Civil Engineering and Architecture 11(3): 1569-1575, 2023 http://www.hrpub.org
DOI: 10.13189/cea.2023.110336

The Viscoelastic Comportment of Composite Plates Reinforced with Synthetic and Natural Alfa (*Stipa tenacissima L.*) Fibers for Structural Applications

Sofiene Helaili[1,2,*], Nour Belbachir[3], Mohamed Amine Khadimallah[4]

[1]Tunisia Polytechnic School, Carthage University, LASMAP (LR03ES06), Rue El-Khawarizmi, BP 743, 2078, La Marsa, Tunisia
[2]ISTEUB, Carthage University, Rue de l'Artisanat Charguia 2, 2035, Tunis, Tunisia
[3]IRESA & Jandouba University, Ecole Supérieure des Ingénieurs de Medjez El Bab, 9070, Medjez El Bab, Tunisia
[4]Department of Civil Engineering, College of Engineering in Al-Kharj,
Prince Sattam Bin Abdulaziz University, Al-Kharj, 11942, Saudi Arabia

Received November 16, 2022; Revised January 9, 2023; Accepted February 10, 2023

Cite This Paper in the Following Citation Styles

(a): *[1] Sofiene Helaili, Nour Belbachir, Mohamed Amine Khadimallah , "The Viscoelastic Comportment of Composite Plates Reinforced with Synthetic and Natural Alfa (Stipa tenacissima L.) Fibers for Structural Applications," Civil Engineering and Architecture, Vol. 11, No. 3, pp. 1569 - 1575, 2023. DOI: 10.13189/cea.2023.110336.*

(b): *Sofiene Helaili, Nour Belbachir, Mohamed Amine Khadimallah (2023). The Viscoelastic Comportment of Composite Plates Reinforced with Synthetic and Natural Alfa (Stipa tenacissima L.) Fibers for Structural Applications. Civil Engineering and Architecture, 11(3), 1569 - 1575. DOI: 10.13189/cea.2023.110336.*

Abstract Composite materials are widely used in applications subjected to low, medium, and high loading frequencies. The viscoelastic behavior of these materials can significantly impact their performance and behavior under different loading conditions. As a result, it is important to carefully study the viscoelastic behavior of composite materials to design structures that can effectively withstand vibration or time-varying loads. This study investigated the static elastic, vibratory, and viscoelastic behavior of composite materials made from Carbon/Epoxy and PMMA/Natural Alfa fibers using both analytical and numerical approaches. The laminates studied included an asymmetrical laminate and an antisymmetrical laminate, both with a thickness of 2mm and composed of 9 plies. Stresses and strains were calculated for each ply and the overall composite plate. The study showed that the numerical finite element models produced results that agreed with the analytical models. The modal analysis revealed that the first frequency of the symmetrical composite [0/+45/-45/60/0/60/-45/+45/0] was 4.16Hz, which was higher than the first frequency of the antisymmetrical composite (2.61Hz) made from Carbon/Epoxy60% fibers. In terms of the viscoelastic behavior, the relaxation test of a 2mm plate showed that the stresses in the Carbon/Epoxy60% composite were stabilized quickly, while it took 20 minutes for the stresses of Alfa/PMMA45% composite plates. Alfa/PMMA45% can be a candidate for civil applications.

Keywords Composites, Viscoelasticity, Vibration, Alfa/PMMA45% Composite, Carbon/Epoxy60% Composite

1. Introduction

Composite materials, which are composed of a combination of different types of fibers, have a wide range of applications in various fields, such as crash and safety [1], [2], civil engineering [3]–[5], and biomechanics [6]–[8]. Researchers in Tunisia have been investigating using natural fibers [9]–[14], including palm [15] and cellulosic fibers [16]–[18], in composite materials to utilize local resources and promote sustainability. The current study examines the static, vibratory [19], and relaxation behavior of Alfa/PMMA45% composite materials made of Alfa natural fibers and PMMA resin. Composite materials have gained popularity due to their high strength-to-weight ratio and the ability to tailor their mechanical properties by selecting different fiber and matrix materials [20]. The fibers provide strength and stiffness, while the matrix holds the fibers in place and transfers load between them. There are two main categories of composite materials: those made from natural fibers [21], [22], which are derived from plants and animals, and those made from synthetic fibers, which are created from manufactured polymers [20], [23]. Natural fibers are generally less expensive and more widely available, but they may not be as strong or uniform as synthetic fibers. Synthetic fibers, on the other hand, offer greater strength and stability but can be more expensive to produce.

