Stress Behaviour of Composite Materials with Natural Fibers from the South Pacific

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Abstract

New engineered materials with unique properties are essential for space technologies, structural and bio-engineering. The need for sustainability and high strength and stiffness on a weight basis on reinforced composites orients the research efforts towards natural fibers. Coconut, Areca nut and Pandanus fibers are available in impressive quantities in all islands of the South Pacific and are traditionally used in textile and construction applications. The authors focus their research on composite materials with such natural fibers and their behaviour under stress. Finite Element Methods are employed in the evaluation of the behaviour of composites with natural fibers under various stress conditions. Elastic properties of newly created composites are evaluated on computer- controlled environments and they validate the simulations.

Keywords

Sustainable Materials, Natural Fibers, Tensile and Torsion Stress Evaluations, Finite Element Modeling.

Natural Fibers from the South Pacific

Micronesian and Melanesian societies in the South Pacific benefit from many naturally occurring sustainable materials. The Coconut Palm, the Areca Palm and the Pandanus are remarkable plants from the sustainability and cultural points of view. They are abundant, are versatile and the strength of their fibers recommend them for many traditional applications. There are more than 20,000 islands in the South Pacific. Coconut Palm and Pandanus trees colonized most of them long before the arrival of humans. Charles Darwin mentions in his Origin of Species that many dried seeds and fruits are tolerant to sea water, float and germinate when reaching far away sand beaches [01], [02].

The husk fibers fruits of Areca Palm – *Areca Catechu* – show excellent tensile strength. However, the compounds present in the nut are carcinogenic and are not considered in the manufacture of composite materials [03].

Coconuts are well known for their abundance in the tropical regions of the world and also for their versatility. The *Cocos Nucifera* or Coconut Palm Tree belongs to the family *Arecaceae*, genus *Cocos* [04]. The drupes are used for food, charcoal, oil and cosmetics. Modern applications include the biofuel and composite materials. The mechanical strength of the husk fibers is investigated in many research centers around the world [05], [06], [07], [08] and is beyond the scope of this paper.

The roots of Pandanus – *Pandanus Utilis* – form a pyramidal tract to hold the trunk of the plant. Pandanus trees grow in tropical and sub-tropical coastlines and islands of Indian, Atlantic and Pacific oceans and can withstand salt spray, drought and strong winds [09], [10]. The plants growing along seashores have thick aerial roots as anchors in the sand. Such roots keep the trees upright and secure them in the ground – see figure 1.
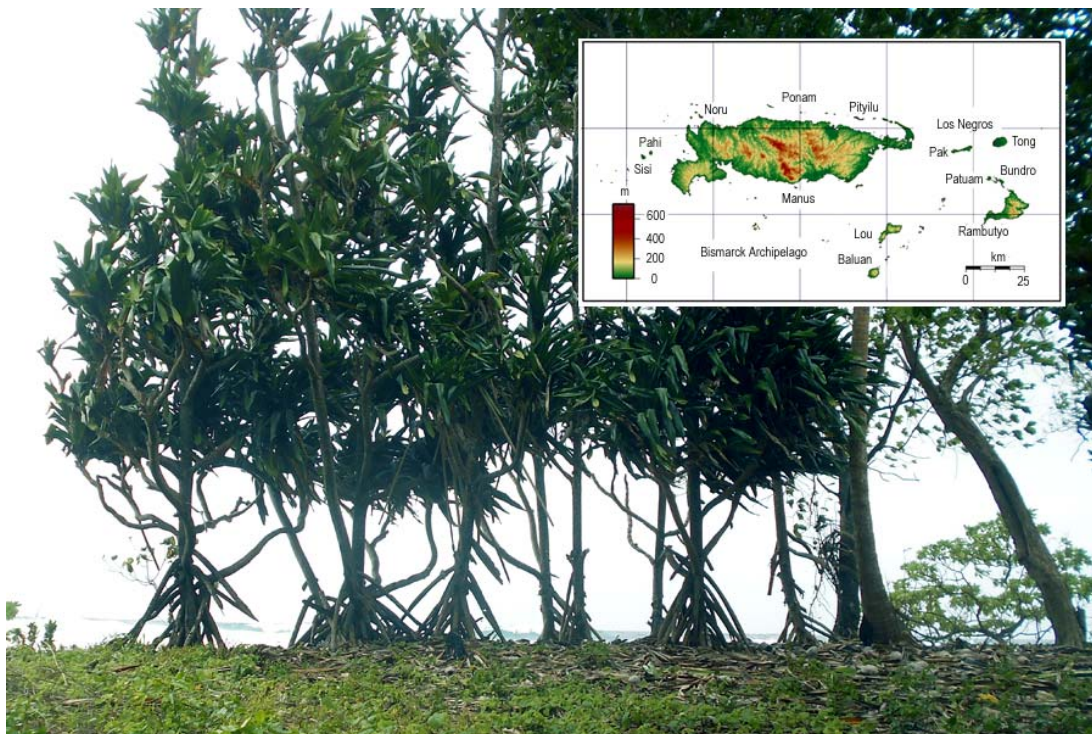

