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Statistical model of strength in compression of *Raphia vinifera* L. (Arecacea)

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Abstract—This paper investigates a statistical model of the resistance of *Raphia vinifera* L. (Arecacea) under compression parallel to the grain. The probability expression governing the failure of the material is established. The parameters entering the statistical law are determined experimentally. Finally, the quality of the adjustment is tested by a goodness-of-fit test.

Key words: *Raphia vinifera* L. (Arecacea); probability of failure; compression; Weibull distribution.

INTRODUCTION

Bamboo is gaining importance in the industrial world because of the possibility of its usage as raw material for paper design and built up layers. There is a variety of species in Bamboo, among which in West Africa is *Raphia vinifera* L. (Arecacea). It is widely used in the West and North-West Cameroon as building material, for furniture and decoration. However, to the best of our knowledge, there is a little information concerning its physical and mechanical properties. Consequently, the material is not well used and large quantities are wasted, leading to the degradation of biodiversity. Thus, the aim of this study was to investigate the failure of this material using statistical techniques.

THEORETICAL BACKGROUND

A number of statistical models have been developed to predict the resistance of woody material [1–3]. Figure 1 shows the stress-strain curve in compression test

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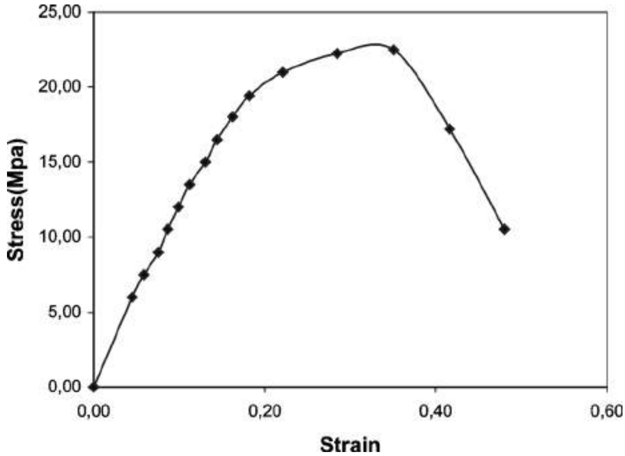

Figure 1. *Raphia vinifera* stress-strain curve.

of *Raphia vinifera* L. (Arecacea). This curve is that of a plastic material having a failure of the ductile type.

The plastic model is a set of elements having each P_i as failure probability [4]. Then, the probability of non-failure of the element is $1 - P_i$ and that of the bulk is

$$1 - P = \prod_{i=1}^{n} (1 - p_i). \tag{1}$$

The distribution function of an element is of the form [4]:

$$p_i = f(\Psi)\,\mathrm{d}V.$$

The function $f(\Psi)$ has the form as in Refs [1, 2, 5, 6]:

$$f(\Psi) = \left[\frac{\sigma - \gamma}{\alpha}\right]^{\beta}.$$

Thus,

$$P = 1 - \exp\left[-V\left(\frac{\sigma - \gamma}{\alpha}\right)^{\beta}\right].$$

Let $k = 1/\alpha^{\beta}$, then we conveniently obtain the expression

$$P = 1 - \exp\left[-kV(\sigma - \gamma)^{\beta}\right]. \tag{2}$$

Equation (2) is a three-parameter Weibull distribution with the mean given by

$$E(\sigma) = \gamma + \Gamma\left(1 + \frac{1}{\beta}\right)(kV)^{-1/\beta}. \tag{3}$$

Here Γ is the Euler function and γ the position parameter. For a given material, γ is the least value of the ultimate strength $\sigma_{\min}$. The variance of the said distribution is given by

$$Var(\sigma) = \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \left\{\Gamma\left(1 + \frac{1}{\beta}\right)^2\right\}\right](kV)^{-2/\beta}. \tag{4}$$

The sample's coefficient of variation is

$$CV = \frac{[Var(\sigma)]^{1/2}}{E(\sigma)} = \frac{\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \left\{\Gamma\left(1 + \frac{1}{\beta}\right)\right\}^2\right]^{1/2}(kV)^{-1/\beta}}{\gamma + \Gamma\left(1 + \frac{1}{\beta}\right)(kV)^{-1/\beta}},$$

where α, β and γ are coefficients of the material under study and are determined experimentally. The difficulty at this point is the determination of the position parameter γ. We use the method proposed by Mukam *et al.* [4], which consists of taking $\gamma = 0$ in the first approximation. Thus,

$$CV = \frac{\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \left\{\Gamma\left(1 + \frac{1}{\beta}\right)\right\}^2\right]^{1/2}}{\Gamma\left(1 + \frac{1}{\beta}\right)}. \tag{5}$$

As such, the knowledge of the CV is sufficient for the determination of β.