Analyzing composite materials is crucial in understanding their properties and potential applications. One common approach is to experimentally determining the properties of individual fibers or laminates rather than using a micromechanical approach [24], [25]. However, this experimental method has limitations as any changes to the constituents or fiber volume fraction during the design process invalidate the material data and require a new set of experiments. A more reliable method is to calculate the elastic properties of the composite using micromechanics formulas, which take into account the properties of the individual fibers and matrix [26]. This allows for the design of composite materials with specific properties without the need for extensive experimental testing. The current study's experimental work will validate a final version of the composite material during the prototyping phase. This is an important step in the development process as it allows for the confirmation of the material's properties and the optimization of its performance. Using micromechanics [27] formulas and experimental testing, it is possible to accurately predict the behavior of the composite material and ensure its suitability for the intended application [28].

In the analysis of composite materials, it is often necessary to consider the properties of individual fibers or laminates. However, in some cases, it may be sufficient to only consider the overall properties of the composite on the macro scale [29], [30], and at the laminate level. This is particularly true for deflection, modal, or buckling analyses that do not require detailed stress analysis. In these cases, it is not necessary to specify the laminate stacking sequence, thickness, and elastic properties of each layer, as only the overall elastic properties of the laminate are needed. This approach is convenient for the design process as it reduces the complexity of the input data, allowing for the modeling of laminates with an unlimited number of layers using only constitutive matrices. By limiting the number of parameters required to describe the composite material, it is possible to more easily predict the behavior of the laminate and optimize its performance. Additionally, this approach allows for a more streamlined design process, as fewer parameters need to be considered and analyzed.

2. Materials and Methods

Materials

The material properties of the matrix and fibers used in calculating the composite material's properties are listed in TABLE 1. These properties are obtained from references [31] and [32] for the Carbon/Epoxy60% ply and Alfa/PMMA45% ply, respectively. It is important to accurately determine the material properties of the matrix and fibers to predict the behavior and performance of the composite material accurately. Using the material properties listed in TABLE 1, it is possible to accurately model the composite and optimize its design for the intended application.

Table 1. Fibers and composites ply mechanical properties

	EL(GPa)	ET(GPa)	νLT	GLT(Mpa)	KL(Mpa)	GTT'(Mpa)
Epoxy [33]	3,00	-	0,35	-	-	-
Alfa Natural Fiber [34]	18,40	-	0,32	-	-	-
Carbon HR [31]	260,00	260,00	0,32	98,48	-	-
Carbon/Epoxy60% [31]	157,40	11,90	0,32	5,06	10,02	4,27
Alfa/PMMA45% [32]	9,92	6,17	0,38	2,27	4,49	1,91

Analytical model development

The behavior of a laminate, a composite material made up of layers of fibers and matrix, can be described by a relation between the external forces (N and M) and the internal deformation (γ and χ). This relation is represented by equation 1, which describes how the laminate responds to external forces and deforms in response. Understanding this relationship is important for predicting the performance and behavior of the laminate under different loading conditions. By accurately modeling the relation between external forces and internal deformation, it is possible to optimize the design of the laminate for a specific application and ensure its suitability for the intended use.

$$\begin{pmatrix} N \\ M \end{pmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{pmatrix} \gamma \\ \chi \end{pmatrix} \tag{1}$$

The stiffness of a laminate, a composite material made up of layers of fibers and matrix, can be described by a matrix with various components representing different types of stiffness. Matrix A represents the stiffness in the laminate plane, while matrix D represents the bending stiffness. Matrix B represents the coupling between bending and extension, and matrix H represents the inter-laminar shear stiffness. These matrix components can be determined using equation 2, which considers the position of the ply (hk).