Figure 1. Pandanus Trees on the Seashore of Manus Island, Admiralty Archipelago. Inlet: Admiralty Islands Map

Composite Materials with Natural Fibers: Opportunities and Challenges

Very important advantages of using natural fibers in composite materials include the low cost, the sustainability and the density. Natural fibers are significantly lighter than glass, with densities around 1.15-1.50 g/cm³ versus 2.4g/cm³ for glass fibers. Despite their low strength, cellulose fibers can lead to composites with high specific properties because of their low densities. Unlike brittle fibers, they are flexible and will not fracture when processed over sharp edges. Their non-abrasive nature permits a high volume fraction of filling during processing, and this result in high mechanical strength without the usual machine wear problems associated with synthetic fibers. In addition, they are non-toxic, easy to handle and present no health problems [11].

The main constituents of all natural fibers include lignin, cellulose, hemi-cellulose and pectin. There are percentage variations of the main constituents from plant to plant and such variations are also influenced by harvesting and growing conditions. Pectin has the function to hold the fibers together. Lignin is an amorphous polymer and has little effect on water absorption. On the other hand, cellulose is responsible for the hydrophilic nature of natural fibers. Hemi-cellulose has a lower molecular weight than cellulose and is partly soluble in water and alkaline solutions.

The large scale production of natural fibers composites is limited by two major factors: mechanical strength and water absorption. The strength of natural fiber composites is very low compared to glass, in many cases a result of the incompatibility between the fiber and the resin matrix. The second factor limiting large scale production is water absorption. Natural fibers absorb water from the environment and this absorption deforms the surface of the composites, lowers the mechanical strength and increases their mass. The absorption of water is thought to occur at the free hydroxyl groups on the cellulose chains and by capping the hydroxyl groups with alkaline treatment this ratio can be reduced.

Technology of Composite Materials with Pandanus Fibers

The technological processing of composite materials involves the preparation of the fibers and the selection of the matrix. The content of water in Pandanus fibers is significant and it can be reduced by combined exposure to heat at around 120°C for two hours and immersion in 10% NaOH for four hours. The length of the fibers subject of experiment in this paper is around 20 mm – see figure 2. The immersion of fibers in NaOH is increasing the exposed surface, with beneficial effects for their adhesion to the matrix material.

Epoxy resins are suitable for the matrix of composite materials because they have low shrinkage and the adhesion to natural fibers is excellent. The hardened epoxy is duro-plastic and not affected by moderate heat or chemicals. The curing time is relatively long, but adhesion to most materials is excellent. They polymerize through a chemical reaction after being mixed in the correct proportions. Our experiments employ the polymer Epiclorhydrin in a ratio 15/2 with the hardener Triethylenetretamine from Struers. The hardened epoxy is duro-plastic and not affected by moderate heat or chemicals – see figure 2.

The curing of epoxy matrix depends on the amount of resin. With small amounts of resin the polymerization takes longer because favorable conditions exist for removing excessive heat generated by the chemical reaction. Larger amounts of epoxy accelerate the curing process by storing heat due to the poor conductive properties of the system. Air bubbles developed during the curing process are caused by higher than acceptable temperatures and can be under control by placing the composite in a Drybox. In addition, the stirring process needs to be moderate. On the other hand, sticky or rubbery sample surfaces after curing indicate a process temperature too low and can be corrected by post-curing in oven at 30°C – 50°C.

