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Preparation of Teakwood Bending Components with Excellent Softening Properties by Vacuum Impregnation with Triethanolamine Compounding Solution

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Abstract: To study the softening bending properties and mechanism of teakwood, it was extractively pretreated by using superheated steam, the triethanolamine compound was used as a softening solution, which was infiltrated into the wood by vacuum impregnation and synergistically softened through saturated steam to improve the bending properties of teakwood. Analysis by Fourier transform infrared spectroscopy (FTIR), Carbon 13 nuclear magnetic resonance (^{13}C NMR), and X-ray photoelectron spectroscopy (XPS) showed that the synergistic softening treatment elevated the content of O and N elements in the softening solution and together with the C elements in the wood, formed C-NH_2 and C-N bonds, which increased the molecular activity and improved the softening properties of teakwood. Scanning electron microscope (SEM) observations revealed that the outer conduits, cell walls, and fibrous tissue structures of the teakwood were stretched after softening and bending, and even microcracks of different degrees were formed between the cell walls. According to the load–deformation relationship of teakwood softening bending, the stress–strain relationship was theoretically derived and the bifold constitutive model of teakwood bending was constructed after fitting the constitutive relationship data, the integrated correlation coefficient R^2 was 96.25%, which proved that the present model can better simulate the constitutive relationship of teakwood in bending.

Keywords: teakwood bending; triethanolamine; softening mechanism; constitutive model

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1. Introduction

Solid wood bending is a processing method which is softened through a certain technology to make it bend and mold. The bending components processed by this method not only maintain the original texture of the wood, but also have good mechanical properties, so it is widely used in furniture, architecture, agriculture implements, and other fields [1,2]. Solid wood bending technology has a long history, but there is a more complex production process, bending tree species are limited, the bending radius of curvature is larger and so on, which limits the development and production of curved wood products to a certain extent [3,4]. Structurally, wood is a porous material with a network structure, and it is due to this property that wood can be softened and modified under certain conditions, and the production and processing of bending components can be conducted under certain external forces [5,6].

Recently, scholars have used chemical–physical synergistic softening methods to improve the softening properties and bending quality of wood, to solve the problems of insufficient softening and softening collapse that exist in a single softening process. For example, Šprdlík et al. [7] used a synergistic treatment of ammonia and steam to

soften beech, which resulted in significantly better plasticity than samples only treated with ammonia and increased the flexibility of the material, which improved the bending properties of the wood. Wang et al. [8] used an ammonia solution to analyze the softening process of teakwood; the bending coefficient is 1/21, and its bending performance is obviously better than hydrothermal treatment. Shen et al. [9] studied the softening process of ammonia solution and steam synergistic treatment of teakwood by response surface methodology and analyzed the effects of alkali concentration, treatment temperature, and treatment time on the softening properties of wood, and the results showed that vacuum impregnation of ammonia solution was conducive to the softening bending of teakwood and mechanical properties such as maximum loading, bending strength, and elasticity modulus of specimens after drying and shaping were improved to a certain extent. Yao et al. [10] adopted a synergistic treatment of triethanolamine and superheated steam to soften teakwood, and its bending properties were significantly improved, and explained the softening mechanism from the changes in chemical constituents, but lack of experimental studies on the process optimization and bending mechanics. Many studies have shown that the chemical–physical synergistic softening method can make the chemical solution enter into the crystalline and non-crystalline regions of wood under high temperature and humidity conditions, wetting cellulose, hemicellulose, and lignin, and providing enough space for molecular movement, as well as lowering the glass transition temperatures of the main constituents in the cell wall, which greatly improves the softening and bending effect of the wood [11,12], but it is prone to cause problems such as wood collapse, discoloration, environmental pollution, and so on [13,14].

Teak belongs to the Verbenaceae teak genus large semi-deciduous tree, with a beautiful texture, aromatic smell, resistance to corrosion and insects, and other excellent characteristics, is recognized as the world's best timber species, but its interior is rich in oleaginous substances, conventional technology is difficult to bend [15]. Therefore, vacuum impregnation by an environmentally friendly triethanolamine combination solution by the synergistic softening bending of teakwood with saturated steam as a medium was carried out to improve its softening properties and bending quality in the study. The research has important theoretical value and practical significance both in improving the bending properties of hardwood species and increasing the high value-added utilization of wood.

2. Materials and Methods

2.1. Materials and Reagents

Plantation teakwood (*Tectona grandis* L.F.) was purchased from Xishuangbanna Dai Autonomous Prefecture, Yunnan Province, and the sample tree was 25 cm in diameter and 15 years old. The specimens were prepared according to the Chinese national standard GB/T1929-2009, with the size of 500 × 40 × 20 mm (L × T × R). The texture was required to be straight, and defects such as knots, cross grain, and decay were not allowed. Triethanolamine (TEA, $C_6H_{15}NO_3$), sodium chloride (NaCl, AR), and sodium dodecylbenzene sulfonate (SDBS, $C18H_{29}NaO_3S$,) were purchased from Shanghai Sinopharm Group Chemical Reagent Co. (Shanghai, China).

2.2. Specimen Preparation

2.2.1. Softening Solution Preparation

Distilled water, TEA, osmotic agent NaCl, and surfactant SDBS were formulated into a teakwood impregnation softening solution in a certain ratio. The mass ratio of distilled water to TEA was 100:5, 100:10, 100:15, 100:20, NaCl: SDBS: TEA = 1:1:7.

2.2.2. Softening and Bending Process

The teakwood specimen softening and bending process mainly consisted of four steps: pretreatment, vacuum impregnation with softening solution, softening, and bending, drying, and shaping. Firstly, in pretreatment, the teakwood specimens were put into superheated steam equipment at 120 °C for 60 min for extractive pretreatment of the

specimens. Next was the softening solution vacuum impregnation, the specimen would be put into the impregnation test tank, extract the vacuum, when the vacuum degree reached −0.08 MPa, for 60 min, followed by the inhalation of the softening solution, and then the 0.5~1 MPa pressure, pressure impregnation for 120 min, then unpressurized. Repeated it 3 to 5 times, so that the softening solution fully penetrated the teakwood. The second was softening and bending, the impregnated teakwood specimens were put into the softening tank, at 100~140 °C saturated steam for heating and softening for 90~210 min. They would be placed in the bending machine for bending under pressure at a constant speed after the specimens were softened. In the process, temperature, time, and concentration of softening solution were selected as the main influencing factors for experiments. Finally, drying and shaping, successful bending specimen were fixed by using an F-type fixture, and then were put into the superheated steam equipment to dry and shape at 130 °C for 120 min, with heating rate at 60 °C/h.

