

Computational Mechanics of Heterogeneous Materials and Structures

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The research group of Prof. Pindera focuses on the development of novel computational approaches and related user-friendly GUI's (Graphical User Interfaces) for modeling and simulation of the response of materials with complex microstructures across multidisciplinary boundaries. The applications range from advanced aerospace engine components, multilayered laminates, asphalt and concrete, to biological tissues.

Prof. Pindera and his students collaborate closely with Prof. Marques and his group of the Federal University of Alagoas in Maceio, Brazil, on the development of these novel computational theories and ensuing algorithms. While the activities at the University of Virginia focus on materials with periodic microstructures, the activities at the Federal University of Alagoas focus on the response of complex microstructure structural components. The common aspects of the already developed and developing computational approaches provide the necessary synergism that enables applications at both the material and structural levels across interdisciplinary boundaries.

Materials with Periodic Microstructures

The parametric finite-volume direct averaging micromechanics (FVDAM) theory has been developed to predict elastic and inelastic response of materials with periodic microstructures characterized by arbitrary architectures shown in the figure below.

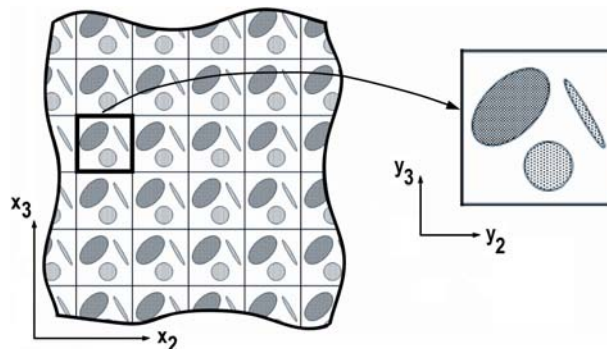


Fig. 1 - A periodic material with unidirectional reinforcement along the out-of-plane direction characterized by the fundamental building block, or the unit cell, shown on the right with an arbitrary internal architecture (Ref. [1]).

The different material classes modeled thus far include:

- 1) traditional unidirectionally-reinforced composites
- 2) multilayers with wavy architectures
- 3) porous materials, including perforated plates

The theory offers a number of advantages over the traditional finite-element approach. Further, it is very accurate in predicting both the homogenized moduli and local stress fields. Hence it can be used for material design, structural optimization and failure analysis. Its theoretical framework is fully analytical, and thus it can be easily adapted to a particular application. Examples of the theory’s predictive capabilities for the above three material types are given below:

- **Unidirectionally-reinforced composites**

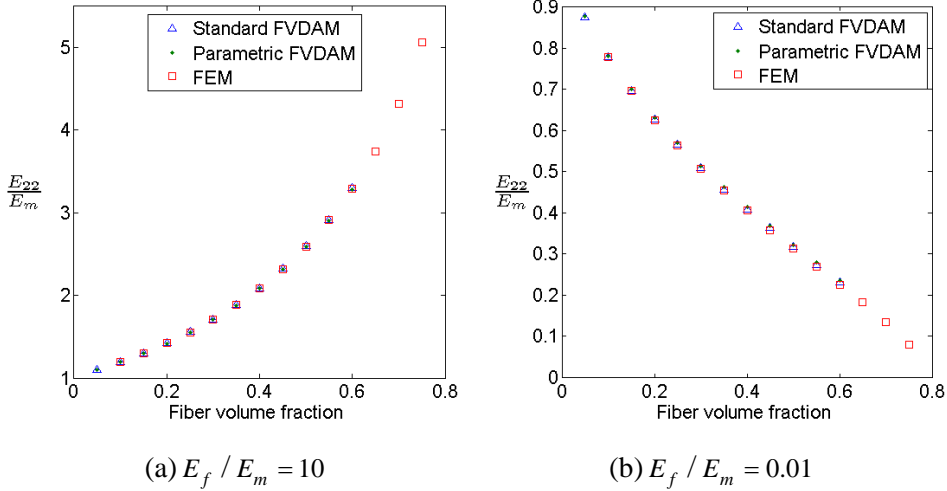


Fig. 2 - Comparison of the transverse Young’s modulus predicted by the FVDAM theory with finite-element calculations for a fiber/matrix composite with stiff and soft fibers (Ref. [5]).

