

LONTAR BORASSUS FLABELLIFER FIBER COMPOSITE: ENERGY DISSIPATION AND THERMAL RESPONSE UNDER DYNAMIC TENSILE TESTING

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Abstract

The energy dissipation mechanism understanding of Lontar fiber composites was essential to overcome the limitations of its composite. This study aims to determine the energy dissipation of Lontar (Borassus Flabellifer) fiber composite under tensile (dynamic) testing and validate it by the thermal response. The tensile test was carried out in two phases, under static load to determine the value of Ultimate Tensile Strength (UTS), and under dynamic loads to obtain hysteresis curve of each loading-unloading loop, while a thermocouple was used to record temperature evolution on specimen surface around the hole area. This study showed that the highest energy dissipation at the 80% loading level by mean of 0.215309063 J/cm³, while the lowest dissipation energy is at the 20% loading level by mean of 0.001430625 J/cm³. The amount of dissipation energy at each loading level would affect the mechanical strength and each type of damage propagation that occurs in the composite specimen. The hysteresis loop area must be significantly enlarged before the final damage occurs, indicating more energy absorbed before the damage finally occurs. The relationship between energy dissipation and temperature changes through thermocouples can be caused by energy dissipation from materials that might cause microscopic damage.

Keywords: Borassus flabellifer, Composite, Dynamic testing, Energy dissipation, Thermal response.

1. Introduction

Along with the issue of fuel savings in motorizing vehicles, various studies have been carried out to continue to find new engineering materials that are lightweight and high strength to be applied in the automotive and mechanical industries. So that composite materials, especially fiber-reinforced composites, come as a solution because their specific strength and stiffness are better than other engineering materials in general. The development of fiber-reinforced composites in Indonesia has reached an advanced stage, especially natural fibers. The use of natural fibers as reinforcement of polymer composite materials provides several advantages. After all, natural fibers have low density, biodegradable, easily recycled, inexpensive, low hazard manufacturing processes, excellent mechanical properties, and can be renewed because it's come from nature [1-3].

Lontar Tree (*Borassus Flabellifer*) as seen in Fig. 1, is one of the palm species that grows in areas with minimum rainfall, specifically in the Nusa Tenggara region, Indonesia. The lontar (*Borassus Flabellifer*) fiber is one of the natural fibers that can be used widely to reinforce polymer composites. The mechanical properties of the *Borassus flabellier* FRP composites given enough confidence to fabricate lightweight and reasonably good strength parts for automobile door panels, household applications like doors, window frames, etc. [4]. Lontar fiber composite mechanical properties were also catch up with other common natural fibers such as coir, jute, and sisal [5]. It is interesting to note that alkali treatment of 5-10% of NaOH yielded significant improvement in the mechanical properties of the fibers than the other percentage of alkali at Lontar fiber composite [6-8]. In the case of open-hole tensile specimen used in this study, several papers have been observed the presence of open hole at Lontar fiber composite and its use as joint as well, noting that the differences of hole configurations have an effect on tensile strength of lontar fiber-reinforced composites and the differences of tensile strength depend on the geometric dimensions of the cross-sectional area and stress distribution of each joint prototype configuration, respectively [9, 10].

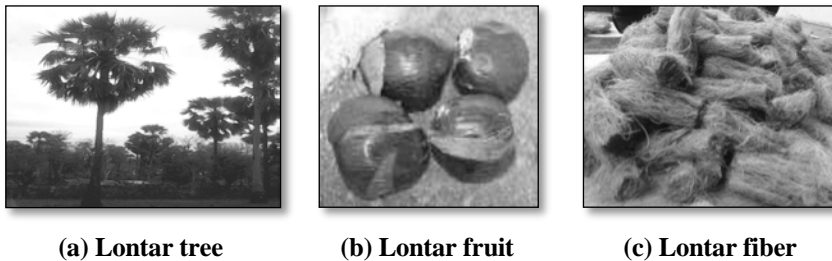


Fig. 1. Lontar plant manifestation.

