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TRANSFORMING EDUCATION, DRIVING INNOVATION AND
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COMPOSITE MICROMECHANICAL ANALYSIS LEARNING TOOL (CMALT)

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ABSTRACT

Micromechanical analysis is essential for predicting the effective stiffness of composite laminas based on fiber and matrix properties. However, the mathematical complexity of models such as the Rule of Mixtures, used to calculate longitudinal (E_1) and transverse (E_2) moduli, often presents difficulties for undergraduate learners. To address this educational gap, the Composite Micromechanical Analysis Learning Tool (CMALT) was developed as an interactive web-based platform aimed at enhancing understanding of composite behavior through real-time simulation. Built using Python and Streamlit, CMALT enables users to input the elastic moduli of constituent materials and fiber volume fraction to compute E_1 and E_2 using established micromechanical equations. The tool features dual case study comparisons, predefined material presets, graphical visualization, and immediate numerical output to support interactive exploration of composite configurations. Validation against analytical calculations showed complete agreement, confirming the tool's computational accuracy. With its clean interface, browser-based accessibility, and integration of theoretical concepts with simulation, CMALT offers a practical solution for improving teaching and learning in composite mechanics. Future developments may include support for advanced micromechanical models, additional property calculations, and exportable results to further enhance its academic and research applications.

Keywords: Composite materials, Micromechanics, Elastic modulus, Rule of Mixtures

INTRODUCTION

Understanding the micromechanical behavior of composite materials is essential in modern engineering education and practice. As composites continue to replace conventional materials across a wide range of industries, the ability to predict and tailor their mechanical properties becomes a critical skill for engineering students (Reddy, Kumar, & Ramesh, 2022; Thakur & Patel, 2021). Micromechanics provides the foundation for analyzing how individual constituents such as fibers and matrix interact to form a composite lamina with specific stiffness and strength properties. This knowledge is vital for

designing lightweight, high-performance structures used in aerospace, automotive, marine, biomedical, and civil applications (Chawla, 2019; Daniel & Ishai, 2006). Despite its importance, micromechanics is often perceived as a challenging subject among undergraduate students due to its mathematical complexity and abstract theoretical models. Many struggle to visualize how changes in material properties and volume fractions affect the overall elastic behavior of composites, particularly when computing longitudinal (E_1) and transverse (E_2) moduli using analytical methods such as the Rule of Mixtures (Kaw, 2021). This learning gap can hinder students' ability to apply composite design principles in practical contexts, reducing their confidence and engagement in material science courses. To address these challenges, interactive learning tools play a pivotal role in bridging theory and application. By integrating simulation and visualization into the learning process, such tools enhance students' conceptual understanding and foster independent exploration of composite behavior. The Composite Micromechanical Analysis Learning Tool (CMALT) was developed in response to this need. CMALT is a web-based application that enables users to input fiber and matrix properties, calculate E_1 and E_2 , and observe how different combinations influence composite stiffness. Developed using Python and Streamlit, it supports structured case scenarios with real-time output, making micromechanical concepts more accessible and intuitive. As industries increasingly rely on composite materials and design optimization, proficiency in micromechanics is becoming a sought-after competency among engineering graduates. Tools like CMALT not only support academic instruction but also prepare students for advanced study and research in material engineering, structural analysis, and composite manufacturing. Equipping learners with such tools fosters deeper understanding, better retention, and stronger readiness to tackle engineering challenges involving advanced material systems.

METHODS

The development of the Composite Micromechanical Analysis Learning Tool (CMALT) involved a structured, iterative approach that integrates both frontend interactivity and backend computational logic to effectively support student learning in micromechanics. The core architecture of CMALT is built using Python as the main programming language and Streamlit as the framework for creating an interactive web-based graphical user interface (GUI). This choice of technology allows for rapid prototyping, cross-platform compatibility, and intuitive deployment without requiring local software installation. The GUI is designed to be clean and user-friendly, featuring dedicated input fields for fiber modulus, matrix modulus, and fiber volume fraction, along with clearly labeled case selection options to guide users through various predefined composite material scenarios. Upon submission of the input values, the tool computes the longitudinal modulus (E_1) and transverse modulus (E_2) using the Rule of Mixtures, with instant numerical output rendered directly within the interface to facilitate real-time learning and analysis. The longitudinal modulus of the composite is calculated using the Rule of Mixtures, expressed as:

$$E_1 = E_f V_f + E_m V_m \quad (1)$$

where E_1 is the longitudinal modulus of the composite, E_f is the modulus of the fiber, E_m is the modulus of the matrix, V_f is the volume fraction of the fiber, and $V_m = 1 - V_f$ is the volume fraction of the matrix. The transverse modulus is calculated using the inverse Rule of Mixtures:

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} \quad (2)$$

where E_2 is the transverse modulus of the composite. These equations, shown in Equation (1) and Equation (2), form the theoretical foundation for CMALT's internal calculation engine and ensure that the computed values reflect established micromechanical modeling principles. The overall system architecture follows a logical and linear flow, beginning with user input, followed by automatic validation, backend computation, and visual display of results, as illustrated in Figure 1. This seamless interaction sequence promotes an intuitive and engaging learning experience by allowing users to observe how changes in constituent properties affect the stiffness of composite lamina. To ensure data integrity and computational accuracy, error handling mechanisms and validation routines are embedded throughout the interface to prevent incomplete or invalid entries from being processed. The lightweight and accessible nature of CMALT makes it especially suited for integration into academic environments. To enable flexible deployment, version control, and collaborative development, the full application is hosted on GitHub. Furthermore, the final tool is deployed publicly using Streamlit Cloud, making it accessible to students, educators, and researchers worldwide from any device with an internet connection.