- **Multilayers with wavy architectures**

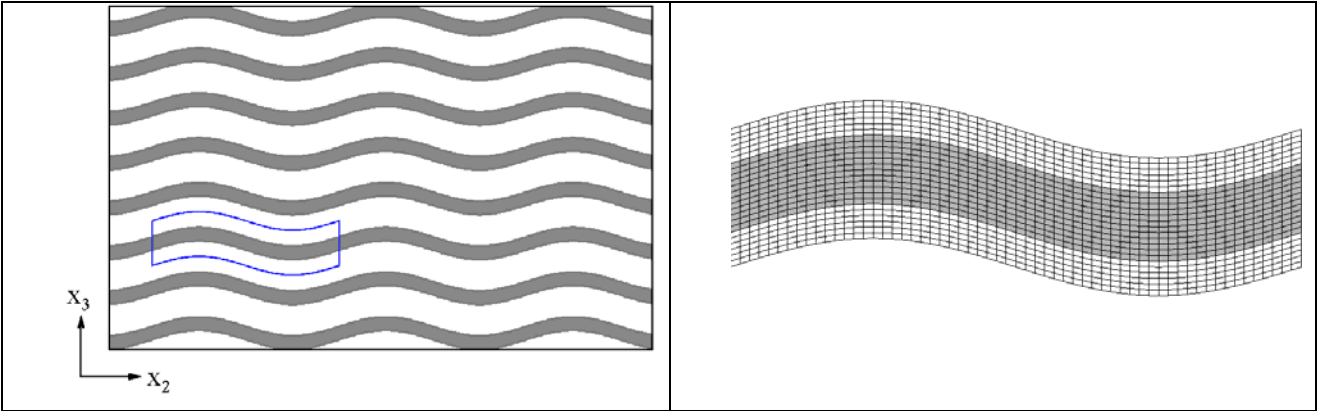


Fig. 3 - A wavy lamellar material with a highlighted unit cell of the periodic microstructure (left); detailed unit cell representation of the lamellar material (right), (Ref. [7,9]).

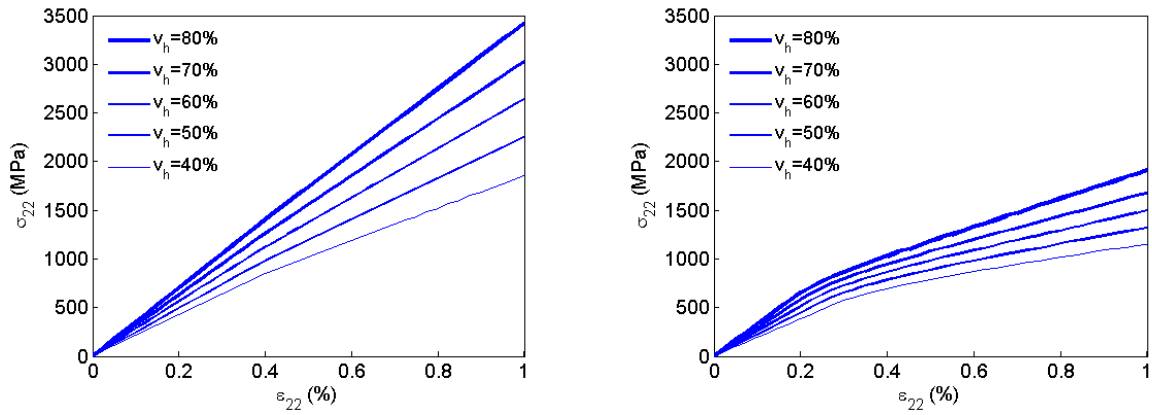


Fig. 4 - Macroscopic stress-strain response of reference flat (left) and wavy (right) periodic multilayers subjected to loading by $\bar{\sigma}_{22} \neq 0$, demonstrating synergistic effects of ply waviness and plasticity (Ref. [9]).