In planning and manufacturing a composite, it is required that the composite must behave adequately so that the composite does not suffer damage, both structural and non-structural damage, when maximum load occurs. One of the various behaviors of composite specimens that must be understood is the composite behavior when experiencing a dynamic load. By understanding the composite's behavior of different types of loading that occurs will provide a guarantee of the strength of the designed composite. Nevertheless, it is worth noting that the ability to absorb impact and dissipate composite's energy is still inferior to conventional metallic materials [11]. Energy dissipation was the part of the energy that is not

given back when the load was released. Most of this energy heats the material because of the internal friction during the loading (stress-strain). Since the energy was not given back, this energy leads to damage of composite structure, such as matrix (resin) or fiber cracks, debonding, or fiber pullouts. By this destruction of the structure, the viscoelasticity of composite changes [12].

Therefore, it is essential to understand the energy dissipation mechanisms of Lontar fiber composites to overcome these limitations and will open new opportunities to replace synthetic fibers and, thus, can be used for various applications of industries. The sources of energy dissipation in fiber-reinforced composites are viscoelastic behavior of fiber and matrix, damping due to the viscoelastic nature of the interface between fibers and matrix, damping due to damage, and viscoplastic damping [13, 14].

In recent years, numerous papers have indicated that the thermal response may also be the most parameter to monitor the intrinsic energy dissipation of composites materials under fatigue and dynamic loads. Fatigue damage in a composite laminate is characterized by measuring heat dissipation, hysteresis energy, the energy associated with thermal capacity, damage energy, temperature variation, and thermodynamic entropy [15, 16]. Dissipated energy and damage accumulation can be characterized using the infrared thermography technique for fully reversed bending of a GFRP composite. It was also used as an indicator to determine the high cycle fatigue strength, providing support for the thermographic approach [17, 18]. For this reason, energy intrinsically dissipated can be another point of view to face up to sudden failure. In this way, energy-related parameters assessed by the analysis of thermographic signal can be useful for assessing information related to the onset of irreversible damage [19]. Even the mechanical impact energy dissipated as heat is spent in the formation of different damage modes as matrix cracks, delamination, and rupture of fibers [20]. The composite will absorb a certain amount of the input energy: an elastic recoverable part and a dissipated part that will cause damage in its different form [21].

It is, therefore, the aim of this study to investigate the energy dissipation of Lontar fiber composites from the experimental stress-strain under tensile dynamic load and will be validated with the thermal response to complete reliable Lontar fiber composite design compare to synthetic fiber composite since this is the first research taken to observe mechanical testing of lontar fiber composite in direction to close to the reality-imminent condition of loading, fulfilling the current state of Lontar fiber composite research still struggling at basic mechanical properties, the effect of pre-treatment, early prototyping, etc. To the knowledge of the authors, this is a novel result for Lontar fiber composite material.

2. Materials and specimens

The material used in this study is an open-hole tensile (OHT) specimen of polymer composite reinforced by Lontar fiber of 5 cm length and random orientation against each other. The composite specimen contains 30% of nominal fiber volume, which has been treated using 5% of NaOH for 1 hour, and the rest is Polyesters resin. The specimen is rectangular type based on American Society for Testing and Materials (ASTM) D5766 (Standard Test Method for Open-Hole Tensile Strength of Polymer Matrix Composites Laminates) [22], fabricated by hand lay-up method with the dimensions of 200 mm × 50 mm × 4 mm and has an open-hole of 10 mm diameter at the center, as seen in Fig. 2.

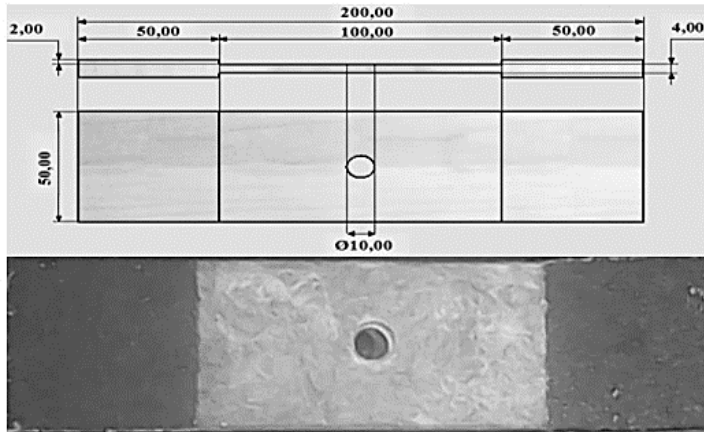


Fig. 2. Specimen of lontar fiber composite.