Based on the above process, high-temperature steam pretreatment enabled the pit membrane of the teakwood to be partially penetrated and the inclusions in the conduit to be partially expelled to improve its permeability [16]. The teakwood was impregnated by using the method of "negative pressure—positive pressure" to deeply penetrate the softening solution into teakwood. Then, under saturated steam conditions, the reaction between the softening solution and the chemical constituents of the teakwood, not only penetrated the non-crystalline zone but also made the crystalline zone of cellulose wetting and swelling, thus improving the softening effect and plastic deformation capacity [17]. The teakwood bending components were deformation fixed by superheated steam to reduce their deformation recovery capacity and improve dimensional stability in the process of drying and shaping. The softening principle and bending process are shown in Figure 1.

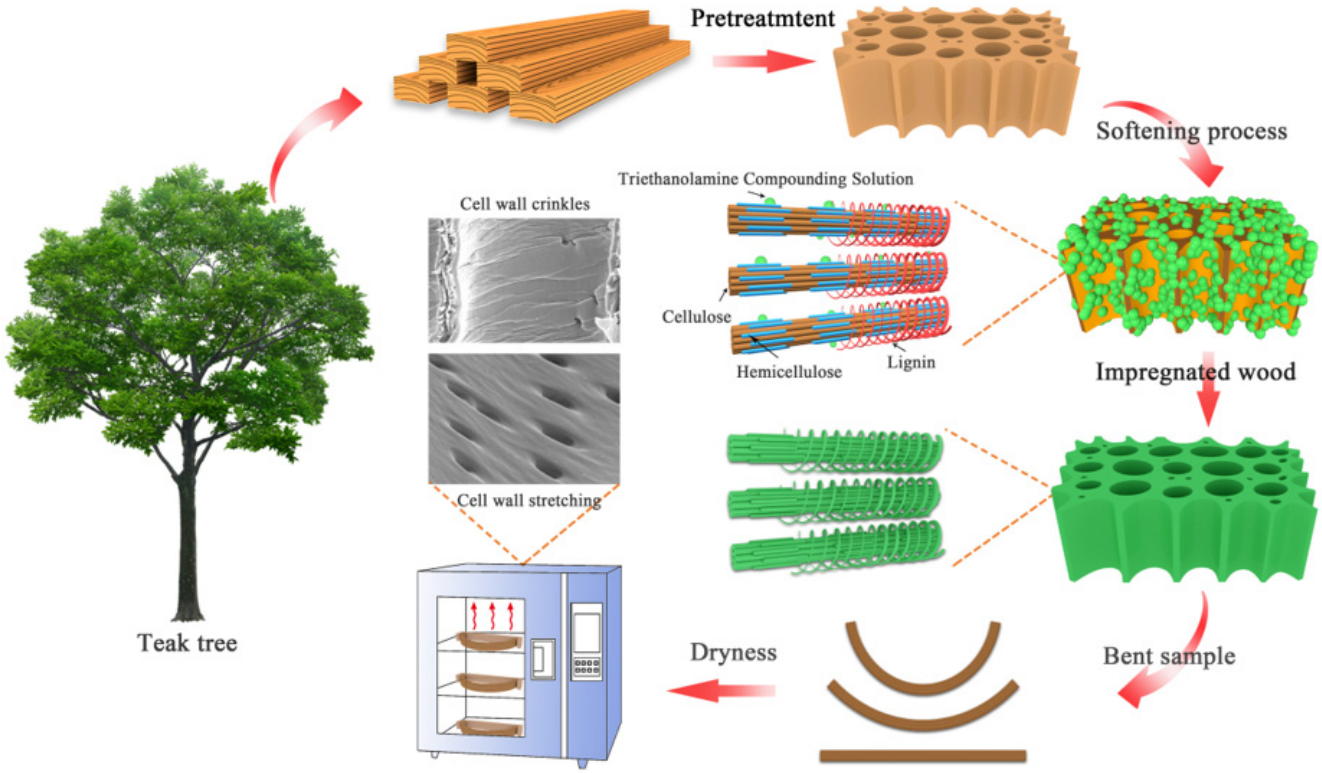


Figure 1. Specimen softening principle and bending process flow diagram.

In order to deeply study the effect of softening solution vacuum impregnation on the bending of teakwood, the softening and bending properties of impregnated and unimpregnated wood will be compared and analyzed in the experiment. Softening bending of unimpregnated wood means that the specimens are not impregnated with softening

solution vacuum impregnation, but only by steaming, including two process parameters: softening temperature and time.

2.3. Properties and Characterization

2.3.1. Evaluation of the Softening Bending Property

The evaluation criteria for the softening bending properties of teakwood are expressed by the bending coefficient (K_b). The minimum bending radius of curvature (R_{min}) and the bending coefficient (K_b) of a specimen are calculated according to Equations (1) and (2), respectively.

$$R_{min} = a^2/8b + b/2, \quad (1)$$

$$K_b = h/R_{min}, \quad (2)$$

where a is the inner chord length of the bent component (mm); b is the distance from the inner wall to the chord length (mm); h is the thickness (mm).

It is noted that based on a smaller bending radius of curvature of the specimen, such as cracking of the outer tensile surface of the bending components and creasing of the inner compressive surface are also evaluated comprehensively.

2.3.2. Evaluation of Drying and Shaping

The drying and shaping of teakwood bending components are evaluated by the rate of change of chord length. The rate of change in chord length (Y) was calculated using Equation (3):

$$Y = (L_1 - L_0)/L_0, \quad (3)$$

where L_0 is the chord length of the bent component (mm); L_1 is the rebound stable chord length of the bent component (mm).

2.3.3. Characterization of Samples

- Fourier transform infrared spectroscopy (FTIR) analysis

A total of 2 mg of absolutely dry wood powder was mixed well with 6 mg of potassium bromide powder and pressed into a thin slice, which was tested using an FTIR spectrometer (Bruker Tensor 27, Germany) with a spectral range of 4000–400 cm^{-1}, a resolution of 4 cm^{-1} and scans of 64.

- ^{13}C Nuclear magnetic resonance (^{13}C NMR) analysis

The specimens were crushed and screened for wood powder before and after the softening treatment, and the spectral changes of the specimens were examined by ^{13}C NMR spectrometer (Bruker AV300, German). The spectrometer was operated at 100.7 MHz and nuclear magnetic resonance kinematic spectroscopy with cross-polarized/magic-angle spin (CP/MAS) was used, where the magic-angle spin speed (MAS) was 2.5 MHz and the rotational frequency was 5000 MHz.

- Analysis X-ray photoelectron spectroscopy (XPS) analysis

The specimens were prepared as 10 × 10 × 1 mm slice, and the chemical elemental changes in the untreated and treated materials were detected by XPS (Escalab 250, USA). An aluminum-targeted X-ray source (Al Kα, hv = 1486.6 eV) with a power of 225 W and a contaminated carbon (internal standard) of 284.8 eV was used, and the data were processed by CasaXPS 2.3 software for analysis.

