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e-Stress3D: A Web-Based Educational Tool for Interactive 3D Stress Tensor Visualization in Solid Mechanics

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Abstract. We present *e-Stress3D*, a web-based educational tool designed to enhance the learning of Solid Mechanics in undergraduate and graduate engineering curricula. The application enables interactive visualization of the 3D stress tensor, integrating mathematical formulations with graphical representations. Key features include stress decomposition into isotropic and deviatoric components with their invariants, a dedicated module for Cauchy traction vector analysis on arbitrary planes, visualization of principal stresses, and construction of the 3D Mohr's circle. The platform supports real-time manipulation of input parameters and provides immediate visual feedback. This interactivity promotes a deeper and more intuitive understanding of fundamental concepts. Overall, the tool contributes to the growing integration of digital tools in engineering education, responding to the increasing demand for more engaging and effective pedagogical approaches.

Keywords: Stress tensor visualization, Solid mechanics, Teaching tools, Interactive learning, Engineering education.

1 Introduction

Solid Mechanics is among the most challenging courses in undergraduate and graduate engineering programs, primarily due to the inherent complexity of stress analysis concepts. The study of the stress tensor, with its mathematical and graphical representations, is a fundamental pillar of this discipline and essential for understanding material behavior under various loading conditions.

Although there are some tools aimed at two-dimensional stress analysis, especially those focused on the construction of Mohr's circle, as described by Ressler [1], Mokaddem and Moller [2], Moller and Mokaddem [3], Pallares-Muñoz and Rodríguez-Calderón [4] and Martha [5], there is a significant lack of resources that enable interactive visualization of three-dimensional stress tensors. Furthermore, available solutions, such as the one proposed by Hennessey and Hacker [6], usually require installation on desktop environments and depend on additional software, such as mathematical or graphical computing programs, which limits their accessibility in educational contexts.

In light of this scenario, this work presents *e-Stress3D*, a web-based application developed to support the learning of Solid Mechanics, with emphasis on stress analysis, in undergraduate and graduate engineering courses. The proposed solution addresses this educational gap by offering an accessible, interactive platform aligned with current demands for digital learning resources.

2 Tool Architecture

e-Stress3D was developed as a client-side web application, aiming for maximum accessibility and ease of use, without requiring additional software installation. The application is built using *TypeScript*, which provides greater robustness, security, and facilitates code maintenance. An overview of the tool's homepage is presented in Fig. 1.

The interface is implemented with *React*, enabling a dynamic and responsive user experience. For graphical data visualization, specialized libraries are used: *Three.js*, for rendering and manipulating 3D objects, and *Plotly* for generating interactive 2D and 3D graphs.