3. Experimental Procedures

The tests are performed with a SHIMADZU Servopulser type EHF-EB20 (capacity of 100 kN). The experimental test is carried out in 2 (two) phases. The first phase is a tensile test under static load to determine the value of UTS (Ultimate Tensile Strength). The second phase is a tensile test under dynamic loads to have the hysteresis curve of each loading-unloading percentage of UTS.

The used machine was capable of conducting a dynamic tensile test but could not automate it. Thus, the load had to be adjusted manually. After getting the maximum UTS at the first experimental runs, then the 20, 40, 60, and 80 percent of the maximum load (UTS) has determined to run at dynamic testing. Firstly, adjust the load's knob to 20 percent of UTS, then release the load to zero immediately after hitting the 20 percent of the UTS mark. Then repeat the process for 40, 60, and 80 percent of UTS. And in the end, give the continued load until the specimen failed. Meanwhile, a thermocouple was used to record temperature evolution on specimen surfaces around the hole area. The thermocouple is connected to the National Instrument USB-9162 data logger. Figure 3 shows the set-up of the experiment.

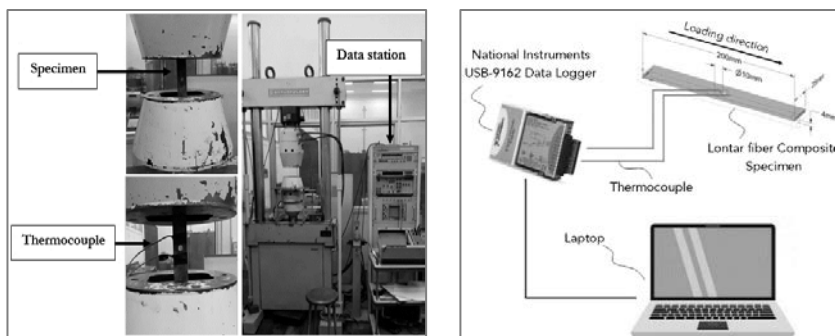


Fig. 3. Experimental setup (schematic diagram).

4. Results and Discussion

4.1. Tensile static test

The specimens are submitted to several tensile loadings tests until failure under a fixed displacement rate of 0.01 mm/s. From the tensile test results below (see Fig. 4), it is known that the maximum tensile load of the Lontar fiber composite specimens is 1197 N at 1.2 mm of displacement. The linearization of the load-displacement increases and suddenly decrease shows that the Lontar fiber composite specimens are a brittle type of material, same as polymer composites in general.

From the tensile results, the stress-strain curve and elastic modulus values of Lontar fiber composite specimens are obtained (see Fig. 5), where the ultimate tensile strength (UTS) is ≈ 20 MPa at a maximum strain of 0.6%. The stress-strain relationship generates the stiffness modulus E is equal to 3.3 GPa based on the equation:

$$E = \frac{\sigma}{\varepsilon} \quad (1)$$

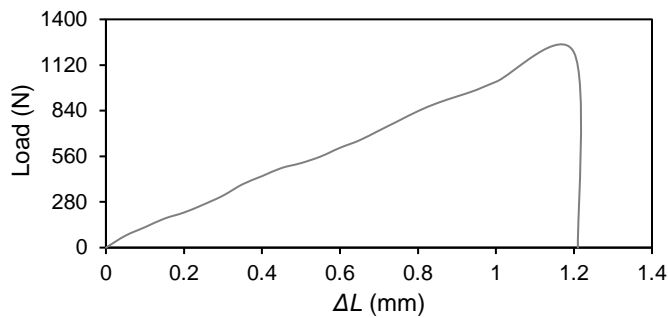


Fig. 4. Load-displacement curve.

