Statistical approach to tensile strength of abaca single fiber

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Abstract
Related to the importance of selectivity to natural fibers that can be used and qualify as one of the raw material composite engineering substitute for Fiber Reinforced Plastics (FRP) or Fiber Reinforced Metals (FRM), one plants that have the potential of fiber and volume growth is very abundant, namely abaca. This research aims to clarify scattering in tensile strength of an abaca single fiber through statistical approach and to search a way of suppression in the scatter with intention that abaca fibers can be used as a raw material for engineering structural components. Tensile test specimens were prepared from fiber samples from two different areas, East Aceh and North Aceh, Indonesia. Specimen gauge length is 25 mm, then as the holder of a fiber made of paper (20mm x 100mm), where the specimen size for fiber tensile test in accordance with JIS standard K-760. Diameter the specimen fibers obtained varied from 0.060 mm to 0.140 mm. The tensile strength of abaca fiber varies in the wide range from 100 MPa to 900 MPa. Coefficient of variation was calculated for East Aceh abaca fibre 0.32 and North Aceh abaca fibre 0.35. It was examined whether Weibull distribution or log-normal distribution could well express scatted experimental results. The results showed that both the distribution types could well express the experimental probability density, but log-normal distribution could be more rational for expression of biological and chronological effects. To reduce scattering of tensile strength, pre-screening concept was proposed.

Keywords : Statistical approach, Tensile strength, Abaca fiber, Weibull, Log-normal

1. Introduction

Climate change and global warming have triggered extensive researches on ecological or environmentally friendly materials. Automotive industry tries to use advanced high strength steel to reduce plate thickness of vehicle structures that eventually aims to lighten vehicle weight resulting in enhancement of fuel economy. From viewpoint of ecology and environmental friendliness, total CO₂ emission is evaluated in a period of life span from mining of raw materials to depositing process after usage. It is defined as life cycle assessment of CO₂ emission, namely LCA of CO₂ emission. LCA of CO₂ emission of metallic and plastic materials is rather high, for instance, it is around 2.3 t CO₂ emission/t steel (Fujita et al., 2010) and 2.0 to 9.0 t CO₂/t plastic (Groot, and Boren, 2010). In addition, that of carbon fiber used for carbon fiber reinforced plastics (CFRP) is around 20.0 t CO₂/t carbon fiber (JCFMA, 2014). Density of CFRP is much smaller than metallic materials, and consequently, vehicles and aircrafts fabricated with CFRP are significantly lighter than metallic vehicles and aircrafts resulting in lower emission of CO₂ in their life cycle than those manufactured by metallic materials (JCFMA, 2014).

Therefore, composite materials reinforced by strong and advanced fibers, such as carbon, glass, kevlar fibers and so on, receive great attention as environmentally friendly materials. However, as described above, LCA of CO₂ emission of the advanced fibers is not necessarily low. Hence, more ecological reinforcement fibers are recently sought. One potential candidate is cellulotic natural fibers. Cellulosic natural fibers are extracted from leaves, trunks,
basts, and seeds of plants. Absorption of CO$_2$ by photosynthetic reaction during their growing process can be considered to be counterbalanced with CO$_2$ emission during depositing process of burning and chemical decomposition. Thus, LCA of CO$_2$ emission for cellulosic natural fibers is much lower than one of synthetic fibers like carbon fibers, glass fibers, and kevlar fibers. For instance, LCA of CO$_2$ emission for flax fibers is 1.07 t CO$_2$/t fiber (Deng, 2014), which is around 5 % of one for carbon fiber. There are several cellulosic natural fibers that have been used for clothes, bank bills, papers, marine cordages, handicrafts such as a bag, a floor mat, a tray, and others. Recently, application of natural cellulosic fibers to engineering structural components was initiated merely in automotive industry (Akova, 2013).

When natural cellulosic fibers are used for engineering structural components, one of critical issues is wide scattering in fiber strength. An index of scattering in tensile strength is a ratio of standard deviation $\sigma$ to mean value $\mu$ called coefficient of variation. The coefficient of variation of natural fiber strength is larger than 0.28 for curaua, jute, coir, piassava, and sisal (Fidelis et. al., 2013), while for man-made materials like steel, E glass and aramid in yellow rows, the coefficient of variation is less than 0.14. The man-made materials have been used for engineering structural components over a long period of industrial history and safe design concepts based on fail-safe, and damage tolerance have been effectively applied to dimensional decision of engineering components manufactured by those materials.