Understanding the stiffness of a laminate is important for predicting its behavior and performance under different loading conditions. By accurately modeling the stiffness of the laminate using the matrix components described above, it is possible to optimize the design of the composite material for a specific application and ensure its suitability for the intended use.

$$A_{ij} = \sum_{k=1}^{N} \bar{Q}^{k}_{ij}(h_{k} - h_{k-1})$$

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{N} \bar{Q}^{k}_{ij}(h^{2}_{k} - h^{2}_{k-1}) \tag{2}$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{N} \bar{Q}^{k}_{ij}(h^{3}_{k} - h^{3}_{k-1})$$

Q_{ij}, expressed in equation 3, is the reduced stiffness constants expressed in the principal axes as a function of the elastic moduli of the composite ply indicated in TABLE 1.

$$Q_{11} = \frac{E_L}{1 - {v_{LT}}^{2}\frac{E_T}{E_L}};\; Q_{22} = \frac{E_T}{E_L}Q_{11};\; Q_{12} = v_{LT}Q_{22};\; Q_{66} = G_{LT} \tag{3}$$

Laminate models

The current study considers a composite material consisting of unidirectional Carbon/Epoxy60% and Alfa/PMMA45% fibers, with thin squares of dimensions ax=ay=100 mm. The total thickness of the laminate is 2 mm, with each ply having a thickness of 0.22 mm (as shown in FIGURE 1). The laminate comprises 9 plies in a symmetrical configuration [0/+45/-45/60/0/60/-45/+45/0] for the first composite and an antisymmetric configuration [0/+45/-45/60/0/-60/45/-45/0] for the second composite.

The use of composite materials is becoming increasingly common due to their high strength-to-weight ratio and the ability to tailor their mechanical properties by selecting different fiber and matrix materials. In this study, the unidirectional Carbon/Epoxy60% and Alfa/PMMA45% fibers were chosen for their specific properties, and the way they were arranged in the laminate affects the overall behavior and performance of the composite material. By carefully selecting the fibers and their arrangement, it is possible to optimize the design of the composite for a specific application and ensure its suitability for the intended use.

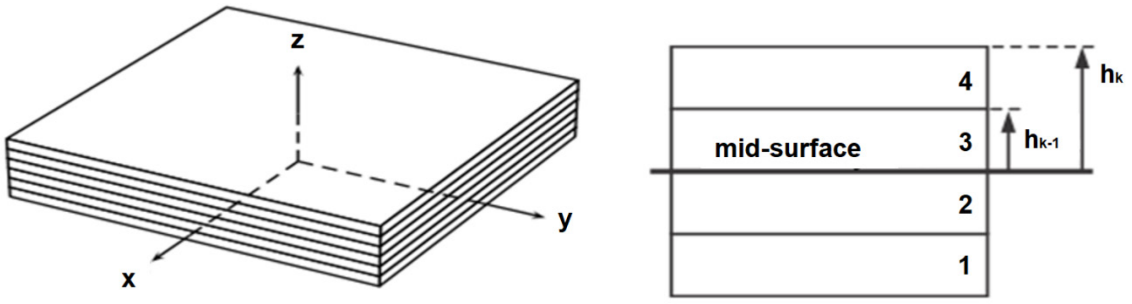


Figure 1. Section of multilayer laminated plate

Finite elements model

There are several ways to specify the properties of a composite laminate, including using the constitutive matrices A, B, D, and H, defining the stiffness matrix C or specifying the Laminate Stacking Sequence (LSS) and properties for each layer of the laminate. When the laminate constituent matrices A, B, D, and H are used, the finite element shell element cannot differentiate between different laminate layers. Instead, it can only relate generalized forces and moments to generalized deformations and curvatures. In contrast, layered shell elements can compute the properties of the laminate using the LSS and the properties of each layer. The method used to specify the properties of a composite laminate can significantly impact the analysis's accuracy and efficiency. In some cases, using the constitutive matrices may be more appropriate, while in others, the LSS and individual layer properties may be more suitable. Careful consideration should be given to the appropriate method based on the analysis's specific requirements and goals.

The use of matrices A, B, D, and H to define the finite element analysis of a composite laminate allows for the accurate calculation of the material's stiffness but does not provide information about the Laminate Stacking Sequence (LSS). As a result, the finite element model (as shown in FIGURE 2) can accurately predict the strain response of the laminate, including buckling and vibration, as well as the strain distribution through the thickness of the shell. However, it cannot calculate the composite's stress properties.

