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Failure analysis of curauá fiber composite structures

Keywords: curauá fiber, composite structures, failure criteria, finite element analysis

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***Abstract*—[1] This document describes a process to investigate the strength and failure performance of composite structures reinforced with curauá fiber. A commercial software of finite element analysis is used to understand whether the behavior of this natural fiber can be accurately described with classical composite failure criteria. The numerical results are to be compared with the experimental results of failure of composite structures. The effect of selected processing techniques and composite matrices in the failure performance of the structures will be explored.**

***Keywords:* Composite structures, curauá fiber, failure criteria, finite element analysis (FEA)**

I. Introduction

Curauá (*Ananas erectifoliu*) is an Amazonian bromelia of the pineapple family (Fig. 1). The fiber processed from this plant (Fig. 2) has been used by indigenous peoples for centuries, and due to its outstanding mechanical properties is now an established, industrial-scale material (Fig. 3) (Silva and Aquino, 2008 [1]). Owing to its high strength, low density, and sustainability, applications of curauá fiber have been explored, for example, in ballistic armory (Monteiro et al., 2015 [2]), as the main material in clothing (de Queiroz et al., 2020 [3]), and as fiberglass substitute in a variety of composite structures (Zah et al., 2007 [4]; Souza et al., 2015 [5]).

Fig. 1. Curauá plant, a bromelia of the pineapple family.

Current industrial applications of curauá fiber, however, often aim primarily at replacing the environmentally harmful fiberglass, rather than at taking advantage of its striking strength properties. This is partly due to our understanding of its mechanical behavior being much below that of more traditional, artificial composites. As a result, some manufacturing processes consist of grinding up the fiber in order to make it injectable (Santos et al., 2009 [6]), which forfeits the increased strength offered by long fibers. The aim of this work is to improve our understanding of the mechanical behavior of curauá fiber composite structures. We propose to use finite element analysis, together with selected failure criteria, to understand the intricacies of their failure mechanisms. We used previous experimental results to calibrate and guide the numerical analysis, with a focus on failure reports of weaved, long-fiber curauá beams.

[1]Report on the progress of the student's scientific research project for Unicamp's PIBIC, as a requisite for the maintenance of her CNPq scholarship, which was granted on September of 2021 and is to last for 12 months.

(a) (b)

Fig. 2. (a) bundle of curauá fibers and (b) plate of epoxy-matrix curauá fiber composite (Monteiro et al., 2015).

Fig. 3. VW Fox, whose trunk hatch and roof linings bring curauá fiber since 2003.

Due to the promotion of this sustainable alternative in direct industrial composite applications, this project is well within MCTIC's Priority Investigation areas [2]. This project is also strongly connected to the work of Unicamp Compósitos [3] – the extracurricular dedicated to the design, simulation, manufacturing, and testing of high-performance composite materials and structures.

One of Unicamp Compósitos' main activities is competing in SAMPE's [4] yearly international competition, in which composite three-point beams are subjected to a prescribed load and the winning team is the one whose beam is the lightest (Fig. 4). For their 2019 natural-fiber category entry, a loom-weaving manufacturing technique was created to help preserve the length of curauá fibers (Fig. 5), which was commended by SAMPE's organization for its ingenuity. In addition to the contribution of this research work to its field of study, understanding the behavior of the long-fibered, three-point curauá beams will give the team a crucial edge at the competition.

[2]MCTIC Portaria 1.122 from March 19 2020: Tecnologias para o Desenvolvimento Sustentável.

[3]Unicamp Compósitos' Instagram page

[4]SAMPE: The Society for the Advancement of Material and Process Engineering

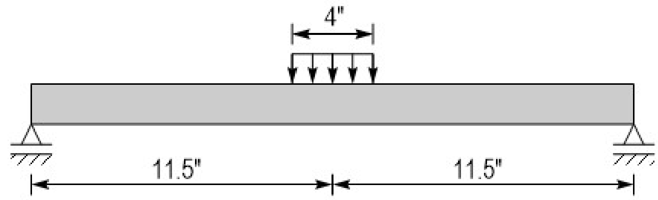

Fig. 4. SAMPE competition standards: the beam must fit within a 4" by 4" gauge and be able to withstand a 25,000-lb uniformly distributed load.