On the other hand, cellulosic natural fibers (hereafter natural fibers) extracted from plants are still new to engineers. Statistical data on these materials are not sufficient enough to safely design structural components using these materials. Recently several researchers carried out experiments on natural fiber strength. Many of them used Weibull distribution theory for statistical approach to widely scattered tensile strength of natural fibers (Joffe et.al., 2009) and (Liu et.al.,2013). Torres et. al. (2017), recently provided statistical data for natural fiber composites using more than 500 samples. Tensile properties, Young’s modulus, ultimate strength, and fracture strain, of jute, flax and carbon fiber reinforced composite plates are reported in their statistical data. Statistical analysis was conducted using two-parameter Weibull distribution. On the other hand, L. Peponi et al. (2008) pointed out that Weibull distribution could not always reasonably describe widely scattered tensile strength of natural fibers, and they utilized a neural network algorithm to estimate probability density functions so as to fit several experimental results.

It should be noted that tensile strength data of flax uniaxially reinforced composite indicates surprisingly small coefficient of variation, 0.045 (Torres et. al., 2017) while flax fiber tensile strength is scattered so widely that the coefficient of variation is more than 0.28. Natural fibers may be used for engineering structural materials as reinforcement of plastic matrix composites. Abaca fibers can be potentially used for uniaxially reinforced composite materials because of availability of long fibers and high strength. However, statistical approach to abaca fiber tensile strength has been carried out in very limited number (Liu et.al., 2013), (Richter et. al., 2013) and (Agung et.al., 2011).

This research aims to clarify scattering in tensile strength of an abaca single fiber through statistical approach and to search a way of suppression of the scatter with intention that abaca fibers can be used as a raw material for engineering structural components.

2. Experiment

2.1 Specimen preparation

In this study, 120 cm long abaca fibers were supplied from the district of East Aceh and North Aceh, Aceh Province, Indonesia. 80.0 mm long sample fiber is cut from top part of the received abaca fiber. Specimen gage length is 25.0 mm, and 35.0 mm both ends are mounted between two paper sheets with glue as shown in Fig.1.

![Fig. 1 Tensile test specimen of abaca single fiber](image-url)
Diameter of an abaca fiber specimen was measured at three positions, middle and two ends of the specimen gage length using a digital microscope. At each position, the diameter was measured twice in diagonal directions. Fiber cross section is not perfect circle. Aspect ratio of diagonal direction diameters varies from 0.88 to 1.20 and the average aspect ratio is 1.01. The fiber has a conducting vessel in the center of cross section. Therefore cross section area of a fiber should be exactly calculated based on precise configuration of the fiber cross section. However, in this paper, mean value of six measured diameters was defined as the specimen diameter to expediently calculate mean cross section area of the fiber. For statistical analysis of abaca fiber tensile strength, 70 single fiber specimens were prepared from top section of abaca leaf sheath cultivated in two regions, East Aceh and North Aceh Indonesia. F. Gunawan et al. (2009) showed that tensile strength of oil palm fiber was strongly dependent on the fiber diameter. Therefore, in this research, the diameter range was fixed in a narrow band of 0.06 mm to 0.14 and a histogram of specimen diameter was adjusted so as to be the same for two regions samples. Histograms of diameter and tensile strength in two regions were constructed using Sturge’s rule.

2.2 Tensile test

The test was conducted using a tensile test apparatus for a single abaca fiber newly built in the laboratory. One end of a specimen was fixed at the end of a cantilever load cell by a light nylon line, and the other end was pulled by a nylon line connected to a low velocity gear box when the gear box was run by a motor. A displacement rate was around 0.4 mm/sec, but an actual loading rate to a specimen was slowed to 0.014 N/sec by bending of the cantilever load cell. Output from the strain gages mounted on the cantilever was stored as a function of time in a computer through a data logger, National Instruments, NI USB-609. Tensile strength was calculated as the maximum load divided by the mean fiber cross section area.

3. Result and discussion
3.1 Diameter of fibers

Diameter histogram of two regions is shown in Fig. 2. The range of the diameters is divided into 7 intervals, the frequency is 14 at maximum and 7 at minimum. It can be considered that the frequency at each interval is fluctuated, but roughly uniform. Then, the sample number falling in each interval is shown in histograms. A diameter histogram was constructed by randomly selected fiber specimens from North Aceh samples.