To accurately determine the strain and stress at the mesoscale lamina level, it is necessary to have a detailed description of the laminate and the properties of each layer. This requires a more in-depth analysis that considers the individual layers of the laminate and how they interact with one another. By understanding the properties of each layer and how they contribute to the overall behavior of the composite, it is possible to more accurately predict the performance of the laminate under different loading conditions.

The description of the multidirectional laminate includes the laminate stacking sequence (LSS), which specifies each lamina's angle concerning the laminate's x-axis, thickness, and elastic material properties of each lamina. This way, the software can calculate the stress components in each layer.

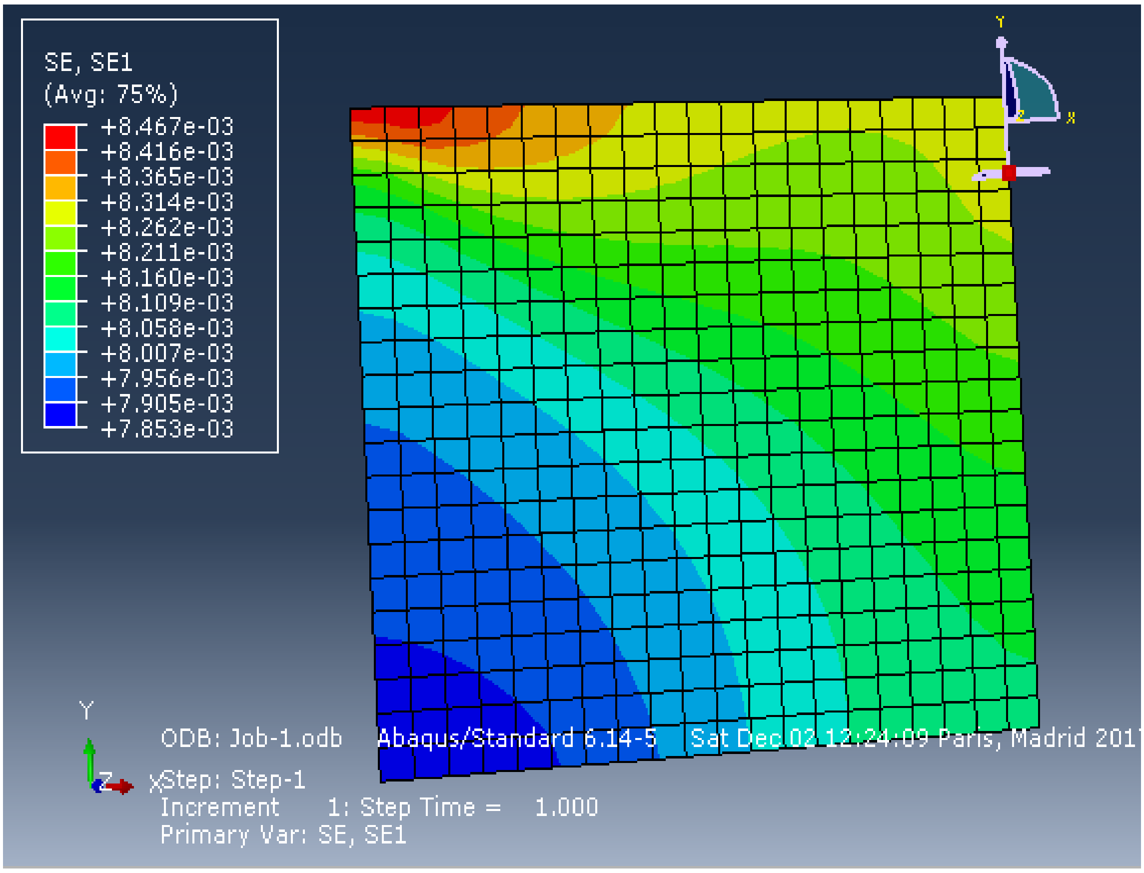


Figure 2. Finite element model of the 2 mm plate

Viscoelasticity/relaxation properties

The plate defined above undergoes an imposed displacement along x equal to 10 mm. The Carbon/Epoxy60% composite has the following Maxwell viscous-elastic model properties:

- g1 = 0,999 / k1 = 0,999 / τ = 58,424 min.