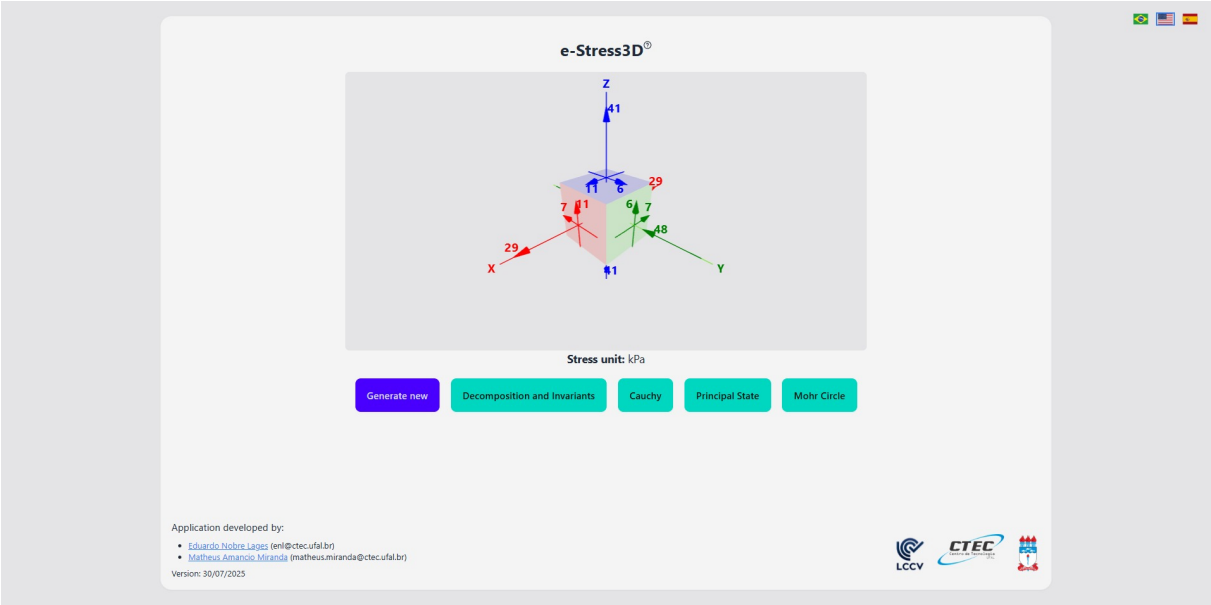


Figure 1. *e-Stress3D* homepage

This web-based architecture ensures the tool is multiplatform, accessible from any device with a modern browser, and eliminates barriers related to installing and configuring complex computational environments.

3 Key Features

e-Stress3D was designed to offer a comprehensive set of features that allow students and professionals to interactively explore and understand fundamental concepts of 3D stress analysis. Each module integrates mathematical formulations with intuitive graphical representations, promoting deeper and more engaging learning. The main features are detailed in the following subsections.

3.1 Interactive 3D Stress Tensor Visualization

This core module of the tool allows users to dynamically explore the three-dimensional stress tensor. Users can generate a random stress tensor for quick experimentation or manually input the six independent components. The tool supports input in various stress units, such as pascal (Pa), kilopascal (kPa), megapascal (MPa), gigapascal (GPa), bar, and pounds per square inch (psi), providing flexibility and applicability to various engineering scenarios.

3.2 Stress Decomposition

The decomposition of the stress tensor into isotropic and deviatoric components is one of the key topics presented in stress analysis, as described by Sadd [7] and Reddy [8]. The stress tensor $\boldsymbol{\sigma}$ can be expressed as the sum of an isotropic component, $\boldsymbol{\sigma}_m$, and a deviatoric component, $\boldsymbol{s}$. The isotropic component is defined by eq. (1), considering a Cartesian coordinate system with axes x, y and z. In isotropic materials, the isotropic component governs volumetric change around a material point, whereas the deviatoric component governs shape (distortional) change, as discussed by Sadd [7].

$$\boldsymbol{\sigma}_m = \begin{bmatrix} \sigma_m & 0 & 0 \\ 0 & \sigma_m & 0 \\ 0 & 0 & \sigma_m \end{bmatrix}; \qquad \sigma_m = \frac{\sigma_{\mathrm{xx}} + \sigma_{\mathrm{yy}} + \sigma_{\mathrm{zz}}}{3}. \tag{1}$$

The deviatoric component is obtained as shown in eq. (2):

$$\boldsymbol{s} = \boldsymbol{\sigma} - \boldsymbol{\sigma}_m. \tag{2}$$

Associated with the stress tensor and its components are scalar quantities, known as invariants, which encode intrinsic information about the stress state at a material point; by construction, their magnitudes are independent of the chosen reference frame. The tool provides interfaces that present both graphical and mathematical representations of the stress tensor decomposition and invariants.

3.3 Cauchy Traction Vector Analysis

The analysis of the traction vector ($\boldsymbol{t}$) on an arbitrary plane is based on Cauchy's formula, which relates the stress tensor $\boldsymbol{\sigma}$ to a unit normal vector $\boldsymbol{n}$ through the eq. (3):

$$\boldsymbol{t} = \boldsymbol{\sigma}^{\mathrm{T}}\boldsymbol{n}. \tag{3}$$

In the tool, the unit normal vector $\boldsymbol{n}$ is defined interactively by the user using azimuth and polar angles, allowing for intuitive selection of the plane orientation, as shown in Fig. 2. The interface allows graphical manipulation of the traction and normal vectors, visualized in 3D on a supporting solid constructed using the convex hull technique. The tool also computes and displays the normal and tangential components of the traction vector, as well as the corresponding values of normal stress and shear stress on the selected plane. This module enables a comprehensive understanding of how the state of stress varies with the orientation of the plane within the material.