Pandanus Fibers Dried at 120°C for 2 Hours

Cross Section on Pandanus Fiber
Optical Magnification 200X

Pandanus Fiber after 10% NaoH Imersion
Optical Magnification 200X

Cured Resin Matrix

Composite with Pandanus Fibers Ready for Torsion Testing

Figure 2. Processing of Composite Materials with Pandanus Fibers

Tensile and Torsion Testing of Composite Materials with Pandanus Fibers

Laboratory-scale tensile or torsion testing machines allow the experimental establishment of the relationship between any applied tensile load and the induced elongation on specimens or any twist and the induced torque. As such, they facilitate the experimental evaluation of yield strength, Young modulus E or shear modulus G with remarkable precision. They can also bring the specimen to the point of destruction in order to establish the failure point of the involved composite material. The experiments discussed in this paper were performed on SM1002 Bench-Top Tensile Testing Machine and SM1001 Torsion Testing Machine, both from Tecquipment.
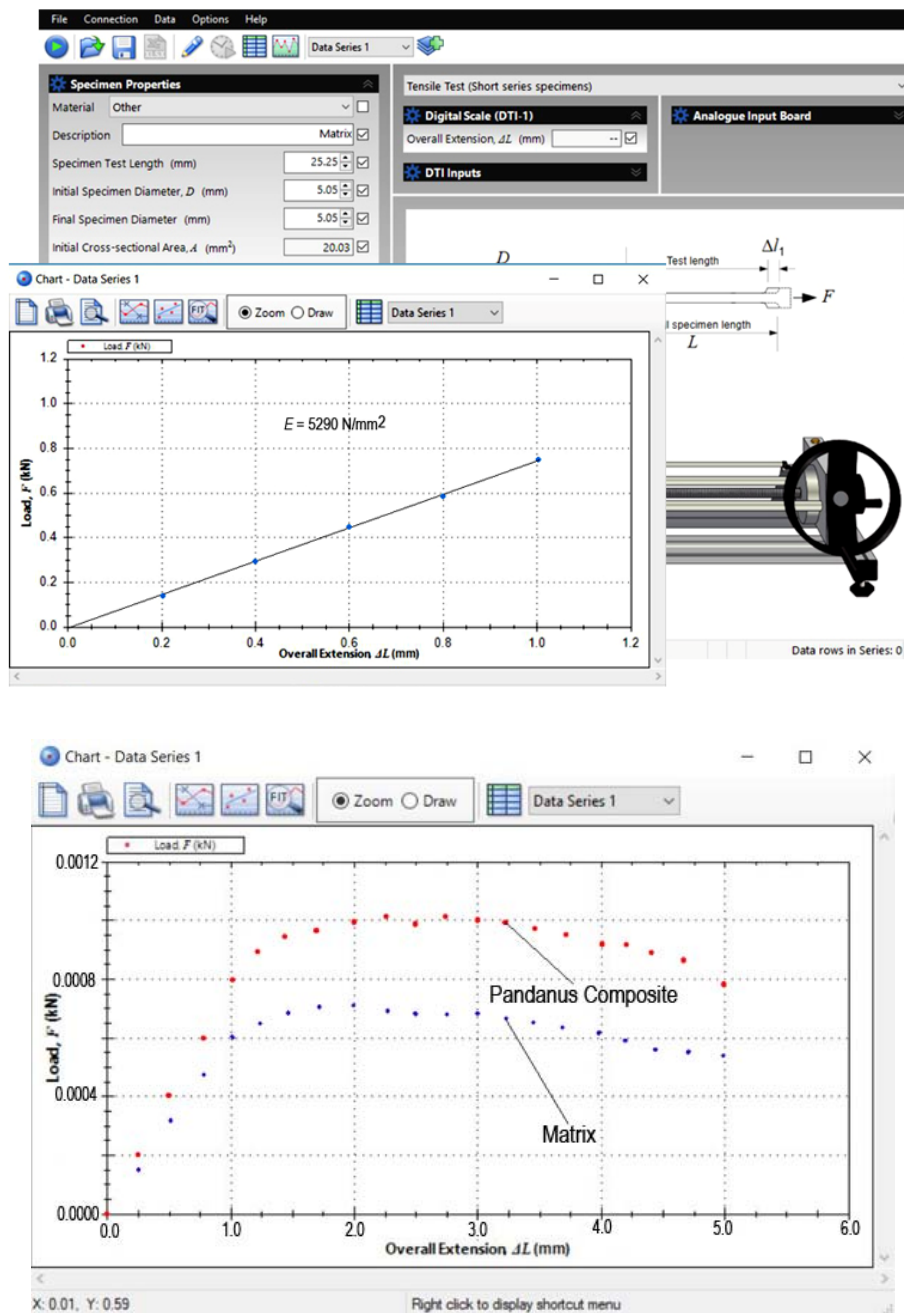