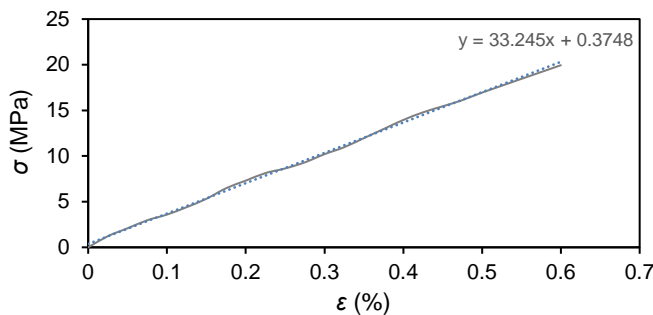


Fig. 5. Stress-strain curve.

4.2. Tensile dynamic test

The energy dissipation of Lontar fiber composite can be obtained through the dynamic tensile test as known as a loading-unloading test, where one loading-unloading cycle creates a hysteresis loop as schematically illustrated in Fig. 6.

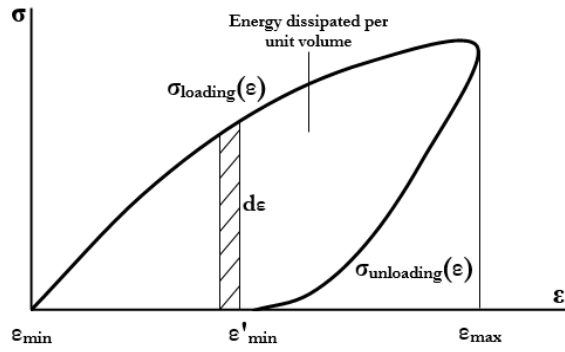


Fig. 6. Schematic of energy dissipation per cycle [23].

The energy dissipated per unit volume E_d describes the difference between the energy introduced during the loading-unloading cycle. The value of energy dissipation was obtained from stress-strain engineering at the hysteresis curve of mechanical tests using Eq. 3. Reference [24] has made a particular way to get the value of dissipation energy. It can be calculated by the following equation:

$$E_d = E_{load} - E_{unload} \tag{2}$$

$$E_d = \int_{\epsilon_{min}}^{\epsilon_{max}} \sigma_{(loading)}(\epsilon) d\epsilon - \int_{\epsilon'_{min}}^{\epsilon_{max}} \sigma_{(unloading)}(\epsilon) d\epsilon \tag{3}$$

Figure 7 shows the energy dissipation of Lontar fiber composite, i.e., the area within the hysteresis loop. The process of loading-unloading is repeated for each percentage of UTS until failure. The hysteresis loop represents the value of energy dissipation (mean value), as seen in Fig. 8.

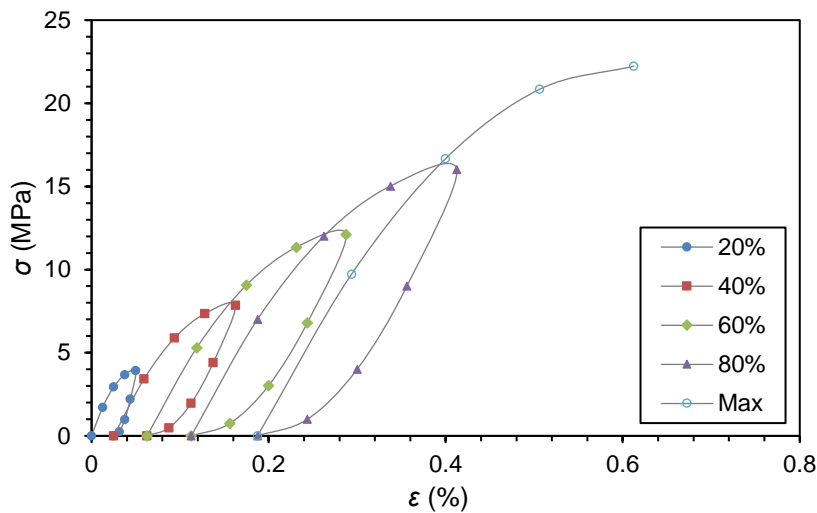


Fig. 7. Stress-strain plots showing energy dissipated of Lontar fiber composite.