The Alfa/PMMA45% composite, is isotropic with properties E0 = 9912 MPa and v23 = 0.279 and has the following Maxwell viscous-elastic model coefficients:

- g1 = 0,165 / k1 = 0,165 / τ1 = 6.12 e-3 min;
- g2 = 0,626 / k2 = 0,626 / τ2 = 1.79 e-1 min;
- g3 = 0,207 / k3 = 0,207 / τ3 = 2.67 min.

Initial displacement is applied over a short period of 1 min using automatic incrementation. Then, a second step is implemented to calculate the relaxation over 250 min with fixed intervals to facilitate the interpretation of the data.

3. Results

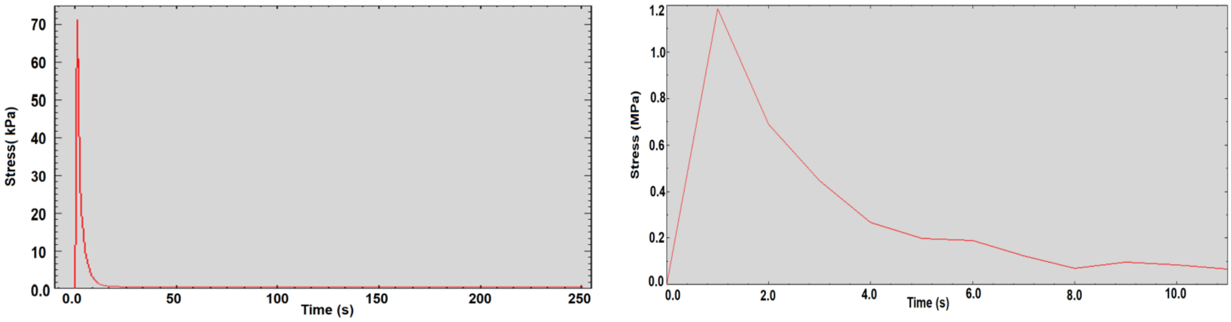
The results of the numerical finite element models were in good agreement with the analytical models, with only minor differences observed. For example, the deformation along the x-axis was determined to be 8.11e-3 using the analytical model and 8.16e-3 using the finite element model for the symmetric laminate made from Carbon/Epoxy60% composite plies.

The modal frequencies for the two composite laminates are listed in TABLE 2. The modal analysis results show that the symmetrical composite's first frequency [0/+45/-45/60/0/60/-45/+45/0] is 4.16Hz, which is higher than the first frequency of the antisymmetrical composite, which is 2.61Hz and made from Carbon/Epoxy60% fibers. These results demonstrate the importance of the Laminate Stacking Sequence (LSS) in determining the overall behavior and performance of the composite material. By carefully selecting the LSS, it is possible to optimize the design of the composite for specific applications and ensure its suitability for the intended use.

Table 2. Modal frequencies of symmetric composite plates

	Anti-symmetric Carbon/Epoxy60% (Hz)	Symmetric Carbon/Epoxy60% (Hz)
Mode 1	2.6163	4.1672
Mode 2	6.7977	15.059
Mode 3	16.846	17.392
Mode 4	21.226	32.783
Mode 5	23.335	37.507
Mode 6	29.844	41.445
Mode 7	32.560	56.642
Mode 8	42.755	63.687
Mode 9	54.281	69.957
Mode 10	57.801	77.292

Relaxation curves are indicated in Figure 3.



(a) Carbon/Epoxy60%

(b) Alfa/PMMA45%

Figure 3. Traction stress relaxation curve over time

4. Discussion

The visco-elastic behavior of composite materials, as shown in FIGURE 3, reveals that the stresses in the Carbon/Epoxy60% composite stabilize within 5 minutes, while it takes 20 minutes for the stresses in the Alfa/PMMA45% composite to stabilize. These results suggest that for applications where the loading varies within a time frame of less than 20 minutes, the effect of viscoelasticity should not be neglected when designing with the Epoxy/Alfa45% composite plates.