- Scanning electron microscope (SEM) observation

SEM (Sigma300, Germany) was used to observe the morphological changes in the cell walls, ducts, and pits of teakwood before and after bending. The size of the specimen was less than 10 × 10 × 5 mm, and the sample was fixed on the tray with conductive adhesive

and then sprayed with platinum during the test. The resolution of the instrument was 1.0 nm@15 kV, and the accelerating voltage was 10 kV.

2.3.4. Bending Mechanical Properties Test

The test of the load–deformation relationship in softening bending of teakwood was carried out by using a bending machine (customized, China) that cooperated with a mechanical testing machine (KHQ-002H, China), which was set at a maximum load force of 10×10^3 N and a testing speed of 100 mm/min.

3. Results and Discussion

3.1. Bending Property Analysis

3.1.1. Single-Factor Testing Results

Figure 2 shows the effect of different temperatures on the softening bending properties of teakwood for 180 min and with a 15% concentration softening solution. As can be seen from Figure 2, the softening bending properties of the teakwood showed a tendency to increase and then decrease with the increase of the temperature. The softening bending properties of the specimen (h/r value) reached a maximum average value of 1/9.68 when the impregnated wood was at 120 °C, while the unimpregnated wood was 1/11.62, which indicates that after the softening solution treatment, the softening bending properties of teakwood has been significantly improved, bending properties increased by 20.04%, and the qualification rate can be up to about 85%. When the temperature continued to increase to 130 and 140 °C, the bending properties of teakwood showed a decreasing trend, which is mainly related to the glass transition temperature of the wood, the dissolution of extractives, changes in chemical constituents, and other factors [18–20]. In addition, the experiment also analyzed the effect of steaming only on the softening bending properties of teakwood, and the trend was more consistent with the synergistic softening treatment of wood, but the bending properties were poorer.

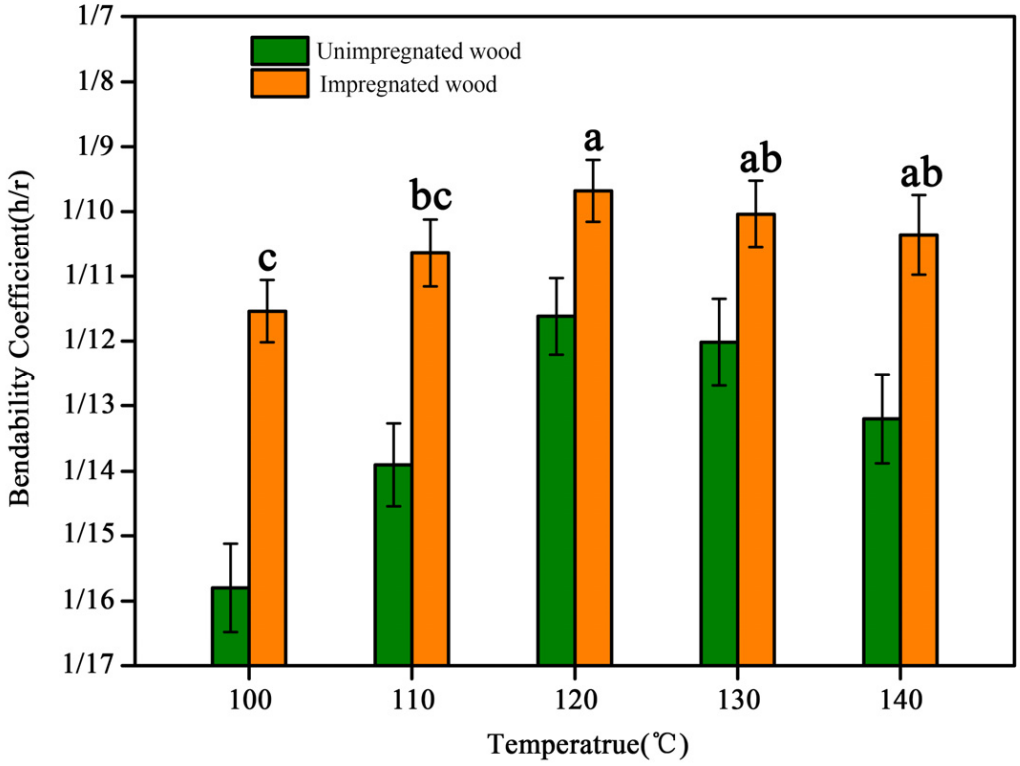


Figure 2. Effect of different temperatures on bending properties of teakwood.

Figure 3 shows the effect of different times on the softening bending properties of teakwood at 120 °C with 15% concentration softening solution. From Figure 3, it is found that the softening time has a significant effect on the bending properties. When the softening time is too short, the main chemical constituents of the wood can not reach the glass transition temperature, and the internal and surface softening degree is different, which makes it easy to cause the bending crack. When the time reaches 180 min, the bending properties reach the maximum. When the time exceeds 180 min, the bending properties start to decrease gradually. It is possibly due to the over-degradation of the main chemical constituents in the teakwood by the long softening time, which may even cause damage to the internal structure of the wood and reduce the bending properties [21,22].

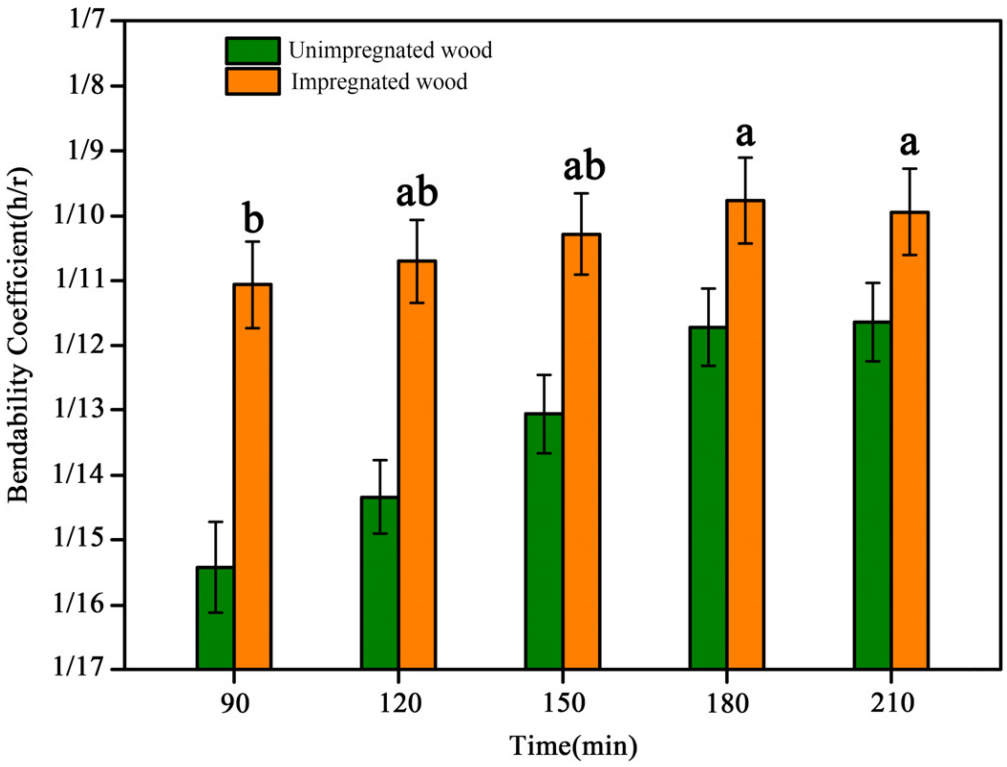


Figure 3. Effect of different times on bending properties of teakwood.