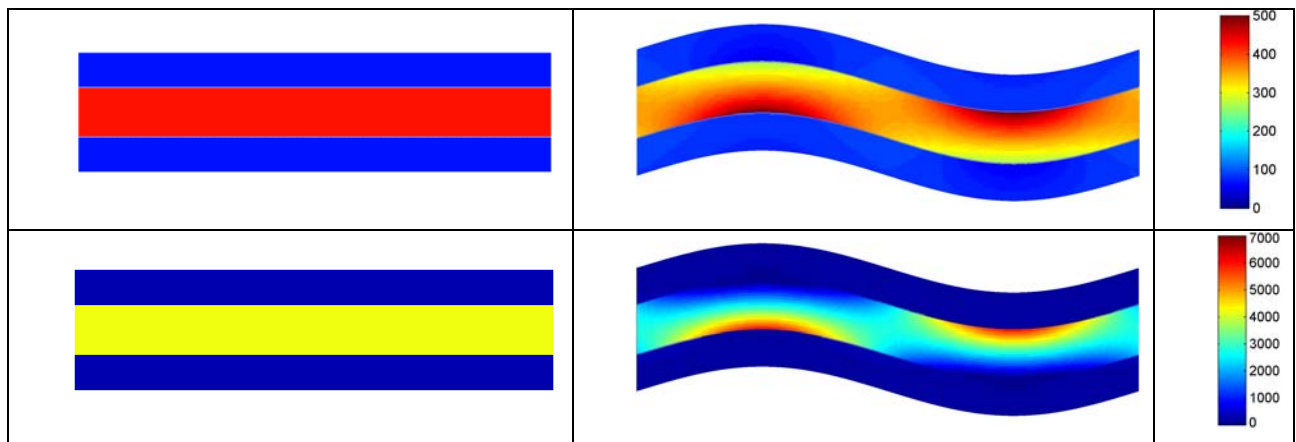


Fig. 5 - Elastic (top) and elastic-plastic (bottom) σ_{22} stress distributions in flat and periodic wavy multilayers subjected to loading by $\bar{\sigma}_{22} \neq 0$ at $\bar{\epsilon}_{22} = 0.1\%$ (top) and $\bar{\epsilon}_{22} = 1.0\%$ (bottom), (Ref. [9]).

- **Perforated plates**

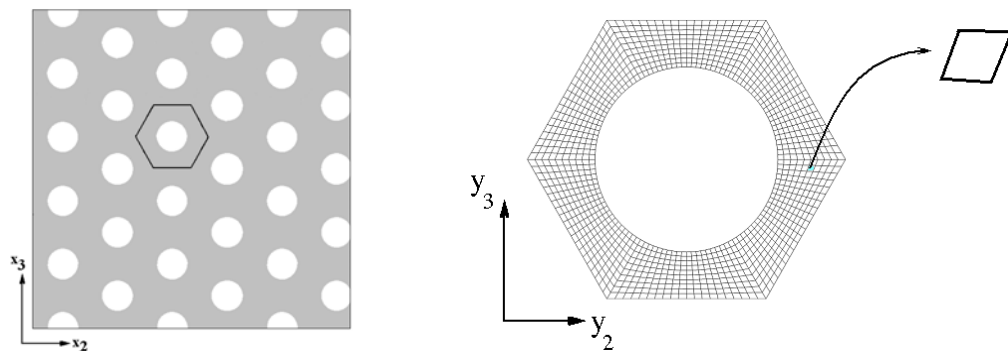


Fig. 6 - Hexagonal array of circular holes showing a highlighted unit cell (left), and discretization of the unit cell using quadrilateral subvolumes (right), (Ref. [10]).

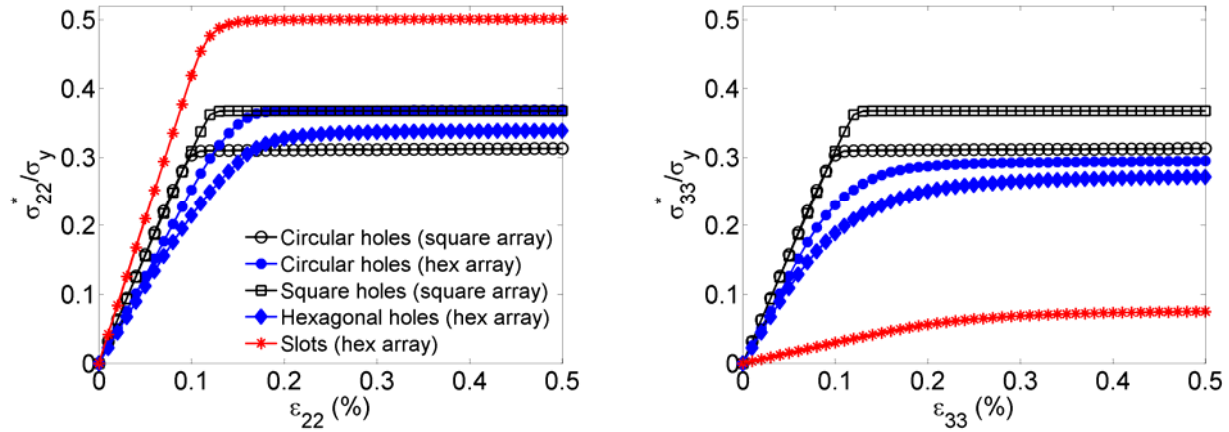


Fig. 7 - Comparison of the macroscopic stress-strain response of five perforated steel plate architectures containing 0.40 porosity fraction under uniaxial loading by $\bar{\sigma}_{22} \neq 0$ (left) and $\bar{\sigma}_{33} \neq 0$ (right), (Ref. [10]).