Viscoelastic materials exhibit both viscous and elastic behaviors, with the relative importance of each varying depending on the time scale of the loading. For composite materials, the viscoelastic behavior can significantly impact the overall performance and behavior of the material, particularly under dynamic loading conditions. Therefore, it is important to consider the viscoelastic behavior of the composite when designing for specific applications to ensure that the material is suitable for the intended use.

5. Conclusions

This study on the viscoelasticity of thin composite plates with a thickness of 2 mm has shown that natural fiber composites are suitable for applications where forces are applied slowly. These materials exhibit both viscous and elastic behaviors, with the relative importance of each varying depending on the time scale of the loading. When forces are applied slowly, the elastic behavior becomes more pronounced, and the material can return to its original shape after removing the load.

Using natural fibers in composite materials offers several advantages over synthetic fibers, including lower cost, good mechanical properties, and improved environmental sustainability. However, it is important to carefully consider the specific application and loading conditions when selecting a composite material to ensure that it is suitable for the intended use. Natural fiber composites may be a suitable choice in cases where forces are applied slowly due to their viscoelastic behavior.

Acknowledgments

This study is supported via funding from Prince Satam bin Abdulaziz University project number (PSAU/2023/R/1444).

Conflict of Interest Statement

The authors declare no conflict of interest.

REFERENCES

[1] S. Helaili, M. Chafra, and Y. Chevalier, “Hybrid Aluminum and Natural Fiber Composite Structure for Crash Safety Improvement,” in *Proceedings of the TMS Middle East — Mediterranean Materials Congress on Energy and Infrastructure Systems (MEMA 2015)*, I. Karaman, R. Arróyave, and E. Masad, Eds. Cham: Springer International Publishing, 2016, pp. 249–258. doi: 10.1007/978-3-319-48766-3_25.

[2] O. Dorival *et al.*, “Experimental study of impact energy absorption by reinforced braided composite structures: Dynamic crushing tests,” *Composites Part B: Engineering*, vol. 78, pp. 244–255, Sep. 2015, doi: 10.1016/j.compositesb.2015.03.083.

[3] S. Helaili, A. Guizani, F. Najar, and M. Chafra, “Novel Rebar Made from Epoxy and Braided Natural Alfa Fibers,” in *Design and Modeling of Mechanical Systems - V*, L. Walha, A. Jarraya, F. Djemal, M. Chouchane, N. Aifaoui, F. Chaari, M. Abdennadher, A. Benamara, and M. Haddar, Eds. Cham: Springer International Publishing, 2023, pp. 188–194. doi: 10.1007/978-3-031-14615-2_22.

[4] S. Helaili, T. Rezgui, A. Guizani, and F. Najjar, “Reinforcement of Load-Bearing Structural Elements by Curved Composite Plates Made from Braided Natural Fibers,” in *Design and Modeling of Mechanical Systems - V*, L. Walha, A. Jarraya, F. Djemal, M. Chouchane, N. Aifaoui, F. Chaari, M. Abdennadher, A. Benamara, and M. Haddar, Eds. Cham: Springer International Publishing, 2023, pp. 171–178. doi: 10.1007/978-3-031-14615-2_20.

[5] S. Helaili, M. Chafra, and Y. Chevalier, “Alfa Natural Fiber Composite Reinforcement for Concrete Beams,” *Civil Engineering and Architecture*, vol. 9, no. 6, pp. 1677–1686, Oct. 2021, doi: 10.13189/cea.2021.090602.

[6] M. R. Abdullah, A. Goharian, M. R. Abdul Kadir, and M. U. Wahit, “Biomechanical and bioactivity concepts of polyetheretherketone composites for use in orthopedic implants-a review: Biomechanical and Bioactivity Concepts of Peek,” *J. Biomed. Mater. Res.*, vol. 103, no. 11, pp. 3689–3702, Nov. 2015, doi: 10.1002/jbm.a.35480.

[7] S. Helaili, W. Mankai, and M. Chafra, “Pressure Calculation and Fatigue of a Trans-tibial Prosthetic Socket Made from Natural Fiber Composite,” in *Advances in Acoustics and Vibration III*, vol. 17, N. Feki, M. S. Abbes, M. Taktak, M. Amine Ben Souf, F. Chaari, and M. Haddar, Eds. Cham: Springer International Publishing, 2021, pp. 199–209. doi: 10.1007/978-3-030-76517-0_22.