Figure 4 shows the effect of different concentrations of softening solution on the softening bending properties of teakwood at 120 °C for 180 min. The chemical reagent softening mechanism is different from hydrothermal, it can not only penetrate the wood of hemicellulose, lignin non-crystalline region but also penetrate the cellulose crystalline region, causing the internal expansion of the wood under the action of high-temperature steam and increase the distance between the cellulose molecular chain to improve the softening bending properties of teakwood. However, when the concentration of softening solution is too high, the bending properties of teakwood specimens are slightly decreased; this may be due to the alkaline nature of the solution, and can partly dissolve the lignin and destroy the internal structure of the wood, which results in changes to the bending properties of teakwood.

3.1.2. Response Surface Optimization Analysis

Based on the single factor analysis, the teakwood softening process was further analyzed by using the response surface process optimization method to obtain the optimal softening solution of impregnation–steam synergistic softening parameters. Table 1 shows the factors and levels tested in the experiment design.

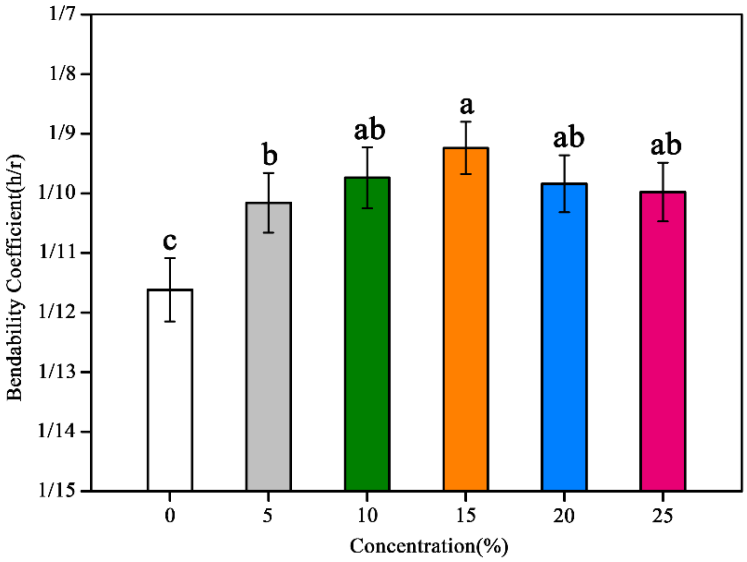


Figure 4. Effect of different softening solution concentrations on bending properties of teakwood. Different colors represent different concentrations.

Table 1. Factors and levels of response surface methodology experiment design.

Factors	Codes	Levels		
		−1	0	1
Temperature (°C)	A	110	120	130
Time (min)	B	150	180	210
Concentration (%)	C	10	15	20

The experiment was carried out according to the optimization scheme of the Box–Behnken design and its results are shown in Table 2. The results of the experiment were calculated and analyzed by the software Design Expert 12, considering the value of the bending coefficient h/r is too small. The model and ANOVA were analyzed by the percentage, and the results are shown in Table 3.

Table 2. BoxBehnken response surface experiment results.

No.	A	B	C	h/r Value
1	110	180	10	1/11
2	110	210	15	1/10.6
3	110	150	15	1/10.1
4	110	180	20	1/10.5
5	120	150	10	1/10
6	120	180	15	1/9.24
7	120	180	15	1/9.17
8	120	210	20	1/10.2
9	120	210	10	1/10.5
10	120	180	15	1/9.56
11	120	180	15	1/9.4
12	120	150	20	1/10.5
13	120	180	15	1/9.1
14	130	210	15	1/9.6
15	130	150	15	1/9.7
16	130	180	10	1/10.1
17	130	180	20	1/10.7

Table 3. Model and ANOVA analysis.

Variance Sources	Quadratic Sum	Degree of Freedom	Mean Square	*F* Value	*p* Value	Significance
Model	5.40	9	0.5997	16.27	0.0007	**
A	0.51	1	0.5116	13.88	0.0074	**
B	0.04	1	0.0356	1.05	0.3402	
C	0.01	1	0.0127	0.34	0.5761	
AB	0.0825	1	0.0825	2.24	0.1784	
AC	0.2441	1	0.2441	6.62	0.0368	*
BC	0.1430	1	0.1430	3.88	0.0896	
A^2	1.04	1	1.04	28.29	0.0011	**
B^2	0.2635	1	0.2635	7.15	0.0318	*
C^2	2.69	1	2.69	73.10	<0.0001	**
Residual	0.2581	7	0.0369			
Lack of fit	0.0760	3	0.0253	0.5569	0.6709	
Pure error	0.1820	4	0.0455			
Total departure	5.66	16				
R^2	0.9544					
R^2_{Adj}	0.8957					

Note: *, $p < 0.05$, significant; **, $p < 0.01$, particularly significant.

In Table 3, the regression model of the response surface has a *p*-value of 0.0007 ($p < 0.01$), which is particularly significant, and the softening bending property of the lack of fit item has a *p*-value of 0.6709 ($p > 0.05$), which is insignificant, indicating that the model is well fitted. At the same time, the response factor softening bending property corresponds to the degree of fit $R^2 = 0.9544$, indicating that the model equation can explain 95.44% experiments in softening bending teakwood, which indicates that the model fitted value is significantly correlated with the actual value, which can be explained to a high degree, and the model accuracy can meet the requirements.

The quadratic multinomial regression fitting equation for the teakwood softening bending process was obtained by ANOVA of the response surface as shown in Equation (4):

$$Y = 10.76 + 0.24A - 0.25AC - 0.50A^2 - 0.25B^2 - 0.80C^2, \quad (4)$$

where A, B, and C are the corresponding coded variables for softening temperature, treatment time, and softening solution concentration.

From the above analysis, it was concluded that the order of significance of the effect of each parameter on the softening bending of the teakwood was A > B > C, and the interaction between items A and C was the most significant.