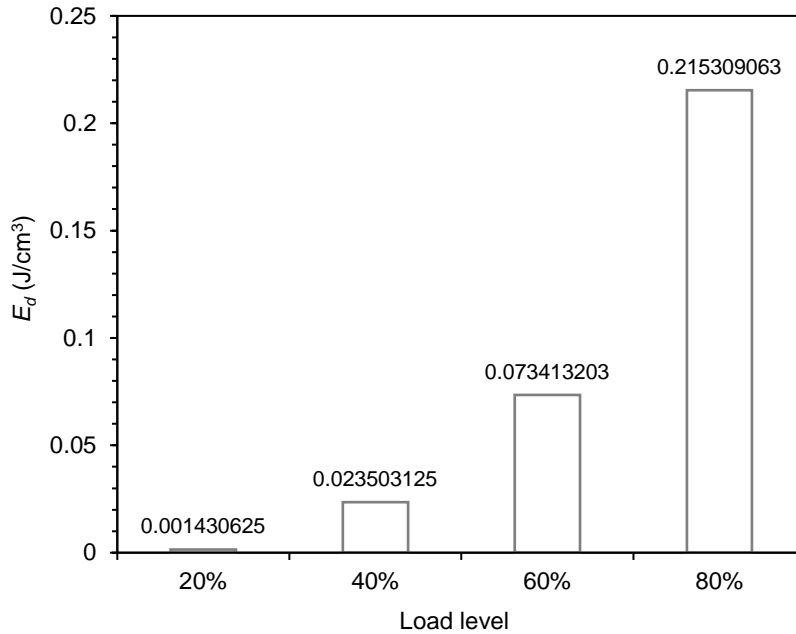


Fig. 8. Energy dissipation-%UTS graph of Lontar fiber composite.

The hysteresis area and UTS percentage show similar behavior in increment trend (see Fig. 7), which means that energy dissipation increases. The amount of dissipation energy at each loading level will affect the mechanical strength of the composite specimen refers to damage propagation observed as a function of its thermal response in the following section. The hysteresis loop area tends to expand significantly before the final damage occurs, indicating more energy is absorbed before the final damage occurs.

We defined our findings as an improvement from previous research in terms of dissipation energy on common natural fibers composite by comparing the result from Mohamed et al., study on energy behavior assessment of rice husk fiber composite. Dissipation energy held by the specimen was in the range of 2 - 30 kJ/m³ [25]. Meanwhile, our specimen was able to detain the dissipate energy in the range of 1.4 - 215.3 kJ/m³ by mean.

The hand lay-up fabrication produces a non-homogeneous structure that causes the load to be not equally distributed, so in one of the specimens, the final damage occurs before passed the 80% of UTS loading level (see Fig. 9). It is caused by the amount of energy that dissipated at each loading level (20-60%) is much higher than the mean value (see Fig. 10). Start from the 20% UTS loading and so on, the specimen experienced higher elongation than any other specimen, so when entering level 80% UTS of loading specimen enters its critical displacement and absorbs energy with a broader range of strain. Therefore, before reaching 80% of the UTS mark, specimens have experienced the final failure.

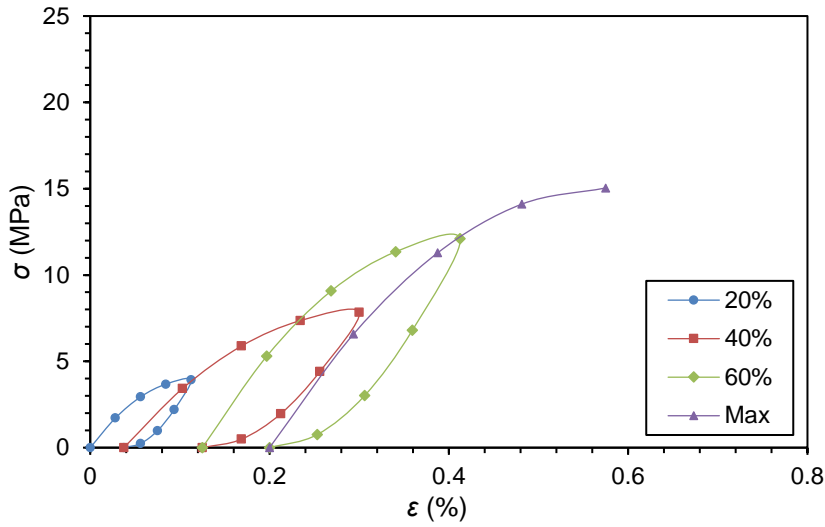


Fig. 9. Stress-strain curve of early failure specimen.