![Fig. 2 Histogram of fiber diameter of two regions. Diameter the specimen fibers obtained varied from 0.060 mm to 0.140 mm, the frequency is 14 at maximum and 7 at minimum. It can be considered that the frequency at each interval is fluctuated, but roughly uniform.](image)

Then, diameters of specimens from East Aceh were selected so as to be the same histogram as one from North Aceh. As seen in Fig. 2, although frequencies of two bins are slightly higher than those of other bins, all the data fall near the mean frequency 10. It should be noted that fiber diameter almost uniformly distributes over the range.
3.2 Tensile strength of fibers and statistical data analysis

Tensile strength of abaca single fiber is plotted as a function of fiber diameter. In Fig. 3 as seen the tensile strength of East Aceh fiber apparently decreases as the fiber diameter increases and the scatter is narrow is clearly indicated in Figure 4. While tensile strength of North Aceh fiber is scattered widely and seems to decrease as the fiber diameter increases. Scattering in data is significantly wide and weak dependence on diameter is indicated in Figure 4. It should be noted that when the tensile strength increases as the fiber diameter decreases and reaches around 900 MPa. This is corresponding to steel strength and shows potential for engineering structural material. However, the lowest strength is around 100 MPa, and the wide scatter is fatal disadvantage for safety design of engineering structure using these natural fibers. This dependence on diameter is the same as the results obtained by other researchers (Gunawan et.al., 2009) and (Nonteiro et.al., 2012). To conduct statistical approach to tensile strength of abaca fibers in two regions, tensile strength data shown in Fig. 3 were used to draw histograms of tensile strength for two regions. The same method used for the diameter histogram was also used. Experimental data of probability density was calculated by dividing a frequency of each histogram bin by the total sample number 70 and the histogram bin width for a middle point of each bin width of the histogram.

![Diameter dependence of tensile strength is clearly for Abaca fiber East Aceh.](image)

![Scattering in data is significantly wide and weak clearly of dependence on diameter of Abaca fiber North Aceh.](image)

Fig. 3 Tensile strength of fiber from two regions as a function fiber diameter. It should be noted that when the tensile strength increases as the fiber diameter decreases and reaches around 900 MPa. This is corresponding to steel strength and shows potential for engineering structural material. However, the lowest strength is around 100 MPa, and the wide scatter is fatal disadvantage for safety design of engineering structure using these natural fibers.

In Figure 4, the experimental data of probability density is compared with a probability density function of two-parameter Weibull distribution. Shape parameter $m$ and scale parameter $\beta$ were determined by the median rank and the mean rank method. Weibull parameters obtained by two rank methods were slightly different, but probability densities of Weibull distribution were almost identically calculated as a function of tensile strength. In the figure, the probability density is shown for the shape and size parameters obtained by the median rank method. In the figure, probability density is also for log-normal distribution.

Mean value and standard deviation of a parent population must be known to calculate the probability density of log-normal distribution. For the first approximation, a mean value and a standard deviation obtained from 70 sample data of tensile strength were used to calculate the probability density. The calculated probability density function did not well fit the experimental data. Then, the mean value and the standard deviation were determined by a graphical method so as to minimize error between the experimental data and probability density function calculated using the two parameters. For Weibull distribution, adjustment of shape and scale parameters is possible to fit the probability density with experimental data. This means that the sample mean and standard deviation are not good representative for those of parent population. As seen in the figure, Weibull distribution and log-normal distribution seem to fit the experimental data, reasonably.
Basically, Weibull distribution theory is based on the weakest link theory. Therefore, Weibull distribution can be rationally applied to statistical fracture behavior of man-made materials of which fracture is dominated by pre-existing flaws. On the other hand, plant fibers have received chronological effects through their growing period. Accumulation of chronological effects in biology can be well represented by log-normal distribution (Gronholm and Annila, 2007). Because abaca fibers have grown receiving biological and chronological effects, it can be considered that log-normal distribution can rationally deal with statistical behavior of abaca fiber tensile strength as shown in Figure 4. Therefore, in this study, log-normal distribution is preferably used hereafter.

![Weibull and log-normal distribution approach to tensile strength of abaca fibers.](image)

(a) Comparison between Weibull distribution and log-normal Abaca fiber for East Aceh. (b) Comparison between Weibull distribution and log-normal Abaca fiber for North Aceh.