Figure 5 shows the response surface and contour plots of the effect of the interaction between A and C on the bending properties of softened teakwood after treatment for 180 min. From Figure 5, it can be seen that the bending properties of teakwood show a tendency of increasing and then decreasing with the increase of the temperature and the concentration of softening solution. This is mainly because when the concentration of softening solution is too low, the decomposed substances from the heated softening solution cannot fully react with the chemical constituents of teakwood to increase the activity of the internal molecules of the wood, which limits the expansion and plasticizing ability, and the lower temperature does not allow the main chemical constituents of teakwood to reach the glass transition temperature [12]. However, under the combined effect of a higher concentration of the solution and sustained high temperature, the dissolution of lignin and cellulose will destroy the internal structure of the wood, causing a decline in the mechanical properties, which in turn affects the bending properties and product quality.

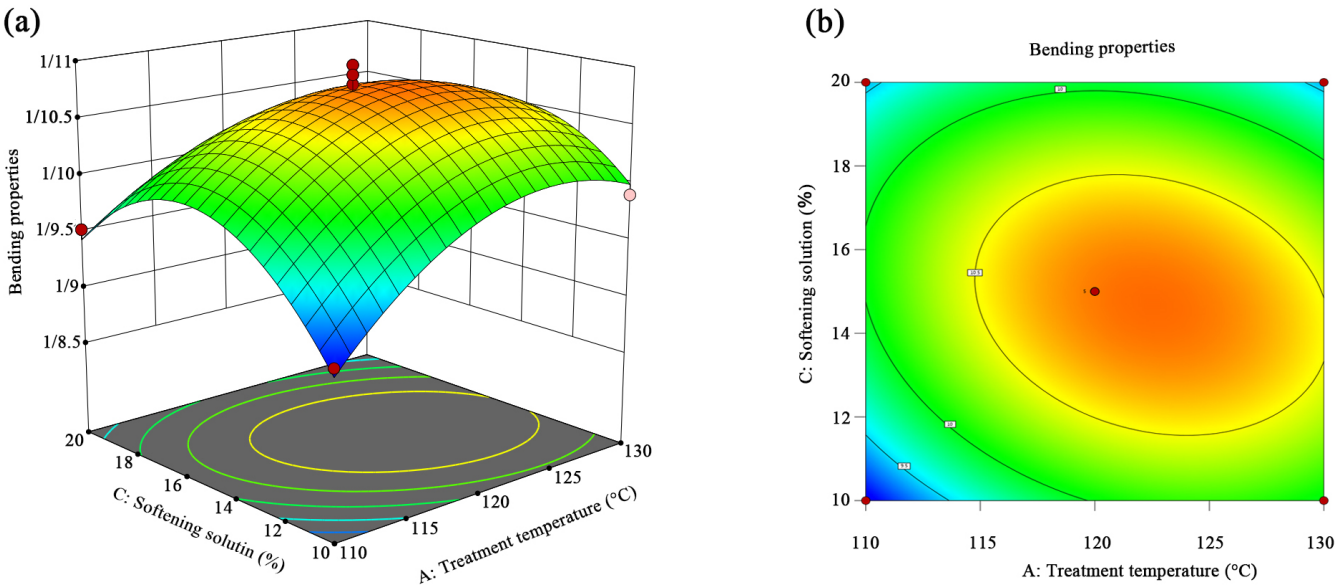


Figure 5. (**a**,**b**) Response surface and contour plots of the interaction between treatment temperature and softening solution concentration (color change: the significant degree to the bending properties; red dots: Extreme values on the response surface).

According to the response surface optimization results, it showed that the optimal synergistic softening process parameters were derived: the temperature was 123.59 °C, the treatment time was 177.19 min, and the concentration of softening solution was 14.62%, at which the maximum value of Y was 1/9.26. To operate conveniently, the experimental process parameters are verified at 125 °C for 175 min, and with the concentration of softening solution of 15% in the process of the experimental comparison.

3.1.3. Experiment Comparation Verification

The bending experiments on teakwood were verified according to the process parameters of softening solution impregnation–steam synergistic softening treatment, and the results are shown in Table 4. As shown in Table 4, the bending properties of the teakwood were significantly improved after the synergistic softening. The teakwood which is not impregnated with softening solution can also be bent to a certain extent after steam softening, but the bending radius of curvature is larger. If bent according to the bending radius of the impregnated wood, it will be more seriously cracked and had breakage. It is mainly due to the reaction between the softening solution and the chemical constituents of the teakwood in the steam treatment, which not only can penetrate the non-crystalline region of the wood but also can make the cellulose of the crystalline region of the wetting and expand to achieve the effect of enhancing the softening and improving the bending property.

3.2. Mechanism Analysis

Figure 6a shows the FTIR spectra of teakwood before and after softening. After the synergistic softening, the main chemical constituent of teakwood reacts with the softening solution in the way of undergoing superposition, grafting, and cross−linking, which causes different diffraction changes in the infrared spectrum before and after the softening [23]. The absorption peak of the softened treated material was significantly enhanced at 3410 cm^{-1}, where the absorption peak was mainly caused by O-H stretching vibration, which was mainly due to the superposition or mutual reaction between the functional groups in the softening solution and those in teakwood, promoting the bonding between teakwood cellulose molecules [24]. There are two new absorption peaks at 1598, and 1072 cm^{-1}, which are due to N-H bending vibration and C-N stretching vibration, respectively, which is possibly due to the grafting and cross-linking reaction between nitrogen in the softening solution and the chemical constituents in teakwood [25]. Meanwhile, the absorption peaks

were also strengthened around 2921 and 1460 cm^{-1}; 2921 cm^{-1} was caused by the C-H stretching vibration in methyl and methylene, and 1460 cm^{-1} was caused by the methyl C-H deformation and -CH_2 deformation vibration in lignin and polyxylose [26]. This is due to the nudity of microfibrils on the surface of the cellulose crystalline zone after the synergistic softening and the expression of active substances, so that the chemical constituents inside the teakwood changed to some extent, and its softening bending was improved after it was synergistically softening of solution impregnation and steam.

Table 4. Comparison between impregnated and unimpregnated bending components.