Figure 3. Tensile Strength Experiments on Composites with Pandanus Fibers
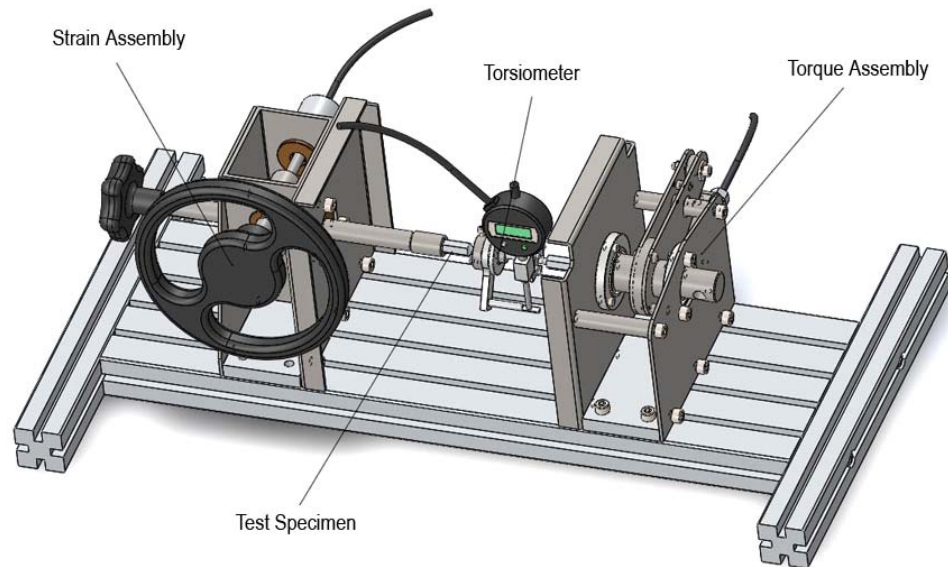
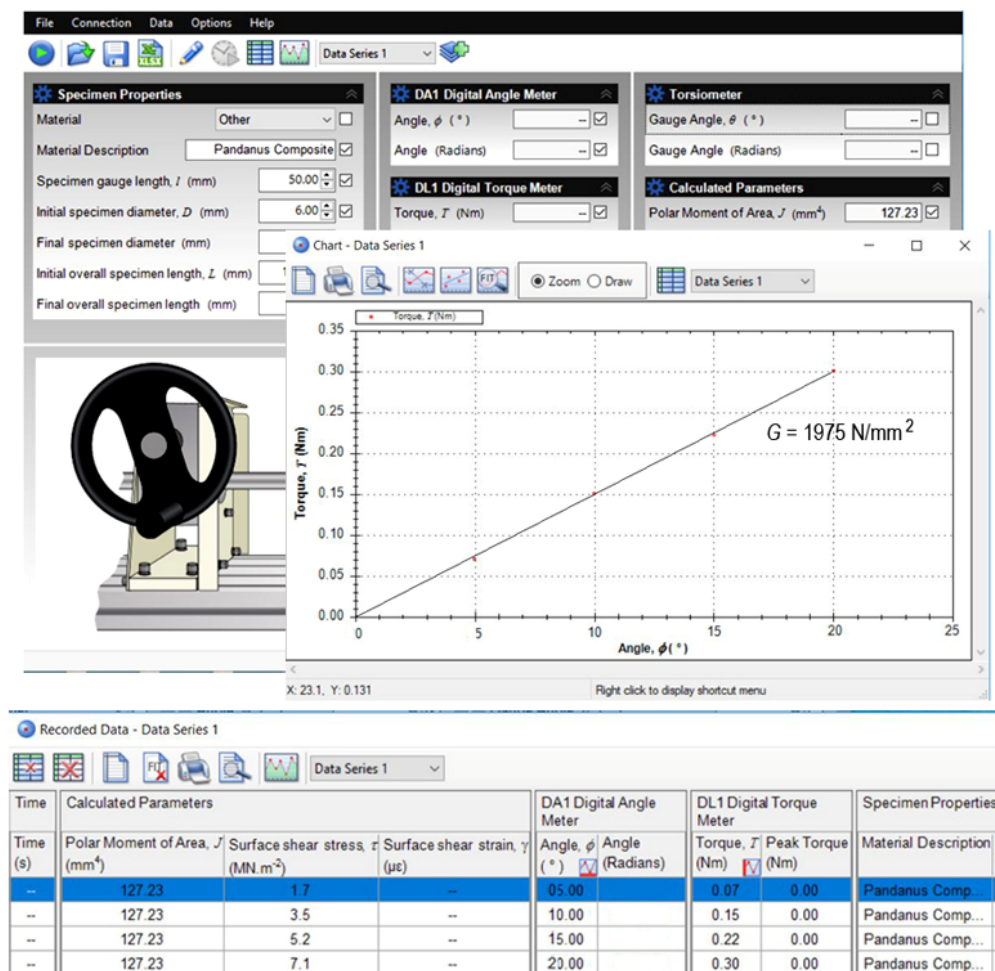Figure 4. 3D Model of Torsion Testing Machine for Shear Modulus Evaluation