In reality, the position parameter has a minimum value [1] that can be determined experimentally with the help of the strength-oven dry density curve.

The value of k is given by

$$k = \frac{1}{V}\left[\frac{\Gamma\left(1 + \frac{1}{\beta}\right)}{\mu}\right]^{\beta},$$

where μ is the mean of the distribution and V the volume of the test piece. To test the quality of the adjustment, we use the chi-square test [7]

$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e_i}.$$

Here, n_i is the observed frequencies, and e_i the theoretical frequencies. The number of degrees of freedom of such a distribution is

$$\nu = m - l,$$

where m is the number of cells of the distribution and l the number of quantities obtained from the observed data that are used in the calculations of the expected frequencies.

EXPERIMENTAL SET-UP

Raphia culms were harvested in swampy areas in the neighbourhood of Dschang, West Cameroon. The determination of the species has been taken care of by the National Herbarium of Cameroon. After 35 days of air-drying, 111 defect-free test-pieces were selected randomly on the basis of two cross-sectional areas being almost equal and around 12 cm^2; the length of the pieces is 10 cm. The diameters of the test pieces range from 3.74 ± 0.01 cm to 3.82 ± 0.01 cm. The experiment consisted of a parallel to the grain compression test. During the test, the main target was ultimate strength. The tests were conducted using a universal press. This press has displacement gauge and a force gauge. Once the ultimate strength is reached, a red signal indicates its value. Prior to this test, the samples were weighed and after the test they were placed in an oven at 103°C. This drying process lasted until the mass of all the test-pieces were constant. Then the dry mass was measured at the nearest 0.01 g. The experiment was conducted in 'Genie rural' laboratory of the University of Dschang. Table 1 presents the main results obtained using a two-parameter Weibull distribution and Table 2 presents the case of a three-parameter Weibull distribution.

Table 1.
Weibull distribution with two parameters

Mean of the distribution μ (MPa)	30.47
Standard deviation (MPa)	3.71
Coefficient of variation (CV, %)	12.2
α parameter	9.76
β parameter	32.05
Moisture content H (%)	17.34 ± 0.01
Number of test-pieces	111
Average volume of the test-pieces (cm^3)	112.00 ± 0.02

Table 2.
Weibull distribution with three parameters

Position parameter γ (MPa)	25.10
Mean of the distribution μ (MPa)	6.70
Standard deviation (MPa)	3.67
Coefficient of variation (CV, %)	54.8
α parameter	1.99
β parameter	7.47
Moisture content H (%)	17.34 ± 0.01
Number of test-pieces	87
Average volume of the test-pieces (cm^3)	112 ± 0.02
Abnormal failure	24
Percentage of abnormal failure	22

A simple regression analysis was performed to describe the relationship between the strength and the oven-dry density, from which we determined the position parameter γ as shown in Fig. 2. The values of the ultimate strength less than γ are eliminated, for they correspond either to an internal defect or an error during measurements.

Figure 3 presents the histogram obtained from the test.

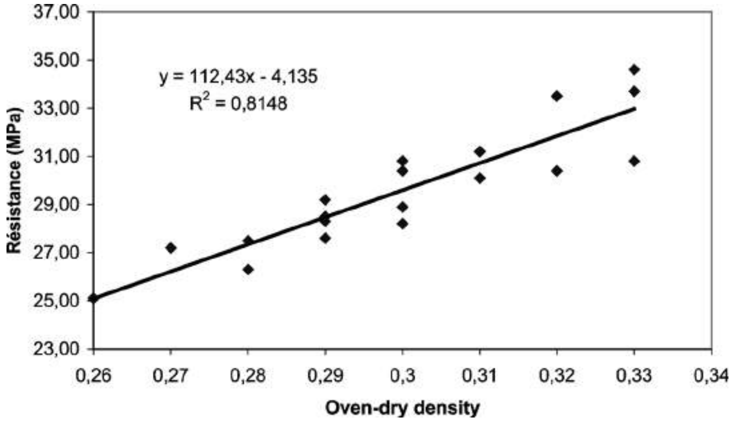

Figure 2. Resistance as a function of oven-dry density.