[8] M. Wahbi, B. S. Brahim, C. Moez, B. C. Ridha, and A. Jomah, “Modeling of a Fatigue Test Performed on a Trans-Tibial Prosthetic Socket Made of Natural Fiber,” in *Design and Modeling of Mechanical Systems - IV*, Cham, 2020, pp. 204–213. doi: 10.1007/978-3-030-27146-6_22.

[9] S. Helaili, achref guizani, and moez chafra, “Natural Cellulosic Alfa fiber improved with environment-friendly treatment cementitious composites with a stable flexural strength,” In Review, preprint, Aug. 2022. doi: 10.21203/rs.3.rs-1459832/v1.

[10] S. Hamza, H. Saad, B. Charrier, N. Ayed, and F. Charrier-El Bouhtoury, “Physico-chemical characterization of Tunisian plant fibers and its utilization as reinforcement for plaster based composites,” *Industrial Crops and*

Products, vol. 49, pp. 357–365, Aug. 2013, doi: 10.1016/j.indcrop.2013.04.052.

[11] S. Belkhir, A. Koubaa, A. Khadhri, M. Ksontini, and S. Smiti, “Variations in the morphological characteristics of Stipa tenacissima fiber: The case of Tunisia,” *Industrial Crops and Products*, vol. 37, no. 1, pp. 200–206, May 2012, doi: 10.1016/j.indcrop.2011.11.021.

[12] K. Labidi, Z. Cao, M. Zrida, A. Murphy, A. H. Hamzaoui, and D. M. Devine, “Alfa fiber/polypropylene composites: Influence of fiber extraction method and chemical treatments,” *J Appl Polym Sci*, vol. 136, no. 18, p. 47392, May 2019, doi: 10.1002/app.47392.

[13] S. Garrouri, W. Lakhal, A. Benazzouk, and E. Sediki, “Potential use of Alfa fibers in construction material: Physico-mechanical and thermal characterisation of reinforced specimen,” *Construction and Building Materials*, vol. 342, p. 127787, Aug. 2022, doi: 10.1016/j.conbuildmat.2022.127787.

[14] Helaili Sofiene and Chafra Moez, “Identification of mechanical properties of a braided alfa stem (Stipa tenacissima L.) by an inverse method,” *Journal of Composite Materials*, Dec. 10, 2022.

[15] M. Lassoued, T. Mnasri, A. Hidouri, and R. Ben Younes, “Thermomechanical behavior of Tunisian palm fibers before and after alkalization,” *Construction and Building Materials*, vol. 170, pp. 121–128, May 2018, doi: 10.1016/j.conbuildmat.2018.03.070.

[16] R. Sana, J. Mounir, and M. Slah, “Study of Structure and Properties of Tunisian Typha Leaf Fibers,” *International Journal of Engineering Research*, vol. 3, no. 3, 2014.

[17] H. Naili, A. Jelidi, O. Limam, and R. Khiari, “Extraction process optimization of Juncus plant fibers for its use in a green composite,” *Industrial Crops and Products*, vol. 107, pp. 172–183, Nov. 2017, doi: 10.1016/j.indcrop.2017.05.006.

[18] F. Mannai, M. Ammar, J. G. Yanez, E. Elaloui, and Y. Moussaoui, “Cellulose fiber from Tunisian Barbary Fig ‘Opuntia ficus-indica’ for papermaking,” *Cellulose*, vol. 23, no. 3, pp. 2061–2072, Jun. 2016, doi: 10.1007/s10570-016-0899-9.

[19] S. Helaili, S. Bouajila, H. Kaddami, and M. Chafra, “Turbine Blade Made of Natural Fiber Composite Structural and Vibrational Behavior,” in *Design and Modeling of Mechanical Systems - V*, L. Walha, A. Jarraya, F. Djemal, M. Chouchane, N. Aifaoui, F. Chaari, M. Abdennadher, A. Benamara, and M. Haddar, Eds. Cham: Springer International Publishing, 2023, pp. 743–749. doi: 10.1007/978-3-031-14615-2_83.