Fig. 5. Loom-weaving technique developed by Unicamp Compósitos.

The aim of this project is to improve our understanding of the failure mechanisms of curauá fiber composite structures. Since the material behavior, not the structure behavior, is the primary object of interest, a simple, yet representative threepoint beam structure under prescribed external load will be considered (Fig. 4). Finite element analyses using various failure criteria will be performed using Abaqus, the leading commercial software for analysis of composite structures in the Brazilian industry, provided by *Dassault Systèmes*.

II. Materials and Methods

This project was planned to be developed in twelve months, starting from September of 2021, and the activities were to be distributed as indicated by the table below (Fig. 6). Following the table, the explanation of each task is given.

Month→ / Task ↓	1–2	3–4	5–6	7–8	9-10	11–12
A	•	•	•			
B		•	•	•		
C				•	•	•
D						•

Fig. 6. Approximate time table for the progress of the study.

Task A. Read Hashin and Rotem [14], Hashin [10], Matzenmiller et al. [15], and Camanho and Dávila [13]. Follow Abaqus tutorials on composite failure modeling for classical artificial composites. Investigate differences between the implemented damage models. Reproduce results from the literature;
Task B. Read Santos [6] and collect material properties of curauá-reinforced polyamide-6 injected composites. Analyze Abaqus built-in damage models for this case. If needed, implement additional models for natural fiber failure through Python scripts;
Task C. Read Unicamp Compósitos' competition reports to gather ply orientation and resin properties in order to model their 2019 SAMPE competition entry. Compare results. Investigate fiber and matrix failure. Propose improvements;
Task D. Write PIBIC report. Organize and publish results.

Through the first half of 2021, which was the semester prior to the beginning of the CNPq scholarship cycle (September 2021 - August 2022), the student took the time to familiarize herself with the software until she was proficient enough to take on the project itself.

Since the student had never previously operated Abaqus, Professor Labaki advised her to explore the software's most frequently used tools and run common essential finite element numerical analyses. She did so by following video tutorials and turning to the Abaqus Documentation [7].

As recommended for beginners, she modeled linear-elastostatic classical beam cases, such as cantilever and simply supported (Fig. 7), with static loads and compared their numerical response to the analytical one.

While following the tutorials for static analysis and running those cases over and over again, but varying a distinct setting or parameter each time, the student eventually learned how to design and mesh complicated objects, with different seeding techniques and element types, as well as how to analyze varying simulation models made from those objects and extract the appropriate data from the results of the analysis.

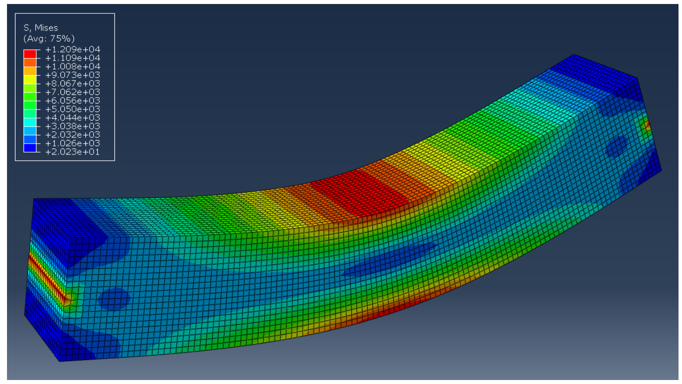

Fig. 7. Von Mises stress map of the beam problem from Fig. 4

Prof. Labaki also taught Karina how to do convergence studies, which ensured that the FEA models she had been doing so far adequately captured the system's behavior while reducing solve time, that is, how to identify the minimum degree of mesh refinement that induces numerical errors within a tolerable range.

In addition to these abilities, she learned how to obtain the natural frequencies and modes shapes of a certain system, run a modal dynamic analysis and obtain the frequency response function of a certain load applied to a beam with a steady-state dynamics analysis (Fig. 8).