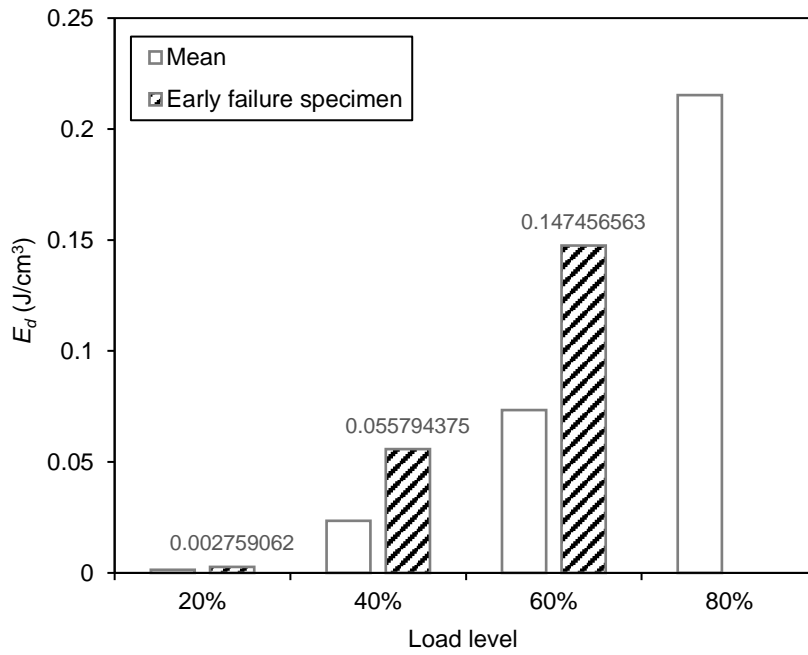


Fig. 10. Dissipation energy per unit volume in each load level graph for early failure specimen.

4.3. Thermal response

Damage propagation of composite materials which invisible (occur at a micro-scale), is another essential thing to investigate in understanding the damage

characteristic of composite materials. Monitoring and observation of the damage propagation can be done in real-time by using non-destructive observation methods. Temperature is one of the parameters of non-destructive testing (NDT) that can be used to analyze the behavior of materials during mechanical loading because the energy produced is a function of the surface temperature of material [26], where one of the hazard effects that occur during composite operations is self-heating. This phenomenon occurs during intensive cyclic loading of composite and causes dissipated energy in the form of heat [27]

Figure 11 shows the curve of recorded temperature at the composite specimen's surface on the hole-side during tensile loading. From this curve, it can be seen that the change in temperature from beginning to end of the test is around 5°C. In the propagation of the composite damage context, this temperature curve is plotted into three stages. The first stage starts with a decrease in temperature at the beginning of loading. This decrease in temperature indicates the initiation of damage by absorbing energy in the form of heat, resulting in microcracks starting to occur in the specimen, followed by a significant temperature rise.

The second stage shows the crack propagation that occurred in the composite specimen until just before the final failure occurred. This stage is characterized by temperatures increment following the trend of temperature change. The third stage is marked by a decrease in temperature and then immediately followed by a bump in temperature. This stage indicates the final failure with the most significant energy dissipation before being rereleased when the specimen reaches the final failure.

Bale et al. [28] also conducted an NDT observation of composite specimens during the tensile test. The results showed the highest temperature change in epoxy-glass composite specimen reached 37 °C, at UTS around 64 MPa. This indicates that (in common with this experiment) the larger stress held by the specimen, the greater the dissipated energy, which will be released at the end of loading in the form of heat. And to note that the performance of natural fibers requires a better fabrication (molding method, fiber length & orientation, etc.) in order to reduce heterogeneous structures, be able to survive greater loading, and provide better mechanical properties.