Fig. 4 Weibull distribution and log-normal distribution approach to tensile strength of abaca fibers. As seen in the figures, both the distributions, Weibull and log-normal can represent the experimental data fairly well. In case of fitting log-normal distribution with the experimental data, two lines are drawn in the figures. Red lines represent the probability density function obtained from the sample mean and variance.

<table>
<thead>
<tr>
<th>Regions</th>
<th>Weibull distribution</th>
<th>Log-normal distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shape</td>
<td>size</td>
</tr>
<tr>
<td>East Aceh</td>
<td>3.85</td>
<td>524.30</td>
</tr>
<tr>
<td>North Aceh</td>
<td>2.90</td>
<td>629.20</td>
</tr>
</tbody>
</table>

In Table 1, the parameters used to calculate probability density of two distributions are shown. From two parameters of log-normal distribution, probability density function $f(x)$, expected value $E(x)$ and standard deviation $\sqrt{V(x)}$ are given as the following equations:

$$
 f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right]
$$

(1)

$$
 E(x) = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right] x dx = \exp(\mu + \frac{\sigma^2}{2})
$$

(2)

$$
 \sqrt{V(x)} = \left[\int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right] (x - \mu)^2 dx\right]^{\frac{1}{2}}
$$

$$
 = \sqrt{(e\sigma^2 - 1)} \exp(2\mu + \sigma^2)
$$

(3)
From Equation (2), the expected value of tensile strength is 451.3 MPa, and 635.5 MPa for East Aceh and North Aceh fibers, respectively. From Equation (3), the standard deviation is 177.9 MPa, and 215.6 MPa for East Aceh and North Aceh fibers, respectively. Comparison between limited fiber samples supplied from two regions indicates that fibers from North Aceh are much stronger than fibers from East Aceh. It should be, however noted that the above comparison cannot be applied for the general difference between fiber strength of two regions.

3.3 A concept on pre-screening of fibers

Coefficient of variation is 0.39 and 0.34 for East Aceh and North Aceh, respectively, and these values are too high to use abaca fibers for engineering structural materials. In this work, one idea is proposed to reduce the coefficient of variation and to use abaca fibers for engineering structural materials. According to Philippines National Standard (2016), abaca fibers are subjected to sampling test to select the normal grade of fibers of which tensile strength ranges 19.5 kgf/g/m and 32.6 kgf/g/m, which are 286.7 MPa and 479.2 MPa when the fiber density is 1.5 kg/cm$^3$. The similar concept can be applied for selection of fiber of which strength is greater than a certain level. A bundle of abaca fibers with a certain length $L$ is prepared for a coupon. Both ends of the bundle are firmly fixed to fixtures with glue. Diameter of each fiber in the bundle is measured and the cross section area $A$ of the bundle is calculated as total cross section area of the fibers. A load of pre-screening test is determined by survival stress multiplied by the cross section area $A$ and is applied to the bundle of abaca fibers by displace-control to avoid unstable fracture. After unloading, the survival fibers can be detected by visual inspection. Thus, survival fibers can be provided for the next test in a laboratory scale.

When the pre-screening method described above is ideally applied to 70 fibers of North Aceh and the maximum stress level is set as 566.0 MPa, 35 abaca fibers of which tensile strength is stronger than 566.0 MPa can survive from this pre-screening. However, ideal pre-screening test is very difficult to conduct. Maybe, there is some possibility for fibers weaker than 566.0 MPa to survive and there is some possibility for fibers stronger than 566.0 MPa to break under a pre-screening test. The survival fibers in each bin of the histogram were estimated by weighted inverse Rayleigh distribution (Fatima and Ahmad, 2017). The frequency in each histogram bin of tensile strength after the pre-screening test may be calculated as follow:

$$ b(x_i) = b_0(i)q(x_i) $$

$$ q(x_i) = q(x_i) \quad x_i < x_{\text{trun}} $$

$$ q(x_i) = 1 \quad x_i \geq x_{\text{trun}} $$

$$ q(x_i) = e^{t} \times exp \left( -\left( \frac{x_{\text{trun}} - x_{\text{min}}}{x_i - x_{\text{min}}} \right)^2 \right) $$

where $x_i$ is a low boundary of a histogram bin, $x_{\text{trun}}$ is the minimum tensile strength of which fibers were not affected by the pre-screening test, $x_{\text{min}}$ is the minimum tensile strength of all the fiber samples.