[20] C. E. Bakis *et al.*, “Fiber-Reinforced Polymer Composites for Construction—State-of-the-Art Review,” *J. Compos. Constr.*, vol. 6, no. 2, pp. 73–87, May 2002, doi: 10.1061/(ASCE)1090-0268(2002)6:2(73).

[21] V. Mittal, R. Saini, and S. Sinha, “Natural fiber-mediated epoxy composites – A review,” *Composites Part B: Engineering*, vol. 99, pp. 425–435, Aug. 2016, doi: 10.1016/j.compositesb.2016.06.051.

[22] F. E. El-Abbassi, M. Assarar, R. Ayad, A. Bourmaud, and C. Baley, “A review on alfa fibre (Stipa tenacissima L.): From the plant architecture to the reinforcement of polymer composites,” *Composites Part A: Applied Science and Manufacturing*, vol. 128, p. 105677, Jan. 2020, doi: 10.1016/j.compositesa.2019.105677.

[23] M. Z. Naser, R. A. Hawileh, and J. A. Abdalla, “Fiber-reinforced polymer composites in strengthening reinforced concrete structures: A critical review,” *Engineering Structures*, vol. 198, p. 109542, Nov. 2019, doi: 10.1016/j.engstruct.2019.109542.

[24] Md. A. Alam and K. Al Riyami, “Shear strengthening of reinforced concrete beam using natural fibre reinforced polymer laminates,” *Construction and Building Materials*, vol. 162, pp. 683–696, Feb. 2018, doi: 10.1016/j.conbuildmat.2017.12.011.

[25] J. Gonzalez ‐ Julian, I. Kraleva, M. Belmonte, F. Jung, T. Gries, and R. Bermejo, “Multifunctional performance of Ti_2AlC MAX phase/2D braided alumina fiber laminates,” *J Am Ceram Soc*, vol. 105, no. 1, pp. 120–130, Jan. 2022, doi: 10.1111/jace.18043.

[26] F. de Francqueville, J. Diani, P. Gilormini, and A. Vandenbroucke, “Use of a micromechanical approach to understand the mechanical behavior of solid propellants,” *Mechanics of Materials*, vol. 153, p. 103656, Feb. 2021, doi: 10.1016/j.mechmat.2020.103656.

[27] R. M. Christensen, *Mechanics of composite materials*. Courier Corporation, 2012.

[28] P. H. Petit and M. E. Waddoups, “A Method of Predicting the Nonlinear Behavior of Laminated Composites,” *Journal of Composite Materials*, vol. 3, no. 1, pp. 2–19, Jan. 1969, doi: 10.1177/002199836900300101.

[29] K. Raju, T.-E. Tay, and V. B. C. Tan, “A review of the FE2 method for composites,” *Multiscale and Multidiscip. Model. Exp. and Des.*, vol. 4, no. 1, pp. 1–24, Mar. 2021, doi: 10.1007/s41939-020-00087-x.

[30] N. Song *et al.*, “USING MULTISCALE MODELING TO ADVANCE INDUSTRIAL AND RESEARCH APPLICATIONS OF ADVANCED MATERIALS,” *Int J Mult Comp Eng*, 2021, doi: 10.1615/IntJMultCompEng.2021039707.

[31] Berthelot, J. M., *Mécanique des matériaux et structures composites.* Institut Supérieur des Matériaux et Mécaniques Avancés., 2010.

[32] S. Helaili and M. Chafra, “Anisotropic visco-elastic properties identification of a natural biodegradable ALFA fiber composite:,” *Journal of Composite Materials*, Jun. 2013, doi: 10.1177/0021998313488811.

[33] S. Helaili, M. Chafra, and Y. Chevalier, “Natural fiber alfa/epoxy randomly reinforced composite mechanical properties identification,” *Structures*, vol. 34, pp. 542–549, Dec. 2021, doi: 10.1016/j.istruc.2021.07.095.

[34] M. Chafra, H. Smaoui, and D. Ben Arfa, “Identification of Mechanical Properties and Damage of Composites at the Mesoscale based on an Inverse Method Coupled with Homogenization,” *Journal of Composite Materials*, vol. 44, no. 5, pp. 529–541, Mar. 2010, doi: 10.1177/0021998309346187.