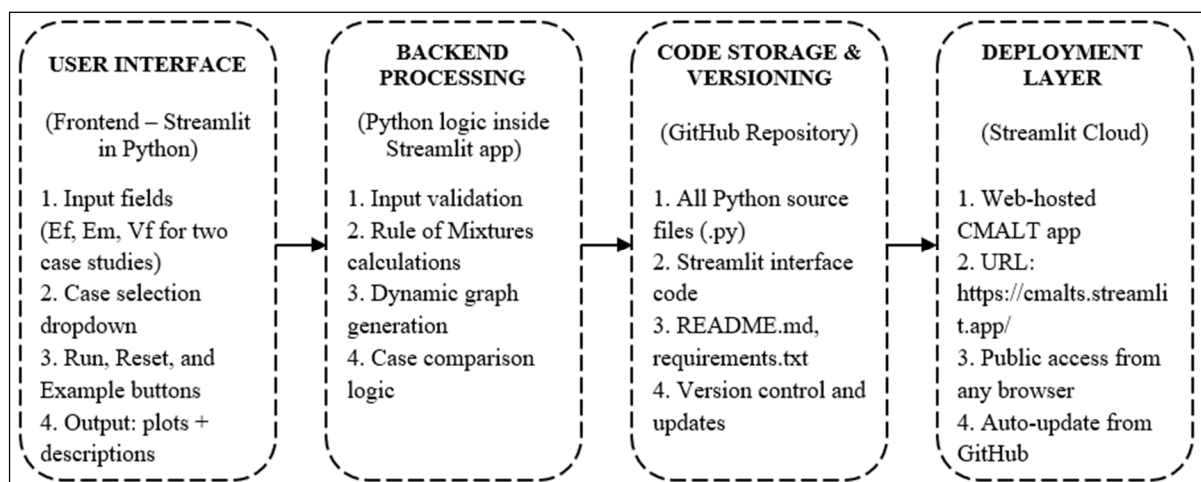


Figure 1.: CMALT System Workflow

Table 1 summarizes the technology stack used in the development of CMALT, highlighting the key components and their respective functions in ensuring the tool’s operational efficiency and educational value. Each element plays a distinct role in delivering a seamless and interactive user experience. Streamlit serves as the frontend framework that facilitates the development of the graphical interface, enabling the creation of input fields, buttons, and controls that guide users through the tool with minimal effort. Python, combined with numerical libraries such as NumPy, manages the backend logic responsible for performing accurate calculations of the longitudinal and transverse moduli using the

Rule of Mixtures. GitHub functions as the central platform for version control and documentation storage, supporting both development and future scalability. Lastly, the deployment of CMALT on Streamlit Cloud ensures that the application is easily accessible via a public URL without requiring any local installation. The integration of these technologies allows CMALT to remain robust, responsive, and adaptable for use in both classroom instruction and independent learning.

Table 1.: Technology Stack Used in the Development of CMALT

Component	Technology Used	Description
Frontend	Streamlit (Python)	User interface, buttons, inputs
Backend	Python (with NumPy, etc.)	Rule of Mixtures logic, validation
Visualization	Matplotlib / Plotly	Optional graphs, E_1 vs V_f
Code Hosting	GitHub	All source code and documentation
App Deployment	Streamlit Cloud	Public link for users to access CMALT

RESULTS AND DISCUSSION

The user interface of the Composite Micromechanical Analysis Learning Tool (CMALT) is structured to guide users through input and output processes efficiently, as shown in Figure 2. The interface provides clearly labeled fields for entering fiber and matrix properties and delivers immediate results for the longitudinal modulus (E_1) and transverse modulus (E_2) upon execution. Users can select predefined cases or manually input custom values, allowing flexibility in exploring different composite configurations. The streamlined layout ensures ease of navigation, making the tool accessible even to first-time users with minimal technical background.

