mm/s had a similar statistical influence on ultimate shear strain compared with 0.6 mm/s.

Tension parallel-to-grain.—The relatively small cross-sectional area of the neck region of the American Society for Testing and Materials (ASTM) D143-94 (ASTM 1994) tension specimen (i.e., 9.5 by 4.8 mm) resulted in wood ray cell rupturing in the temperature range 120°C to 125°C. As such, tension parallel-to-grain experiments were completed for only 80°C to 85°C and 100°C to 105°C temperature ranges.

Observation of the ANOVA statistical output for these tension parallel-to-grain experiments (Table 5) indicated that strain rate is statistically insignificant because its associated *P* value, $P_{SR} = 0.194$, was far greater than a 10 percent significance level. Temperature was statistically significant at a 5 percent significance level because $P_T = 0.039$, and the moisture content covariate was statistically significant at a 1 percent level because $P_{MC} = 0.005$. The

Table 6.—Summary of Bonferroni multiple comparison tests for extended statistical analysis of the main effects associated with compression parallel-to-grain, shear parallel-to-grain, and tension parallel-to-grain experiments.

	Difference in means (t test)	Adjusted P value[a]
Compression parallel-to-grain		
Comparison between different temp. relative to (mean) 82.5°C		
Temp. (°C)		
102.5	0.05798	0.0095
122.5	0.04369	0.0891
Comparison between different temp. relative to (mean) 102.5°C		
Temp. (°C)		
122.5	−0.01429	1.000
Comparison between different strain rates relative to 0.1 mm/s		
Strain rate (mm/s)		
0.2	−0.00294	1.000
0.6	−0.05193	0.0254
Comparison between different strain rates relative to 0.2 mm/s		
Strain rate (mm/s)		
0.6	−0.04899	0.041
Shear parallel-to-grain		
Comparison between different strain rates relative to 0.1 mm/s		
Strain rate (mm/s)		
0.2	0.3637	0.4586
0.6	−0.4331	0.2842
Comparison between different strain rates relative to 0.2 mm/s		
Strain rate (mm/s)		
0.6	−0.7967	0.0037
Tension parallel-to-grain		
Comparison between different temp. relative to (mean) 82.5 °C		
Temp. (°C)		
102.5	0.02171	0.0391

[a] Adjusted *P* value (*X*/*Y*) corresponds to *P* value for level *X* relative to level *Y*.

interaction effect between wood strain rate and wood temperature (i.e., SR × T) was insignificant because its associated *P* value ($P = 0.208$) was far greater than a 10 percent significance level. Finally, the coefficient for moisture content in the regression model was positive (i.e., moisture content covariate $= +2.2 \times 10^{-3}$), which indicates that the higher the moisture content, the greater the ultimate tensile strain in the microwave-softened *E. regnans* tension sample.

Because of the significant influence of wood temperature variation, this main effect was further analyzed using a Bonferroni multiple comparison test (Table 6; Fig. 4) to identify the salient characteristics of temperature associated with mean ultimate tensile strain.

Salient characteristics for wood temperature.—The 80°C to 85°C temperature range resulted in the highest ultimate tensile strain (Fig. 4). Tension parallel-to-grain results indicate that the associated difference in means between 80°C to 85°C and 100°C to 105°C was significant at a 5 percent significance level because its adjusted *P* value = 0.039 (Table 5).

Microwave wood-bending experiments

The selection of the shape of the decreasing radius bending form was based on preliminary bending trials using a typical center-loading bending machine. The custom