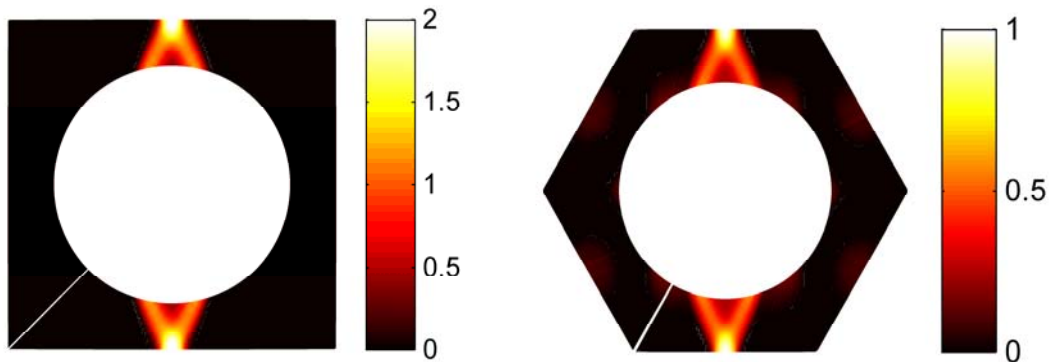


Fig. 8 - Effective plastic strain distributions in unit cells with circular holes containing 0.40 porosity volume fraction subjected to loading by $\bar{\sigma}_{22} \neq 0$, showing the effect of porosity array on plastic strain localization: square array (left) and hexagonal array (right), (Ref. [10]).

Structural Components with Heterogeneous Architectures

The structural version of the parametric finite-volume theory for functionally graded materials developed by Mr. Cavalcante and Prof. Marques of the Federal University of Alagoas enables analysis and optimization of material microstructures of structural components, including performance enhancement through grading. It has been used to analyze the source of failures in thermal barrier coatings and optimize the deflection of plates subjected to thermal loading, among others. The example presented below demonstrates the response of a layered cylinder subjected to a concentrated transient thermal load used to determine the durability of ceramic coatings deposited onto metallic substrates for advanced aerospace applications. The stress distributions during instantaneous heating and cooling portions of a heat up-hold-cool down cycle demonstrate the possibility of horizontal delamination during the heat up portion, and surface cracking during the cool down portion of the cycle. Grading of the top coat/bond coat layers may potentially mitigate these failure modes.

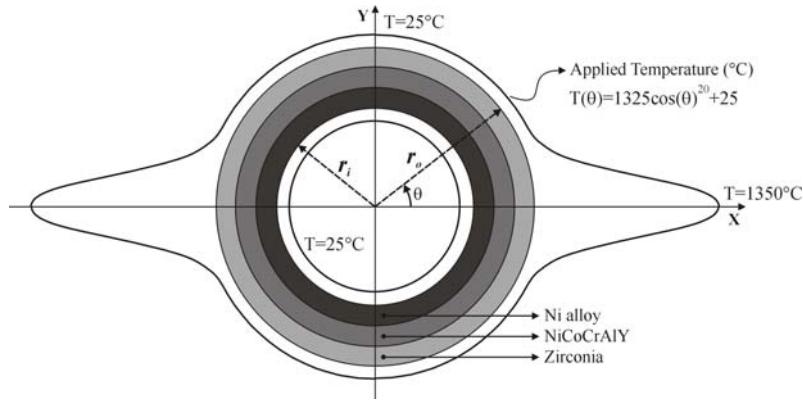


Fig. 9 – A layered tube subjected to a concentrated transient thermal cycle (Ref. [8])