With these fundamental Abaqus skills acquired over the course of the 1st semester of 2021, the student proceeded work on Task A. This was actually the first official stage of the research and it also marked the beginning of the scholarship period.

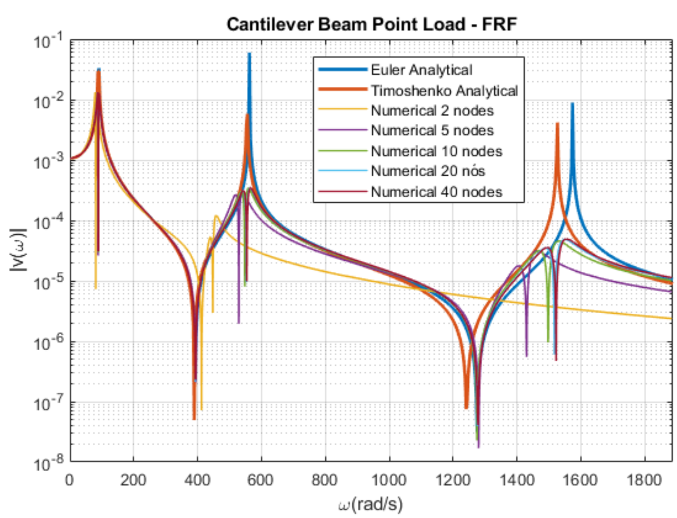

Fig. 8. Frequency Response Function to point load at the end of a cantilever beam - analytical/numerical integration comparison.

A. Understanding composite failure

Abaqus has five inbuilt failure criteria for composite materials whose contour plots are shown by requesting output of a field variable called CFAILURE. Tsai-Hill (Hill, 1948 [8]) and Tsai-Wu (Tsai and Wu, 1971 [9]) are among these inbuilt criteria and are widely used among FEA software users.

Thus, Prof. Labaki at first suggested that Karina should study and try to apply them in the project. **Tsai-Hill** and **Tsai-Wu** are interactive theories in which all stress components are considered and are included in a single expression – the failure criterion - unlike most of the theories the student had previously learned, which only consider one or a part of the stress components but never all of them. Once again, following Abaqus video tutorials, very simple analyses were carried out on models with uncomplicated geometry so that the student could grasp how these particular theories could be applied.

The Tsai-Hill and Tsai-Wu failure theories can predict/indicate failure with a single numerical index, but they fail to identify the particular failure mode. For the current project, it is extremely important that the analysis is able to point out how the material failed so that it can be used to emulate the experimental/practical results. In other words, it is necessary to know if the failure occurred, e.g., in the fibers themselves (fiber failure) or between the fibers (inter-fibre failure). Therefore, these two criteria should not be implemented either.

Many Abaqus tutorials about composite material analyses (especially wire-reinforced concrete beams) used **Hashin**'s theory - a failure criterion, for the fibers and for the matrix, which is able to distinguish between tensile and compression failure. This criterion considers four different damage initiation mechanisms: fiber tension, fiber compression, matrix tension and matrix compression. The Hashin criteria was built into Abaqus to describe Damage Initiation. After some more research, it was concluded that Hashin's criterion may not be perfectly suitable for the analysis that the student needs to do, for it assumes that two distinct fiber and matrix failure modes occur in two different fracture planes and only relevant stress components on the associated fracture plane of each mode will contribute to the failure criteria for that failure mode. Even though Hashin provides an improvement for prediction of intralamina failures, the quadratic failure criteria for matrix mode imply that the fracture plane is the maximum transverse shear plane and this may not always be true, as pointed out by Hashin. (Wang and Duong, 2016 [11]).

Failure criteria for composite materials are usually expressed as a function of the main resistance limits of the laminate. Since the nature of the failure observed on the epoxy-matrix curauá fiber composite beam made by Unicamp Compósitos is yet to be determined, theories that are more sophisticated/thorough and that take into account the influences that the different type of tensions have on one another would be more appropriate for this project. **Puck** (Puck and Schurmann, 2002 [12]) and **LaRC03** (Dávila et al., 2005 [13]) are failure criteria that meet those standards. However, both of the aforementioned criteria are more difficult to apply than Hashin's.