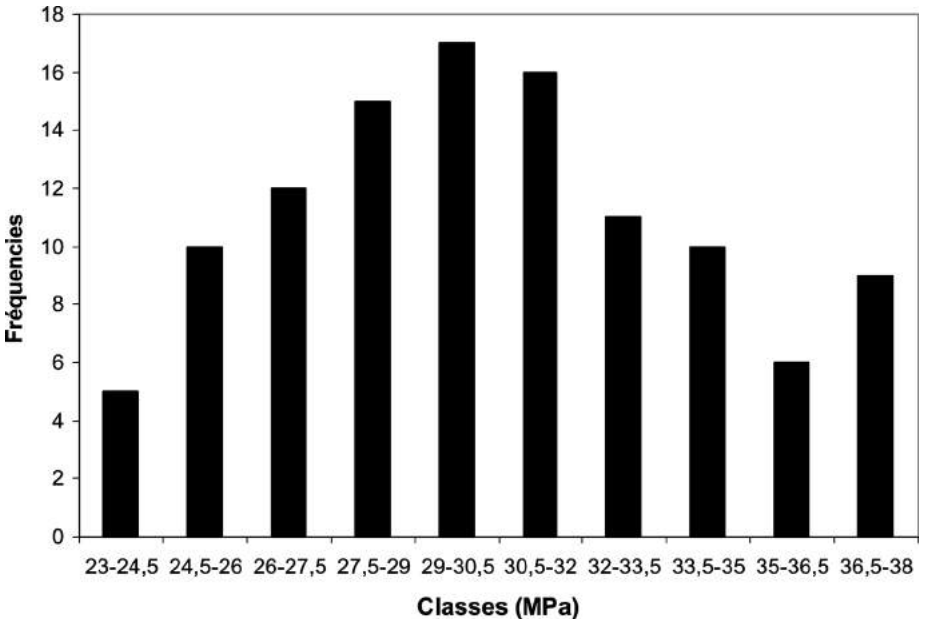

Figure 3. Frequencies distribution of the resistance of *Raphia vinifera*.

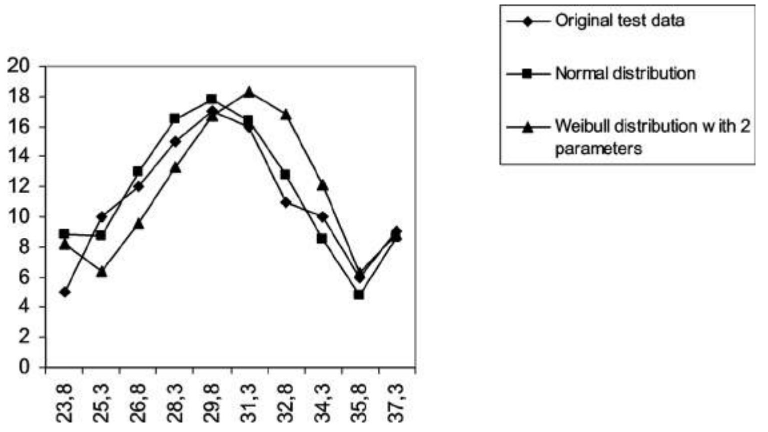

Figure 4. Comparison of the three distributions.

After the value of γ was determined, all the values of the resistance less than the value of γ were rejected, for they correspond either to an internal defect or an error during measurements. We then obtained the data in Table 2.

The results from Chi-square calculations suggested that a normal distribution ($\chi^2 = 2.91$) fitted better the observed frequencies than a two-parameter Weibull distribution ($\chi^2 = 7.75$). Meanwhile, the three parameter Weibull distribution ($\chi^2 = 2.14$) is more preferable than the normal distribution (see also Fig. 4).

CONCLUSIONS

This study has permitted us to model the failure of *Raphia vinifera* L. (Arecacea) in compression parallel to the grain. The calculated statistical coefficients allow us to determine the probability of failure of the test-pieces based on oven dry density. The three parameter Weibull distribution is more adopted for the designing of the failure of *Raphia vinifera* L. (Arecacea) than the normal distribution and the two-parameter Weibull distribution, respectively. Our future work will be based on the statistical model of strength in flexion and traction of *Raphia vinifera* L. (Arecacea).

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