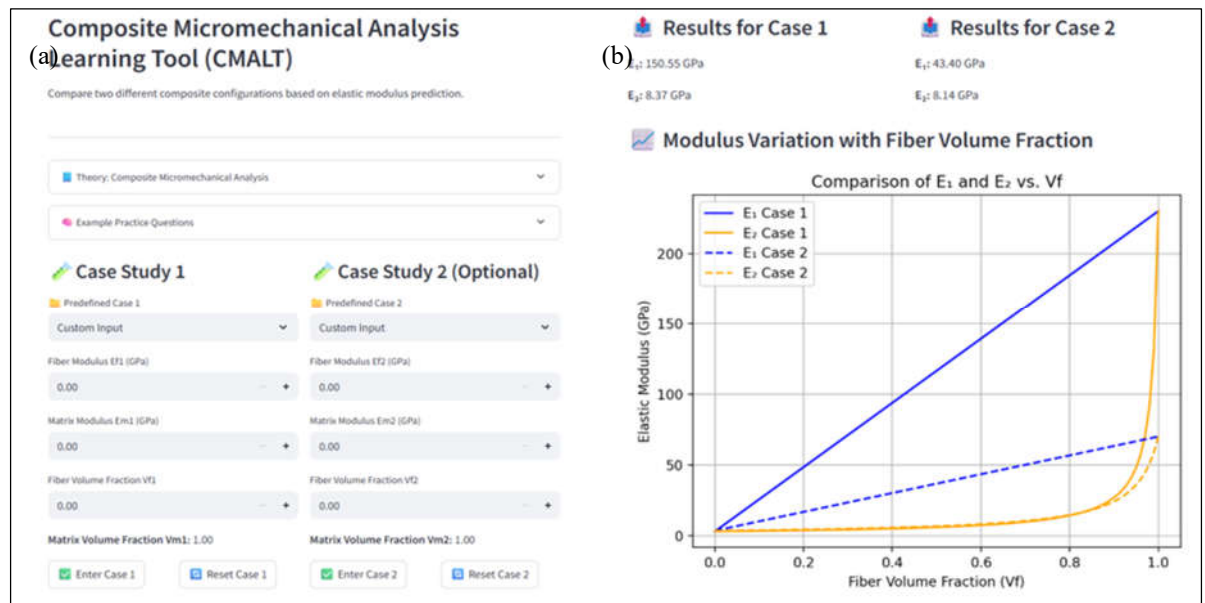


Figure 2.: CMALT User Interface: (a) Before Execution, (b) After Execution

To evaluate the accuracy of CMALT, two case studies were performed and compared against theoretical calculations using the Rule of Mixtures. In Case Study 1, the input parameters were a fiber modulus of 240 GPa, a matrix modulus of 3 GPa, and a fiber volume fraction of 0.6. In Case Study 2, the fiber modulus was 70 GPa, the matrix modulus was 5 GPa, and the fiber volume fraction was 0.5. Analytical values were manually calculated, while CMALT was used to generate numerical outputs. Table 2 presents a side-by-side comparison between the analytical results and CMALT outputs. Both case studies show complete agreement between the values, with a 0% error recorded. This confirms the computational reliability of CMALT in evaluating micromechanical stiffness properties of composite laminas. The consistency and accuracy of the tool's outputs further support its effectiveness as an interactive learning platform for understanding composite material behavior.

Table 2. Comparison of the Results of CMALT with the Theoretical Calculation

Case Study	Variable (GPa)	Analytical (GPa)	CMALT (GPa)	Error (%)
Case 1	Longitudinal modulus, E_1	145.20	145.20	0
	Transverse modulus, E_2	7.36	7.36	0
Case 2	Longitudinal modulus, E_1	37.50	37.50	0
	Transverse modulus, E_2	9.33	9.33	0

CONCLUSION

The Composite Micromechanical Analysis Learning Tool (CMALT) serves as an effective and user-friendly educational platform for enhancing understanding of composite material behavior at the micromechanical level. By allowing users to input fiber and matrix properties and instantly compute the longitudinal (E_1) and transverse (E_2) moduli using the Rule of Mixtures, CMALT bridges theoretical learning with interactive application. The accuracy of its computational engine, validated against analytical solutions with 0% error, reinforces its reliability for both instructional and self-directed learning purposes. From an educational perspective, CMALT addresses key challenges in teaching micromechanics by offering a visual, intuitive, and parameter-driven interface that supports various learning styles. Its real-time feedback mechanism helps learners directly observe the impact of fiber volume fraction and material properties on composite stiffness, promoting active exploration of micromechanical concepts. The lightweight web-based design, built using Python and Streamlit, ensures accessibility across platforms without requiring installation, making it a valuable tool for integration into undergraduate composite materials courses, online modules, or laboratory settings. The broader implications of CMALT lie in its demonstration of how interactive learning tools can demystify abstract engineering principles. By embedding theoretical equations such as the Rule of Mixtures (Equations 1 and 2) into a responsive digital environment, CMALT highlights the pedagogical benefits of simulation-assisted instruction. Its open-source availability on GitHub and public deployment on Streamlit Cloud exemplify scalable, collaborative educational design aligned with modern engineering education practices. Looking ahead, future iterations of CMALT could incorporate more advanced micromechanical models, such as Halpin-Tsai or Mori-Tanaka methods, and extend support to other mechanical properties including shear modulus and Poisson's ratio. Additional features like graphical plotting of moduli trends, multi-case comparisons, and exportable result summaries could further elevate its instructional value. Integrating CMALT with learning management systems (LMS) or interactive quizzes would also enable structured assessments and classroom use. With continued development, CMALT holds strong potential to evolve into a comprehensive educational resource that fosters deeper comprehension of composite mechanics across academic and professional domains.

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