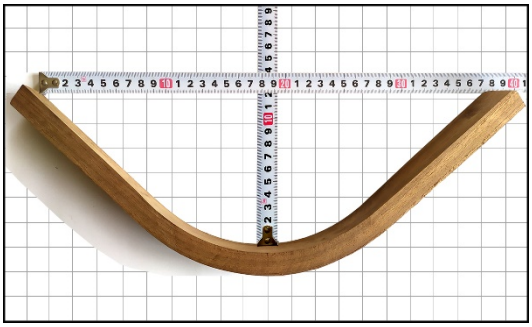
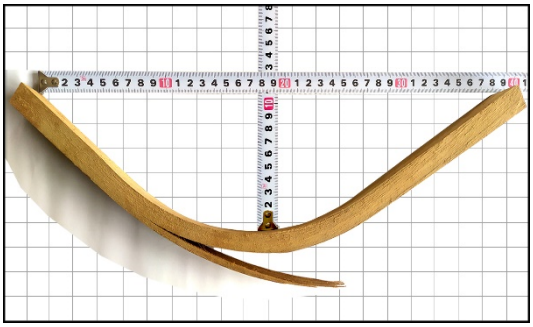
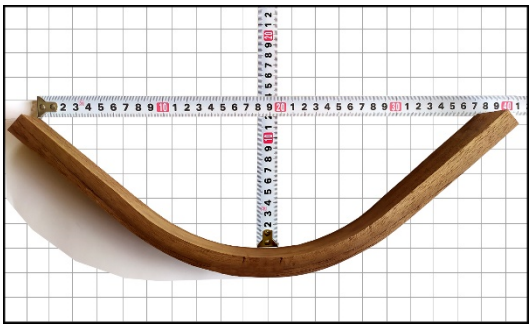
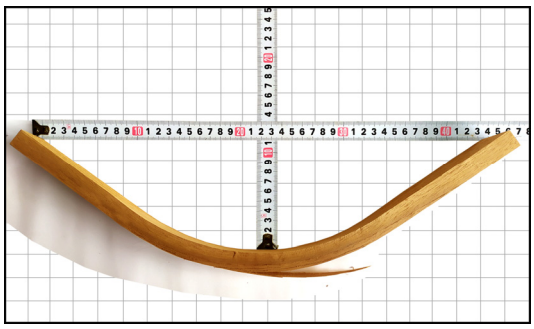
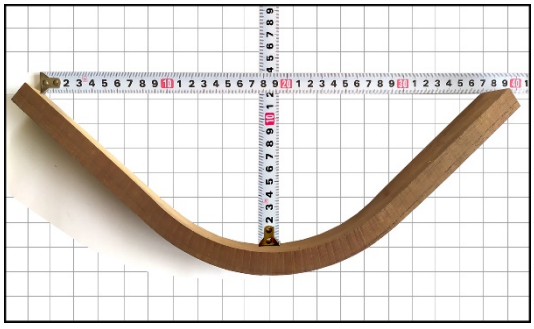
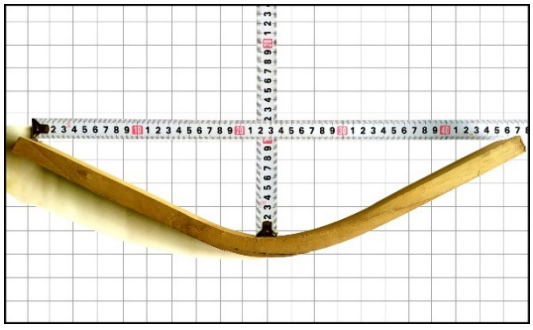
No.	Impregnated Wood	Unimpregnated Wood
Specimen 1		
Specimen 2		
Specimen 3		

Figure 6b shows the ^{13}C NMR spectra of teakwood before and after softening treatment. Compared with the untreated material, the softened showed new characteristic peaks at chemical shifts 58.8 and 55.8 ppm, which corresponded to the main chemical constituents in the softening solution, suggesting that the N element in the softening solution had been successfully introduced into the teakwood after the synergistic softening. The characteristic peaks at 104.7, 83.6, 74.5, 72.1, and 62.3 ppm of chemical shifts were lower than those of the untreated wood, which corresponded to C1 in cellulose, C4 and C6 in the crystalline region of cellulose, and C2, C3, and C5 in cellulose and hemicellulose [27], respectively, which indicated that the holocellulose in the wood was degraded to some extent. In addition, the characteristic peaks near 172.1 and 20.9 ppm almost disappeared, which were mainly attributed to methyl and carboxylic carbons in the hemicellulose acetyl group [28], which was mainly due to the destruction of acetyl and other groups on hemicellulose during

synergistic softening. Meanwhile, the degradation of hemicellulose reduced the number of reactive hydroxyl groups in teakwood and destroyed the hydrophilic groups, which improved the dimensional stability of the bending components.

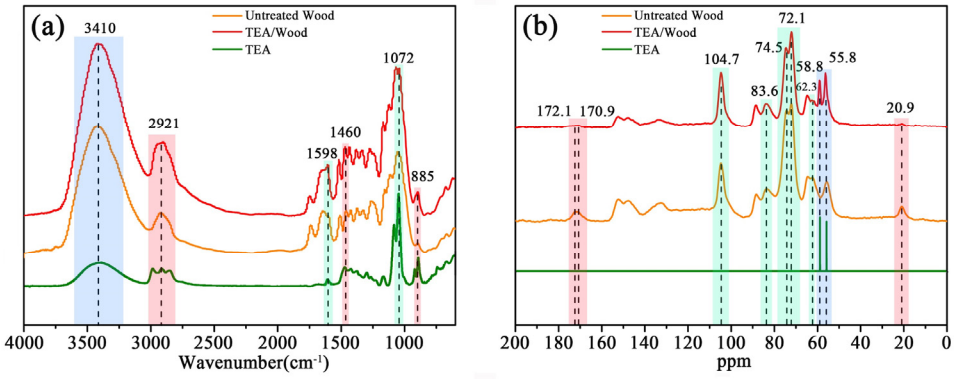


Figure 6. (**a**) FTIR and (**b**) ^{13}C NMR spectra of UW, TEA/Wood, and Triethanolamine (TEA).

The chemical valence of the specimen was analyzed by XPS and the results are shown in Figure 7. Among them, as shown in Figure 7a, are the XPS wide–scan spectra of teakwood before and after softening and the changes of major chemical constituents. The surface of the softened wood is mainly composed of the elements C, O, and N. The content of the chemical elements is changed due to the synergistic softening treatment. Figure 7b,c shows the high-resolution spectra of C1s and O1s of the softened material. From the figure, it can be seen that C1s consists of three fitted peaks at 285, 286, and 288.5 eV attributed to C-C, C-O-C, and C=O [29,30], respectively, and O1s consists of two fitted peaks at 531.5 and 533 eV attributed to C-O and C=O [31], respectively. Figure 7d shows the high-resolution spectrum of N1s with electronic binding energies located at 399.8 and 398.5 eV, attributed to C-NH_2 and C-N [32,33], respectively, which is due to the combination of softening solution and teakwood chemical constituents under synergistic softening conditions, which is also consistent with the previous FTIR analysis. The main component of the softening solution, TEA, is a polar solvent with low molecular weight, which can smoothly enter into the teakwood under vacuum impregnation conditions, and then react with the chemical constituents under saturated steam conditions to improve the plasticity and effect of the softening bending.