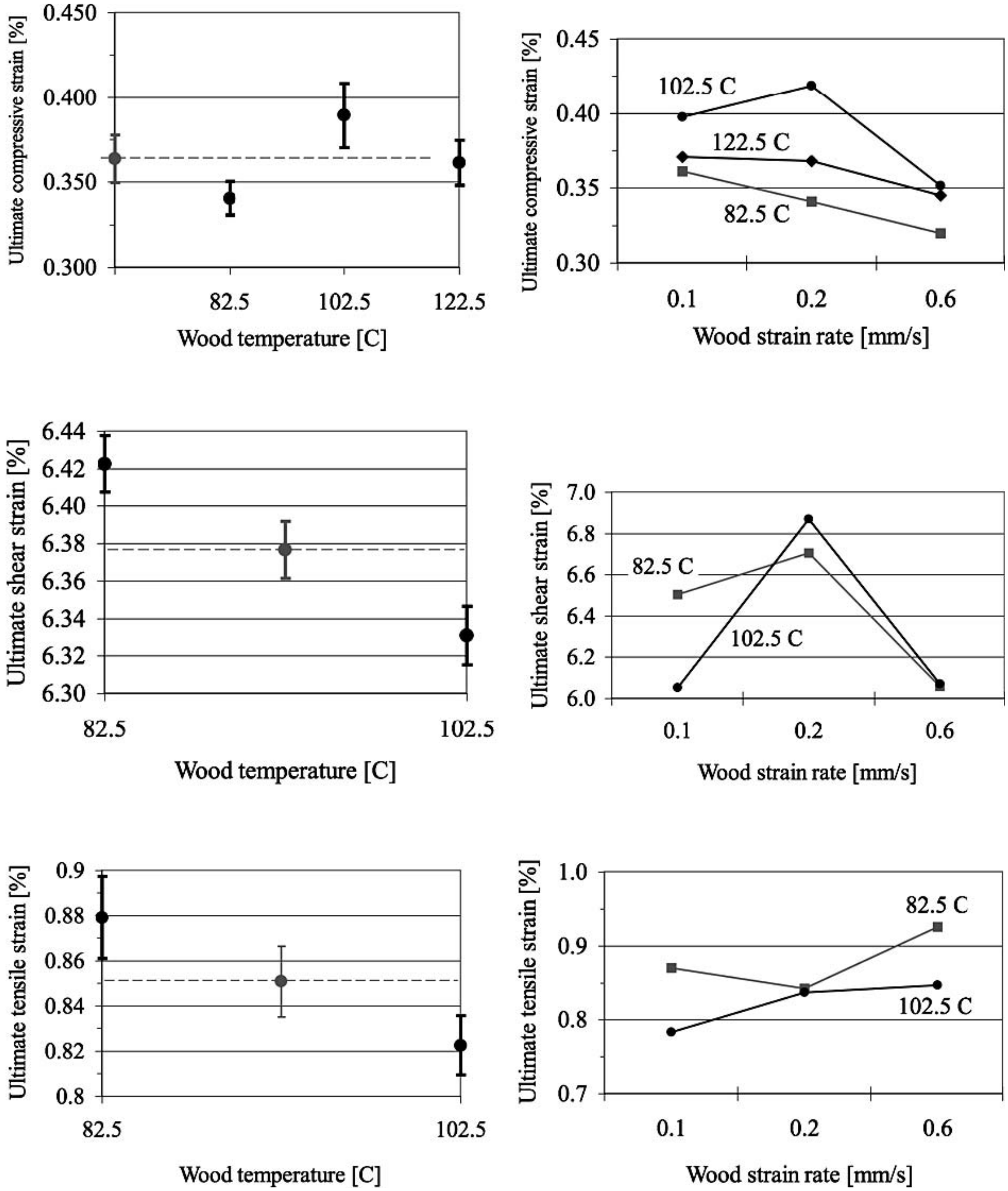

Figure 4.—Graphical summary of the significant main effects from microwave mechanical property experiment statistical analysis. Left charts combine all wood strain rates for each of the examined wood temperatures, and dashed horizontal lines represent overall mean value for ultimate strain.

bending form used in the MWBE had a leading radius of 400 mm and a trailing radius of 200 mm. However, better than expected bending performance of some of the wood specimens resulted in successful bends down to the minimum 200-mm radius. These specimens reached this radius without incurring any failure. Consequently, the ANOVA could not be applied because the response variable (minimum radius) was unknown due to a lack of a failure point in the bending experiments. As such, a regression with life data analysis was used because it allowed for censored data associated with the incomplete bending experiments (Lawless 2003).

The regression with life data statistical analysis required as factors the minimum radius in bending, wood strain rate, and wood temperature, with wood strain rate $\times$ wood temperature as an interaction effect, moisture content of wood at failure location as a covariate, and the incomplete bends as censored data.

After obtaining and arranging the raw data from the MWBE, the regression with life data statistical analysis was completed. χ^2 test results (Table 7) demonstrated that all regression model factors had statistical significance (Moore and McCabe 1993). The main effect of strain rate was strongly significant because its P value $= 0.000$, and the main effect of temperature was significant at a 10 percent significance level because $P_T = 0.075$. The interaction effect between strain rate and temperature (i.e., SR $\times$ T) was

Table 7.—Summary of microwave wood-bending experiments statistical regression analysis.[a]

Model regression terms	Coefficient	P value
Constant	3.69	0.000
Moisture content (covariate)	0.028	0.000
Strain rate: 27	−0.348	0.000
Strain rate: 81	−0.446	0.000
Temp.: 102.5	−0.095	0.311
Temp.: 122.5	−0.212	0.024
Strain rate × temp.: 27 × 102.5	0.162	0.224
Strain rate × temp.: 27 × 122.5	−0.354	0.008
Strain rate × temp.: 81 × 102.5	−0.012	0.930
Strain rate × temp.: 81 × 122.5	−0.288	0.029
χ^2 test results	χ^2	P value
Strain rate	24.459	0.000
Temp.	5.168	0.075
Strain rate × temp.	9.709	0.046

[a] Factors: strain rate at three levels: 13°/s, 27°/s, and 81°/s—regression with respect to 13°/s; temperature at three (mean) levels: 82.5°C, 102.5°C, and 122.5°C—regression with respect to 82.5°C. Covariant: moisture content (%). Response variable: bending performance (mm).

significant at a 5 percent significance level because $P_{SR \times T} = 0.046$.