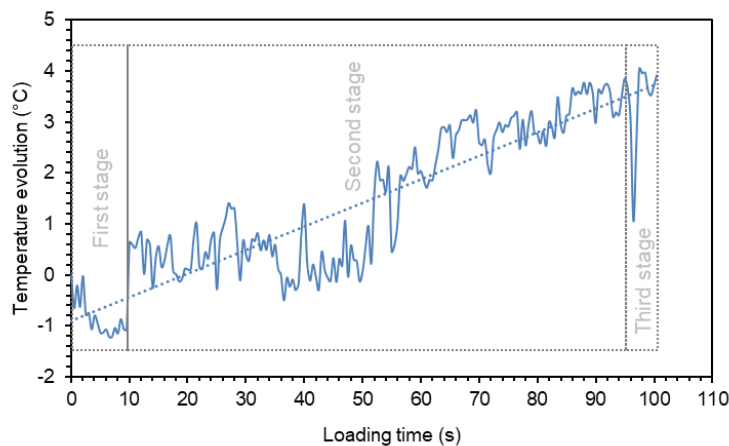


Fig. 11. Temperature evolution-loading time curve.

Figure 12 shows the trajectory of load and temperature changes to loading time. It can be seen that the load-unload process is not linear as function to time due to the tensile testing machine that is being used cannot automate the dynamic loading, so the load-unload process must be done manually, which leads to the inconstancy of displacement rate. The time it takes to load is not the same as unloading. It can also be seen that the trend of temperature changes increases with time and loading levels increment.

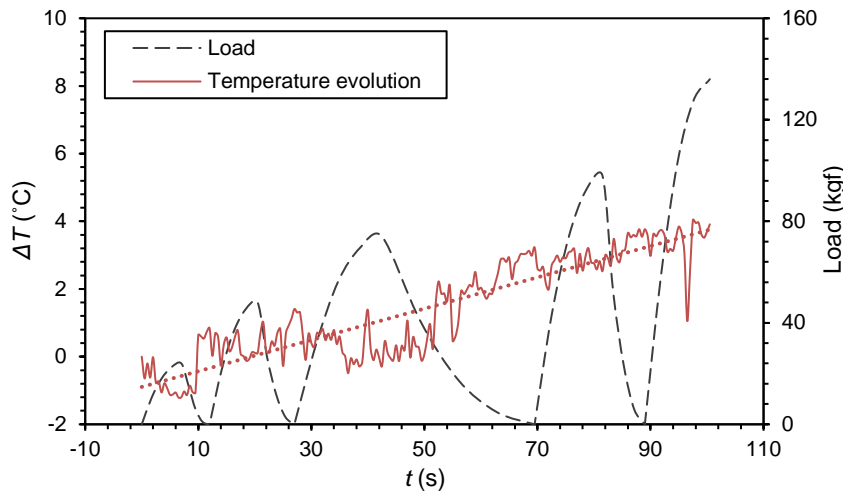


Fig. 12. Load and temperature-loading time curve.

Furthermore, to determine the relationship between energy dissipation and temperature evolutions, a plot has been made, as seen in Fig. 13. The relationship between energy dissipation and temperature evolution can be estimated through a polynomial function with data correlation factors using regression analysis resulting in the determination $R^2 = 0.897$ (close to 1), as shown in Fig. 13. By this relationship can be noted that heat measured by thermocouples apparently caused by energy dissipation from materials that might cause microscopic damage [28].

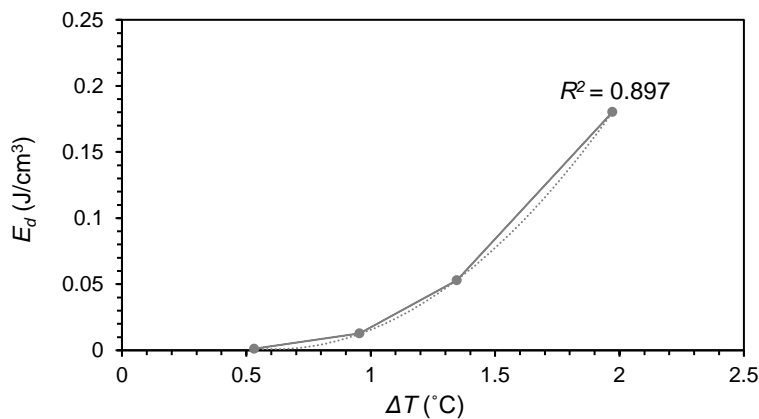


Fig. 13. Energy dissipation per unit volume-temperature evolution curve.