By observing the micrograph of the conduit, cell wall, and fiber tissue of teakwood before and after bending through the electron microscope, the microscopic change characteristics can be investigated to explore the relationship between the microstructure of teakwood bending and the macroscopic bending properties. Figure 8 shows the SEM images of the teakwood before and after softening bending. From it, the conduit cross−section of natural teakwood is round or ovoid, and the fiber organization is relatively natural and regular (Figure 8a–c). In contrast, the outer conduit morphology of teakwood was deformed after bending, and the peripheral fibrous tissues underwent some tensile deformation (Figure 8d–f). In the bending process, when the tensile strain on the outer side is less than the allowable strain of the wood itself, bending components with a smaller radius of curvature can be obtained; otherwise, tensile fracture will be produced at the tensile surface, resulting in bending failure [34,35].

Figure 8g–k shows the micrograph of the chordal sections of teakwood before and after softening bending. During the bending (radial bending), the outermost chordal section (convex side) of the teakwood sustains the maximum tensile stress, while the innermost chordal section (concave side) sustains the maximum compressive stress [36]. In Figure 8j,k, the pits on the tensile side conduit show a large tensile deformation to meet the bending deformation of the teakwood.

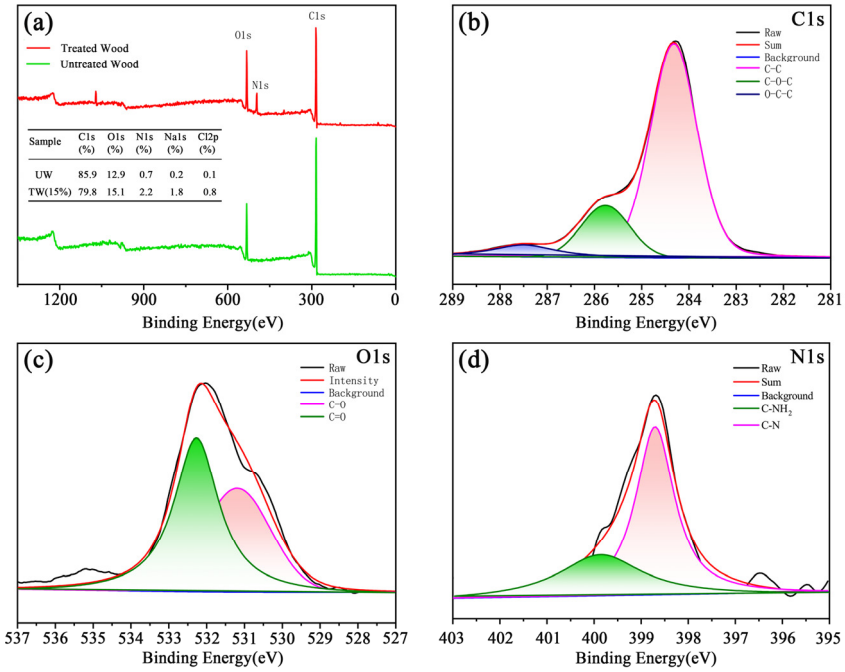


Figure 7. XPS spectra of un-softened and softened wood. (**a**) wide−scan spectra; (**b**) C1s; (**c**) O1s; (**d**) N1s.

3.3. Modeling Constitutive Relationship

Scientific and reasonable characterization of the mechanical behavior of wood is the basis for the analysis of the wood stress process. According to the simplicity of the model, the types of constitutive models can be divided into empirical model characterization based on experiments and theoretical model characterization based on theoretical analysis. Some classical mechanical theories have been applied to the study of the constitutive models of wood, such as the elastic constitutive model [37], the elastoplastic constitutive model [38], and the Boltzmann constitutive model [39]. Based on the theoretical studies, a stress–strain constitutive model which is based on the softened bending conditions of teakwood is proposed by selecting a function that is easy to compute and has a high accuracy rate according to the designed experimental stress–strain curves and determining the stress–strain relationship by the least-squares fitting method.

The wood elastic phase constitutive model is calculated using Equation (4) [37]:

$$\sigma = E_1 \varepsilon. \tag{5}$$

According to the mechanical changes of elastic and plastic deformation of wood under tensile conditions, a bifold model is proposed to be applied to the study of stress–strain at the bottom of teakwood bending specimens, as is shown in Equation (5), in which E_1 represents the elastic modulus in the elastic stage, σ_0 represents the stress when it just enters into plasticity, and E_2 represents the equivalent elastic modulus in the stage of entering into plastic deformation.

$$\sigma = \begin{cases} E_1 \varepsilon \ \varepsilon \le \varepsilon_0 \\ \sigma_0 + E_2(\varepsilon - \varepsilon_0) \ \varepsilon > \varepsilon_0 \end{cases}. \tag{6}$$

According to the proposed teakwood bending constitutive model, substituting the numerical simulation software MATLAB 2020, the stress–strain data are fitted to the constitutive relationship through the FIT function and CFTOOL tool, and the reliability is evaluated by using the correlation coefficient R^2, so the least squares method is used to calculate the correlation coefficient of the fitted function, R^2. Based on the fitted image, it can be seen that by taking the stress to be 0.4, we get the first stage of the constitutive relationship within the elastic stage, see Equation (6), where y represents the value of stress

and x represents the value of stress, and the correlation coefficient R^2 of this stage is 97.21%. The constitutive relationship of the second stage within the range of plastic stage is shown in Equation (7), and the correlation coefficient R^2 of this stage is 95.29%, as shown in Table 5 and Figure 9.