Figure 5. Experimental Evaluation of Shear Modulus on Composites with Pandanus Fibers
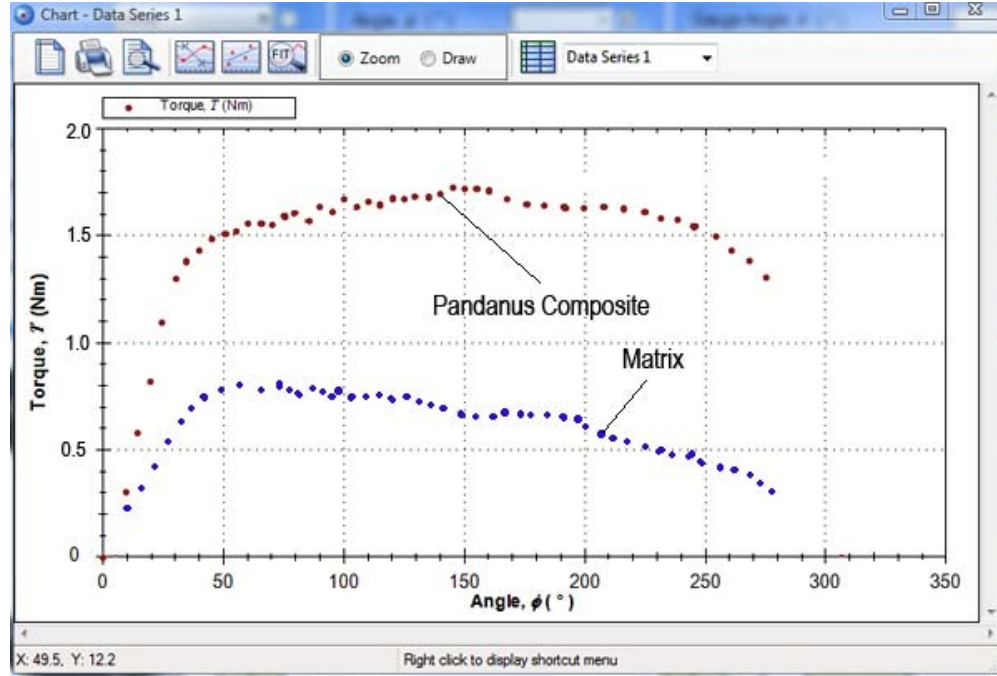
Figure 6. Torsion Experiments on Composites with Pandanus Fibers

The tensile strength experiments allowed the average evaluation of Young elastic modulus E for composites with 20% mass weight Pandanus fibers on resin matrix at $E = 5290$ N/mm^2 and the shear modulus $G = 1975$ N/mm^2. The plots from figures 3 and 6 also show the significant increase in the mechanical strength of composite materials with Pandanus fibers versus the resin matrix.