4.4. Failure analysis

The main mode of accumulation of damage observed in specimens is through micro-crack evolution. Tiny cracks begin to form and spread according to the increased load on the specimen. When the load is released, the crack closes, and the material return to zero load condition. Energy is recovered in parts that have not suffered damage from the material. This observation of the evolution of damage is in line with other observations, where the amount of energy dissipated depends on the amount of load. It is assumed that once damage occurs, a load can be released from the specimen, and as long as the re-loading does not exceed the previous load, no additional damage will occur [24].

Composites with random-oriented fibers produce heterogeneous structures. The hand lay-up and manual molding fabrication process seem to deliver a not bad specimen, where the final failure occurs in the area around the hole, where the hole was made to localize the stress concentration. Composites with imperfect fabrication process will produce specimens with erratic areas of damage even though the hole has been made.

Damage to Lontar composite specimens begins from the hole (edge area), then cracks towards the width of the specimen in a perpendicular direction to the loading axis (see Fig. 14). The brittle properties of the Lontar fiber composite material are strongly due to fibers orientation and the matrix (Polyesters resin). The brittle properties of this composite are also characterized by no occurrence of nacking in the stress concentration area.

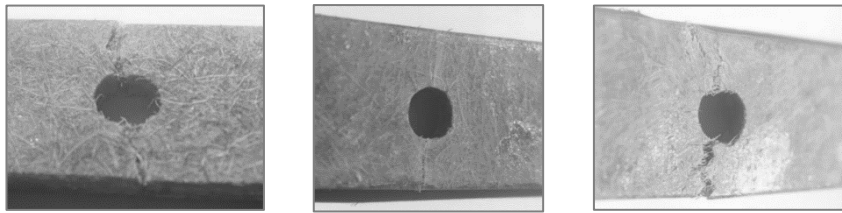


Fig. 14. Damage cross-section of Lontar fiber composite specimen.

The intensity of damage suffered by composite specimens was caused by a response to temperature trends. This indicates that each type of damage propagation that occurs in material as a result of the amount of energy dissipated at each level of loading.

5. Conclusions

Mechanical properties of dynamic tensile loading had been the novelty of this research in the case of advanced and reliable design of Lontar fiber composite on the next stage based on dissipated energy. The amount of energy dissipation of each loading level will affect the mechanical strength of the composite specimen. The hysteresis loop area tends to expand significantly before final failure occurs, indicating more energy was dissipated. The results of this study show that the highest dissipation energy is at 80% of UTS loading level by mean of 0.215309063 J/cm³, while the lowest dissipation energy is at 20% of UTS loading level by mean of 0.001430625 J/cm³. A decrease in temperature and then

immediately followed by a temperature bump at the end of loading indicates the final failure suffered by composite with the most significant energy dissipation before being rereleased when the specimen reaches the final failure. The relationship of energy dissipation and temperature evolution can be explained that heat measured by thermocouples was apparently caused by the energy dissipation of the material, which might cause microscopic damage. Hence this new characterization can fulfill the current state of Lontar fiber composite research with the dissipation energy mechanism and understanding.

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Nomenclatures

E	Stiffness modulus, Pa
E_d	Energy dissipation per unit volume, J/m ³
E_{load}	Load stress-strain engineering, $\int_{\varepsilon_{min}}^{\varepsilon_{max}} \sigma_{(loading)}(\varepsilon) d\varepsilon$, Pa
E_{unload}	Unload stress-strain engineering, $\int_{\varepsilon_{min}}^{\varepsilon_{max}} \sigma_{(unloading)}(\varepsilon) d\varepsilon$, Pa

Greek symbols

ε	Strain
Δl	Displacement, m
ΔT	Temperature changes, °C
σ	Stress, Pa

Abbreviations

ASTM	American Society for Testing and Materials
NDT	Non-Destructive Testing
PMDSU	Pendidikan Magister menuju Doktor untuk Sarjana Unggul
UTS	Ultimate Tensile Strength

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