$$Y = 32650x, \quad (7)$$

$$Y = 3749x + 9.775, \quad (8)$$

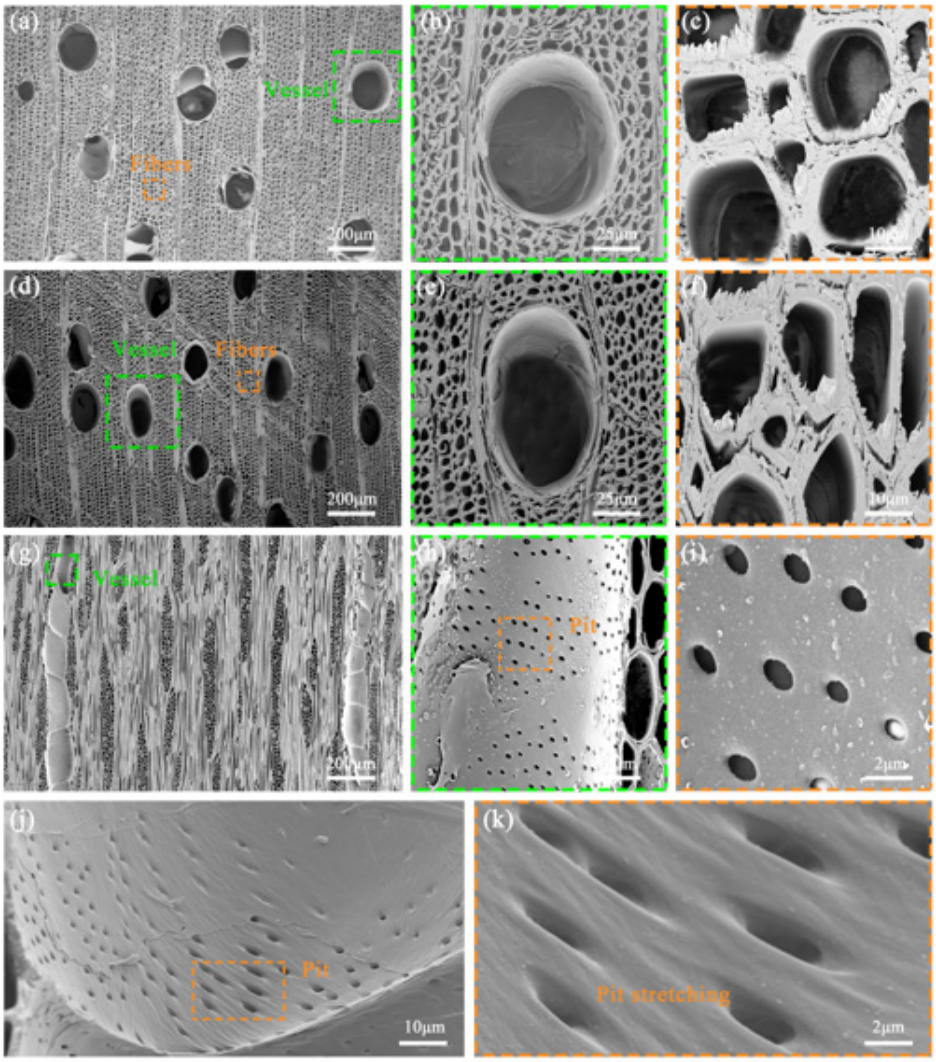


Figure 8. Microscopic images of teakwood before and after bending: (**a**–**c**) cross-section images before bending; (**d**–**f**) cross-section images after bending; (**g**–**i**) chordal section images before bending; (**j**,**k**) chordal section images of the stretched side after bending.

Table 5. Constitutive model and correlation coefficient.

Model	Deformation Stage	Constitutive Relationship	Stage Correlation Coefficient (R^2)	Integrated Correlation Coefficient (R^2)
Bi-fold model	Elasticity stage Plasticity stage	$E_1\varepsilon$ $\sigma_y + E_2(\varepsilon - \varepsilon_y)$	97.21% 95.29%	96.25%

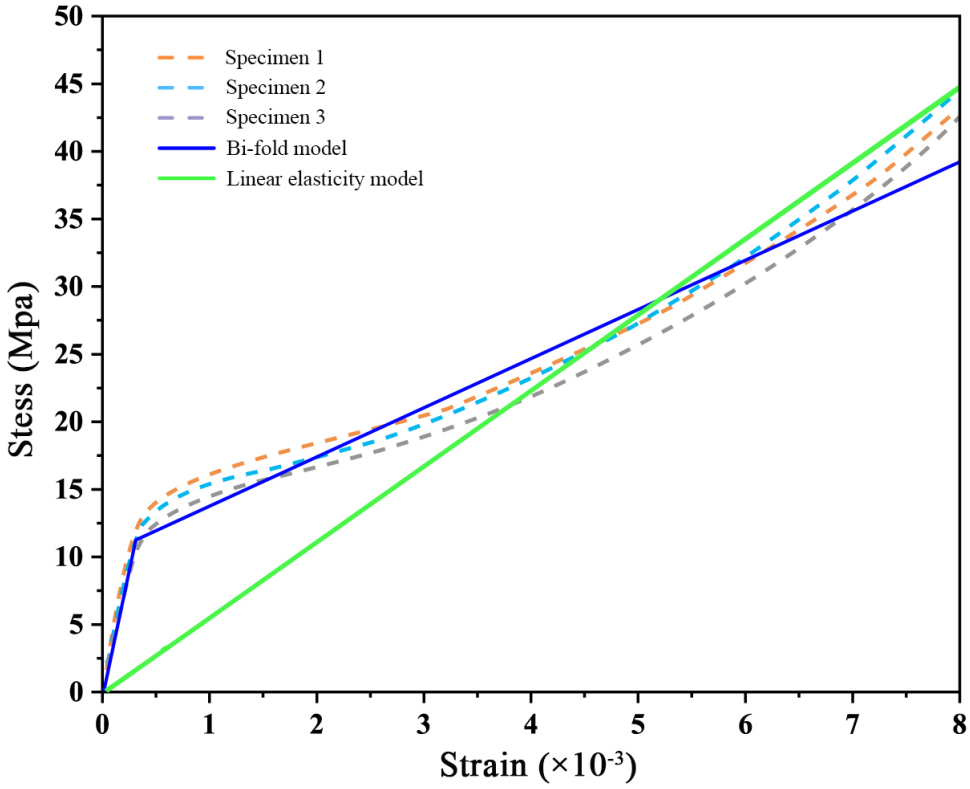


Figure 9. Comparison of the constitutive relationship model with the expertiment.

From Figure 9, teakwood bending specimens 1, 2, and 3 are all in the elastic stage at the beginning of loading, and the stress–strain is in a straight line relationship, at this time the bending elastic modulus is larger, but it enters into the plastic stage after loading to a certain extent (around 0.0004 for this group of specimens). The comparison between theoretical analysis and experiment shows that the integrated correlation coefficient of the bifold principal structure model of wood bending can reach 96.25%, which proves that the model can better simulate the constitutive relationship of teakwood in softening bending.

4. Conclusions

In summary, this study showed that the teakwood softening process can obtain the best bending properties after Response Surface Optimization. When saturated steam was used to synergistically treat the impregnated material with a triethanolamine compounding solution, the functional groups in the softening solution chemically bonded with the chemical constituents in teakwood, forming C-NH_2 and C-N bonds, and the reactive substances were expressed, which improved the softening properties of teakwood. Compared with the traditional hydrothermal softening method, the specimens prepared by vacuum impregnation with triethanolamine compound had excellent bending properties. What's more, based on the mechanical changes of the softening and bending process of teakwood, a bifold constitutive model with a high degree of fitting was constructed, which proved the applicability of the model. Therefore, the preparation of teakwood bending components by using a triethanolamine compounding solution provides an economical and environmentally friendly method for the softening and modification of hardwood materials and has a good application prospect in the field of bending wood product processing.

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Conflicts of Interest: The authors declare no conflict of interest.

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