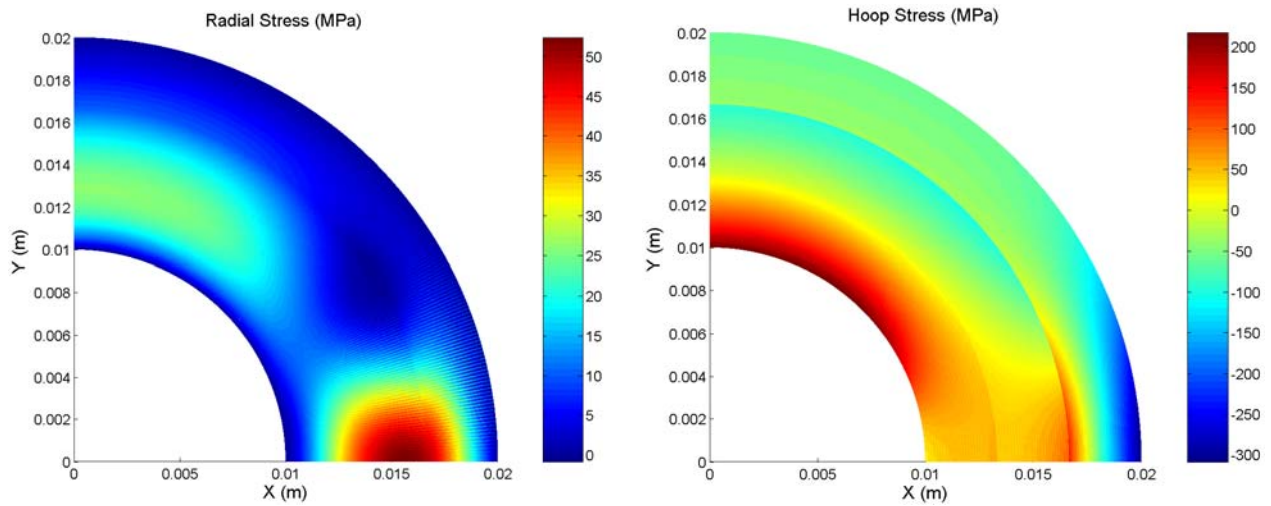


Fig. 10 – Steady-state $\sigma_{rr}(r, \theta)$ (left) and $\sigma_{\theta\theta}(r, \theta)$ (right) stress distributions at 52 seconds of a heat up-hold-cool down cycle (Ref. [8]).

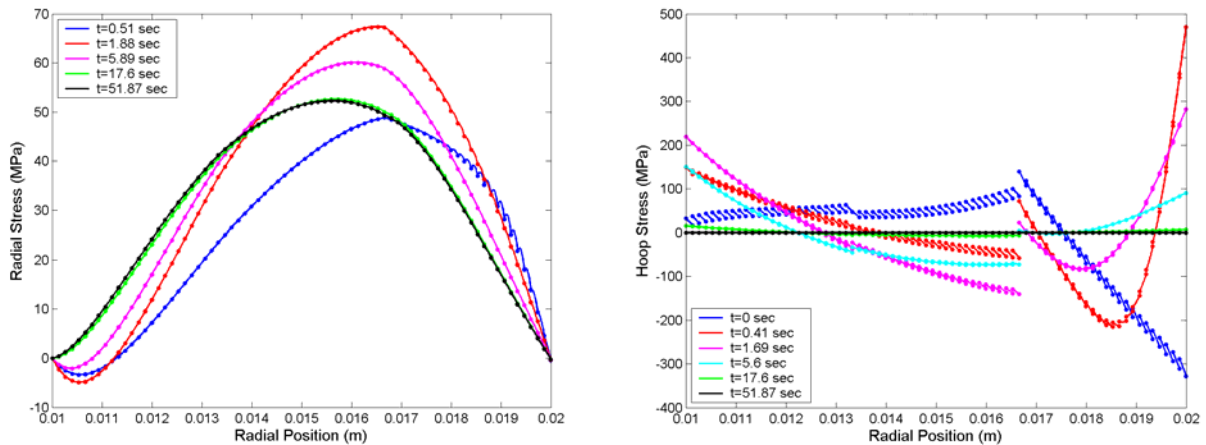


Fig. 11 – Evolution of the radial stress $\sigma_{rr}(r, \theta = 0^\circ)$ (left) and hoop stress $\sigma_{\theta\theta}(r, \theta = 0^\circ)$ (right) with time in the 0-deg cross section of the cylinder during instantaneous heating and cooling, respectively, demonstrating the potential for two distinct failure modes during different portions of the cycle (Ref. [8]).

Related References

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