B. Curauá Fiber Failure

The research work then moved on to understanding the specific case of curauá fiber failure. In this task, the student modeled the case of **groundup curauá fiber used for reinforcement in extrusion and injection processes**. Due to the interest of the automotive industry in their application (Zah et al., 2007 [4]), their material properties have been more thoroughly studied and are more widely available (Maciel et al., 2018 [16]). Polyamide-6 (PA-6) was taken as matrix material due to the abundance of material information in the literature (Santos et al., 2009 [6]).

C. Loom-weaved curauá beam

After this initial assessment, the research is moving on to model the specific problem of UNICAMP Compósitos' loom-weaved, long-fiber, epoxy-matrix curauá beam. In this final stage of the research (task C), the reports of failure from the competition entries are being used to guide and calibrate the numerical results.

There are two main difficulties in this task. The first is that the material properties of long-fibered curauá plies are not available in the literature. This case is expected to present higher anisotropy indices than plies with uniformly-dispersed shortfibers. We expect the loom-weaved plies to be much stronger in the direction in which the fibers are lain.

The second difficulty is that, due to the highly non-standardized nature of its manufacture (Fig. 5, fabrication defects are expected to interfere with the predictions of the damage models. Among these defects are non-uniformities with regards to the ply layout, resin distribution, cure temperature, etc.

In view of these limitations, rather than yielding a precise description of the damage of Unicamp Compósitos' beam, this task will provide guidelines for ways in which to maximize its performance.

III. Results and discussion

After the conclusion of **Task A**, the student decided that she would attempt to consider the Hashin criterion for the next tasks (B and C), even though Puck and LaRC03 are both more sophisticated. This conclusion was reached considering that the Hashin criterion is:

- already implemented in Abaqus, while Puck and LaRC03 would require a lot more proficiency with the software;
- more suitable for the specific case of natural fiber composites (Koh and Madsen, 2018 [17]).

For **Task B**, the damage analysis of the "injected" curauá fiber beam was initially supposed to be done considering Hashin criterion. However, the student found that the experimental data concerning composites made of "injected" curauá fiber in PA-6 that she gathered in the literature did not provide the material properties needed to use the Hashin criterion. In other word, for the models of this specific case (Task B), she would **not** be able to apply the Hashin criterion, precisely because of the nature of the problem. Thus, the student analysed this case limited by the data that was available, meaning that the models were not treated as if they were composites. On the other hand, conventional types of composites, such as CFRP and grass fiber, were successfully modeled using the Hashin criterion since there is plenty of data about those. The student also tested different layups in laminate configurations in these cases (Fig. 9).

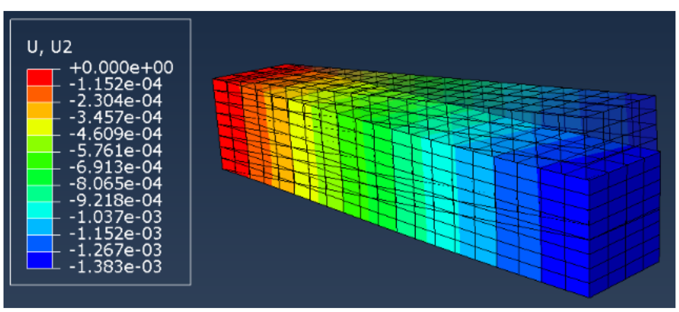

Fig. 9. Displacement map in Abaqus - solid composite beam model made of layup CFRP

Task A and B have already been completed, whereas **Task D** (PIBIC report) has gradually been progressing while the student worked on the research itself. The student is currently in the process of completing **Task C** and is aware that there has been a delay.

IV. Conclusion

The aim of this project is to propose an efficient and sufficiently close numerical finite element model of UNICAMP Compósitos' curauá fiber composite structures, more specifically their prized beam at SAMPE's competition, using the Abaqus. It was found that the software is indeed reliable to approach this particular problem. The student expects to achieve satisfactory results during the final steps.

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