Table 7 shows the statistical significance and influence on bending performance for the main effects and interaction effects relative to a baseline strain rate of 13°/s and temperature of 82.5°C, with the following salient characteristics:

- Strain rates of 27°/s and 81°/s are both strongly significant because their P values = 0.000.
- Strain rates of 27°/s and 81°/s both reduce mean bending performance because their regression model coefficients were negative (i.e., –0.348 and –0.446, respectively).
- A temperature of 102.5°C was insignificant because its P value was far greater than a 10 percent significance level.
- A temperature of 122.5°C was significant at a 5 percent significance level because its $P_{T:122.5} = 0.024$.
- A temperature of 122.5°C reduces mean bending performance because its regression model coefficient was negative (i.e., –0.212).
- The interaction effect of strain rate × temperature at 27°/s × 122.5°C and 81°/s × 122.5°C are both statistically significant, as their P values were less than a 1 and 5 percent significance level, respectively
- The interaction effect of strain rate × temperature at 27°/s × 122.5°C and 81°/s × 122.5°C both reduce the mean bending performance because their regression model coefficients were negative (i.e., –0.354 and –0.288, respectively).

In conclusion, the wood strain rate of 13 mm/s combined with a wood temperature range of either 80°C to 85°C or 100°C to 105°C produced the highest mean bending performance.

The moisture content covariate has a strong statistical influence on bending performance because its P value = 0.000. The regression coefficient for moisture content was positive (i.e., +0.028), which indicates that an increase in the moisture content significantly increases bending performance.

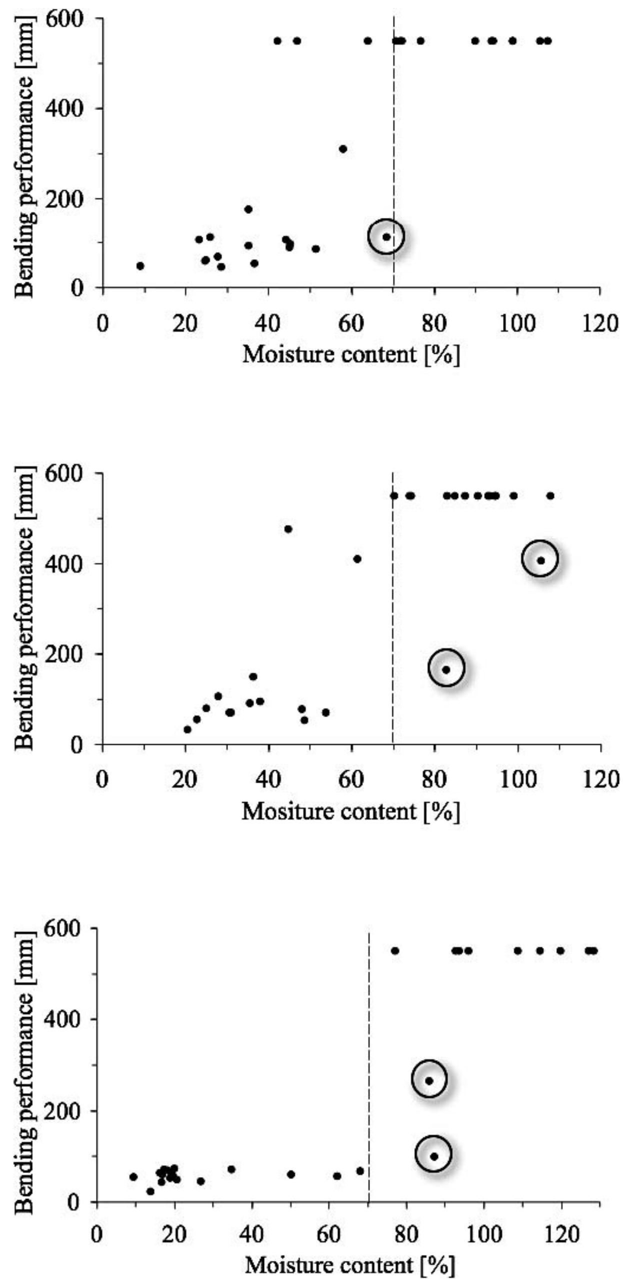

Figure 5.—Scatterplots of bending performance versus moisture content for the best performing strain rate (13°/s) and temperature (top: 80°C to 85°C; middle: 100°C to 105°C; bottom: 120°C to 125°C) combinations during microwave wood-bending experiments to identify optimum moisture content conditions. Bending performance corresponds to the arc length along the convex edge of the decreasing radius bending form, from the start of the decreasing radius to the wood failure measurement location. Moisture contents greater than 70 percent (i.e., to the right of the dashed lines) always resulted in the greatest possible bending performance (i.e., 550 mm). Highlighted data points in each scatterplot represent specimens that contained discontinuities or material imperfections such as large gum veins, knots, or severe checking.