![Fig. 5](image-url) Probability density function vs with experimental data of pre-screened 35 North Aceh Abaca Fibre $\mu=6.46 \sigma=0.22$. 

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The above survival function was used to calculate experimental probability density function. When $x_{\text{trun}}$ is 670.9 MPa, and $x_{\text{min}}$ is 102.4 MPa, experimental probability function was calculated. Histogram bin width was not changed although the sample number decreased from 70 to 47. Probability density data is shown to be compared with log-normal probability density function fitting the experimental data in Figure 5. When this result is compared with the result shown in Figure 4(b), it is seen that the probability density function of tensile strength of pre-screened fiber is almost zero in the range of less than 300 MPa, while that of tensile strength of fiber without pre-screening decreases to zero in the range of less than 200 MPa.

Cumulative probability of tensile strength is shown for the pre-screened and no pre-screened fibers in Figure 6. In the figure, cumulative probability of truncated log-normal distribution is also shown. This is corresponding to the data after the ideal pre-screening test. The truncated log-normal distribution was calculated by use of the equation proposed by L. Zaninetti (2017).

In the future, the pre-screening by elongation must be verified experimentally. If weak fibers are abandoned by this pre-screening method, for instance, the screening criterion is set 566.0 MPa for abaca fiber in North Aceh, 35 abaca fibers of which tensile strength is stronger than 566.0 MPa survive from this pre-screening. For the survived abaca fibers, log-normal distribution is fitted with the experimental data to obtain the mean value and the variance. Those are Mean value: 6.55 and standard deviation: 0.127. Then, expected value and standard deviation of tensile strength for the survived abaca fibers are calculated as $E(x) = 704.7$ MPa and $\sqrt{V(x)} = 89.9$ MPa

Then, coefficient of variation is significantly reduced to 0.13 and approaches that of metallic materials. In addition, when we design a mechanical component using abaca fibers of which tensile strength is 566.0 MPa, and safety factor is defined as 1.5, the fracture probability of this component is less than $10^{-6}$ when applied stress is kept constant, 566.0 MPa. This situation is shown in Figure 6. In the figure, cumulative probability is plotted as a function of stress.

Fig. 6 Cumulative probability of tensile strength of pre-screened fibers and no-screened fibers. when we design a mechanical component using abaca fibers of which tensile strength is 566.0 MPa, and safety factor is defined as 1.5, the fracture probability of this component is less than $10^{-6}$ when applied stress is kept constant, 566.0 MPa.

When we conduct strength design of a component fabricated by abaca fibers based on a statistical method, and the fiber strength is specified as 566.0 MPa that is the pre-screening criteria, the allowable stress applied to the component can be determined based on failure probability, for instance, $10^{-4}$, or $10^{-6}$. From the figure 6, the allowable stress of pre-screened fibers is 240.0 MPa for failure probability of $10^{-6}$, while the allowable stress of no-screened fibers is 130 MPa for the same failure probability. Safety factor of each component is 2.3 and 3.8 for pre-screened fibers and no-screened fibers, respectively. Consequently, if the pre-screening test is properly carried out, abaca fiber can be used for engineering structural material. Coefficient of variation of the pre-screened fibers is 0.21, which is tremendously improved and approaches that of metallic materials. If a pre-screening test approaches the ideal one, the allowable stress can be increased.
4. Conclusion

This research conducted statistical approach to tensile strength of abaca fibers cultivated in two regions, East Aceh and North Aceh Indonesia. In order to eliminate a diameter effect from a statistical analysis of abaca fiber tensile strength of two regions, fiber samples were collected so that diameter histograms of fibers from two regions were the same. Two distribution types, Weibull distribution and log-normal distribution were selected to analyze tensile strength data of abaca single fibers. The conclusions obtained from this research are summarized as follows:

1. Log-normal and Weibull distributions could successfully represent probability density data of tensile strength measured by 70 fiber samples of each region. However, it was deduced that log-normal distribution could more rationally represent statistical results of abaca fibers than Weibull distribution from theoretical aspects of these distributions.

2. From log-normal distributions fitted with tensile strength results of East Aceh and North Aceh fibers, it was indicated that expected value of the tensile strength was much higher for North Aceh than that for East Aceh. The difference between two expected values was significant in t-test.

3. A pre-screening method was proposed here. The pre-screening test was statistically discussed and it was shown that this method could provide abaca fibers that could be used for engineering structural material. However, this method must be examined from a practical aspect.

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