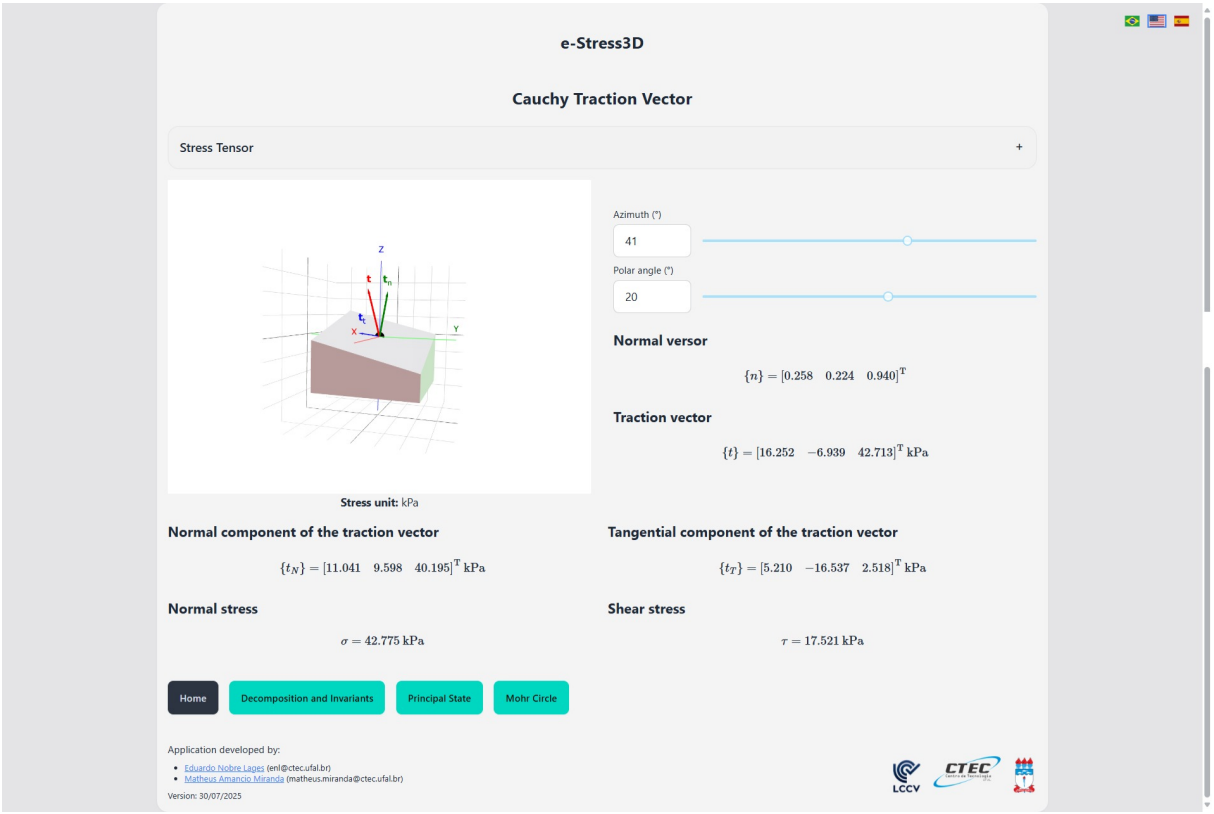


Figure 2. Cauchy traction vector page

3.4 Principal Stresses and Directions

The stress state at a material point can be simplified by identifying three mutually orthogonal directions, called principal directions, where shear stresses are zero. The normal stresses acting on these planes are the principal stresses, representing the maximum, intermediate, and minimum normal stresses. Determining these principal stresses and directions is an eigenvalue problem, as stated in eq. (4), where the principal stresses are the eigenvalues of the stress tensor, and the principal directions are its corresponding eigenvectors.

$$\left(\boldsymbol{\sigma}^{\mathrm{T}} - \sigma\mathbf{I}\right)\boldsymbol{n} = \mathbf{0}. \tag{4}$$

3.5 3D Mohr's circle

After determining the three principal stresses, it is possible to view the principal stress state using the 3D Mohr's circle. This graphical tool allows for a clear visualization of the relationships between the principal stresses, facilitating the analysis of failure criteria as well as stress transformations on different planes.

4 Conclusions and Future Work

e-Stress3D is a web-based educational tool designed to enhance teaching and learning of three-dimensional stress analysis in engineering curricula. By integrating mathematical formulations with interactive visualizations, it addresses the lack of accessible and intuitive resources for exploring complex stress states, including stress decomposition, principal stresses, the 3D Mohr's circle, and Cauchy traction vector analysis.

Deployed successfully over two semesters in an undergraduate Solid Mechanics course, *e-Stress3D* has been actively used by students for review and deeper conceptual understanding, with ongoing improvements driven by user feedback. Future work includes adding modules for coordinate transformations of the stress tensor to visualize component changes under rotated frames, and conducting comprehensive user studies to quantify the tool's pedagogical impact compared to traditional methods. For practical application and further exploration, the tool is openly accessible at: `https://e-stress3d.vercel.app/`.

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