Further moisture content investigation was conducted to identify the most favorable moisture content at the best performing wood strain rate of 13°/s and wood temperature ranges of 80°C to 85°C and 100°C to 105°C. Scatterplots of

Table 8.—Summary of outcomes from optimum bending experiments.[a]

Wood bending variable	Compression parallel-to-grain	Shear parallel-to-grain	Tension parallel-to-grain	Bending
Moisture content (covariate)	Significant* [increase causes positive affect]	Significant (5%) [increase causes positive affect])	Significant* [increase causes positive affect]	Significant* [increase causes positive affect, >70% causes zero failure-rate]
Wood strain rate (main effect)	Significant (5%) [0.1 and 0.2 mm/s]	Significant* [0.1 and 0.2 mm/s]	Insignificant	Significant (1%) [13°/s]
Wood temp. (main effect)	Significant (1%) [100°C–105°C and 120°C–125°C]	Insignificant	Significant (5%) [80°C–85°C]	Significant (10%) [80°C–85°C and 100°C–105°C]
Strain rate × temp. (interaction effect)	Insignificant	Insignificant	Insignificant	Significant (1%), 27°/s × 122.5°C; significant (5%), 81°/s × 122.5°C

[a] * = the wood-bending variable with the strongest statistical significance (i.e., largest *F*-stat) from each microwave mechanical property experiment and the microwave wood-bending experiment; ( ) = confidence interval significance level; [ ] = the most favorable conditions for wood bending purposes.

bending performance versus moisture content (Fig. 5) illustrate that specimens with a moisture content greater than 70 percent consistently produced the highest bending performance with a zero failure rate.

Conclusions

A series of bending experiments using microwave-heated *E. regnans* wood were conducted, identifying the influence of both the main and interaction effects on bending performance using a full factorial experimental design framework research method developed for this study (Table 8).

Moisture content consistently had the strongest influence on both mechanical properties and bending performance. An increase in the moisture content of a specimen caused an increase in ultimate strain and an associated decrease in minimum bending radius. Moisture contents above 70 percent resulted in maximum bending performance for the experiments with 13°/s strain rate and 80°C to 85°C and 100°C to 105°C temperature ranges.

Wood strain rate had a lower but still significant influence on the mechanical properties and bending performance for all MMPE and MWBE except tension parallel-to-grain, in which the slower the wood strain rate, the greater the mechanical and bending performance. The best performing wood strain rates for *E. regnans* were 0.1 mm/s for the MMPE and 13°/s for the MWBE.

Wood temperature outcomes were less consistent than those obtained for moisture content and wood strain rate. Bending experiments demonstrated that the wood temperature ranges of 80°C to 85°C and 100°C to 105°C produced the best outcomes. Compression parallel-to-grain experiments demonstrated that 100°C to 105°C and 120°C to 125°C resulted in the largest ultimate mean compressive strain. However, the 120°C to 125°C temperature range is not recommended for industrial applications because these higher temperatures increase the likelihood of wood structural damage and the additional cost associated with the increased microwave energy requirement. Tension parallel-to-grain experiments demonstrated that the 80° to 85°C temperature range produced the highest ultimate tensile strain mean value. However, because the development of tensile strain during bending is controlled by a support strap to maintain the strain below the specimen's ultimate tensile strength, this tension outcome is less significant than the compression outcome for optimizing wood-bending performance.

For both mechanical properties and bending performance, the best performing wood temperature range for *E. regnans* is 100°C to 105°C.

Interaction effects between bending variables produced statistically significant outcomes during MWBE for the wood strain rate and temperature combinations 27°/s and 120°C to 125°C and 81°/s and 120°C to 125°C. All other experiments resulted in statistically insignificant interaction effects. For example, χ^2 test results (Table 7) show a χ^2 test statistic of 24.459 for strain rate and only 5.168 for temperature, which effectively biases the associated interaction effects. In practice, this means that bending performance is more sensitive to wood strain rate than wood temperature. A consequence of this in a production setting is that wood strain rate requires more precise process control than does wood temperature during the microwave-heated bending of *E. regnans*.

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