In all experiments discussed in this paper the Pandanus fibers are randomly oriented in the matrix and it is acceptable to consider the composite a homogenous, isotropic linear elastic material. As such, its elastic properties are fully defined by the Young modulus and shear modulus and the formula involving them allows the calculation of Poisson ratio v :

$$G = \frac{E}{2(1+v)} \tag{01}$$

$$v = \frac{E}{2G} - 1 \tag{02}$$

For $E = 5290$ N/mm^2 and $G = 1975$ N/mm^2, the calculated value is $v = 0.34$, close to results mentioned by other authors [14], [15]. The experimental density of the composite with Pandanus is $\rho = 1.27$ g/cm^3.

Stress Simulations

The composite material with Pandanus fibers exhibits plasticity in all experiments. The von Mises yield criterion suggests that the yielding of plastic materials begins when the second stress invariant reaches a critical value. Prior to yield, the material response is assumed to be elastic. In materials science and engineering the von Mises yield criterion can be also formulated in terms of the von Mises stress or equivalent tensile stress σ_v, scalar stress value that can be computed from the Cauchy stress tensor. In this scenario, the material is said to start yielding when its

von Mises stress reaches the yield strength σ_y. The von Mises stress is used to predict yielding of materials under any loading conditions from results of simple uniaxial tensile tests and it satisfies the property that two stress states with equal distortion energy have equal von Mises stress. Because the von Mises yield criterion is independent of the first stress invariant it is applicable for the analysis of plastic deformation for ductile materials, as the onset of yield for these materials does not depend on the hydrostatic component of the stress tensor [16], [17], [18].

Complex geometries and combined loads are conveniently investigated by Finite Element Methods. The simulations discussed in this paper are performed on SolidWorks. They are facilitated by the creation of the custom material – Pandanus Composite - into the database of the 3D CAD platform. The material is ductile with a linear stress-strain relationship up to the yielding point. The mechanical properties of the new material are tabulated below and the values are based on tensile and torsion experiments – see figures 3 and 5.

Table 1. Composite Material Properties

Property	Units, SI	Value
Elastic Modulus, E	N/mm^2	5290
Poisson Ratio, ν	-	0.34
Shear Modulus, G	N/mm^2	1975
Density, ρ	kg/m^3	1270
Yield Strength, ρ	N/mm^2	0.407
Density, ρ	kg/m^3	1270

The details and results of tensile and torsion simulations are presented in figures 7 and 8.
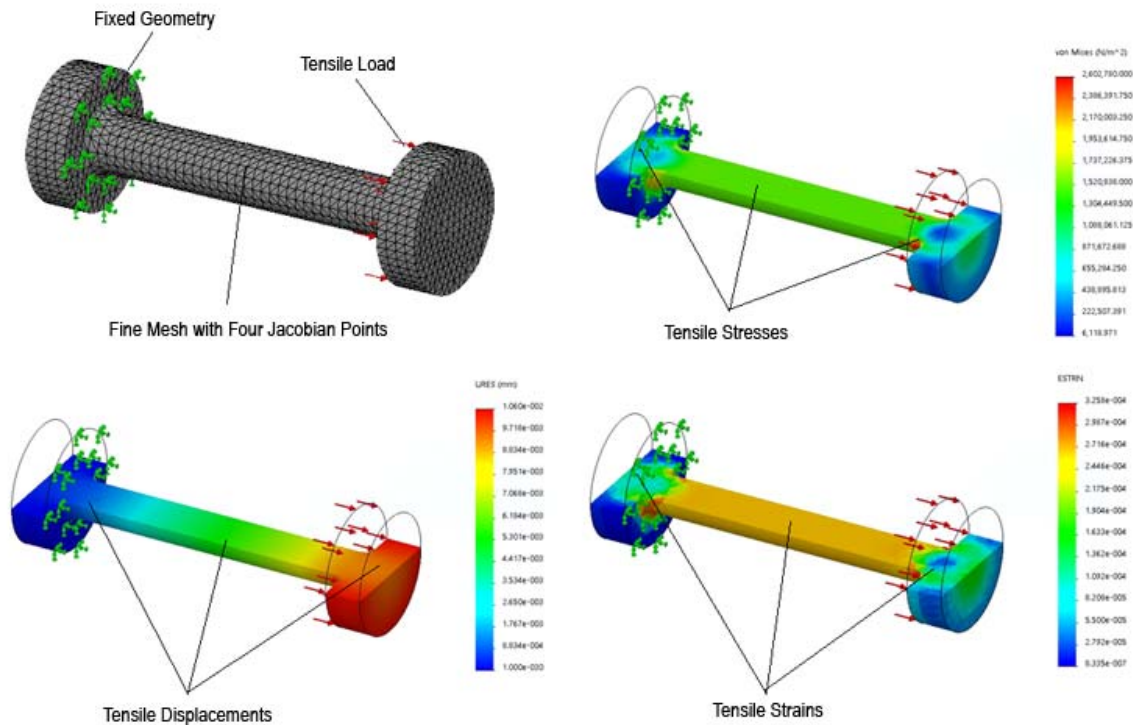

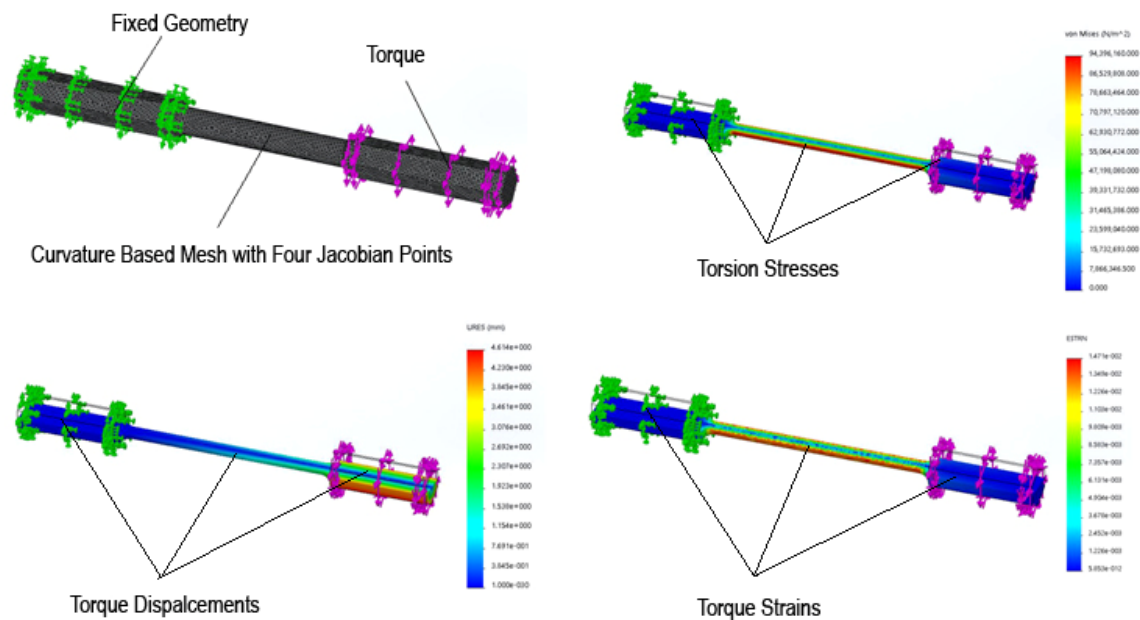Figure 7. Tensile Stress Simulation on Composites with Pandanus Fibers

Figure 8. Torsion Stress Simulation on Composites with Pandanus Fibers

Both tensile and torsion simulations are validated by experiments – see figures 3 and 6 – and bring confidence in simulations on more complex components under combined loads with the newly created composite material [19], [20], [21], [22]..

Conclusions

The mechanical strength of a newly created composite material on resin matrix and fibers from the aerial roots of *Pandanus Utilis* was subject of experimental and simulation research. The plants growing along seashores are abundant and the thick aerial roots can withstand salt spray, drought and strong winds. The paper and related experimental research show the advantages of resin polymers as matrixes for composite materials and discuss the technological challenges encountered during the preparation. Emphasis is placed on thermal and chemical treatment of fibers in order to reduce the water content and the necessity of curing in dry boxes for preparing isotropic composite materials.

Laboratory-scale tensile and torsion testing machines were employed during the experimental research in order to establish allow the experimental establishment of yield strength, Young modulus E and shear modulus G with remarkable precision.

The strength properties of the newly created composite material were used to create a new material entry into the database of materials of the 3D CAD platform used for simulations. Finite Element Modeling under SolidWorks allowed the investigation of the stresses and displacements developed under tensile and torsion static loads. The results are validated by experiments.

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