

## **“Nonlinear analysis of hyperelastic materials and structures using higher-order finite elements”**

In continuum mechanics, hyperelastic materials are used to describe solids that can undergo large, fully elastic, recoverable deformations. These materials are increasingly adopted across multiple engineering fields for their unique mechanical properties, including enhanced flexibility, resilience, and energy absorption. In aerospace and mechanical engineering, these materials are adopted in the design of deployable and adaptive structures, such as inflatable components, seals, and damping elements, which must maintain reliability under extreme conditions. In civil engineering, elastomeric bearings and seismic vibration isolators exploit the nonlinear damping properties of soft materials to mitigate dynamic effects on structures. In particular, hyperelastic materials are widely used in biomedical engineering for modeling soft biological tissues, such as arterial walls, tendons, and ligaments, enabling mechanical characterization for the design and testing of medical implants, prosthetics, and tissue-engineered devices.

The present research is devoted to the development and implementation of refined high-order finite element models for the static, linearized modal, and three-dimensional stress analysis of isotropic and fiber-reinforced hyperelastic structures. The proposed formulation is capable of handling both compressible and nearly incompressible material behaviors, analyzing either the behavior of classical isotropic and multilayered structures, and extending the proposed methodology to the numerical simulations of anisotropic biological tissues. The adopted nonlinear constitutive law is rigorously within the classical continuum mechanics framework, providing a thermodynamically consistent description of stress–strain relationships under finite deformation. The governing equations of the elasto-dynamic problems at finite strain are derived from variational principles under a Total Lagrangian approach, including classical linearization arguments, and solved using incremental-iterative schemes based on the Newton-Raphson method.

The proposed finite element approach based on higher-order structural modeling is implemented within the well-established Carrera Unified Formulation (CUF), which provides a compact, hierarchical, and efficient framework for structural analysis. The CUF provides a unified formalism for beam, plate, and shell theories of structures, allowing the definitions of the governing equations in matrix form in terms of a few elementary building blocks known as Fundamental Nuclei (FN). This recursive notation allows the straightforward implementation of any refined finite element model, independent of the structural approximation theory adopted, thereby improving flexibility, consistency, and generality. The proposed nonlinear formulation incorporates the full three-dimensional kinematics required for large-strain analysis while maintaining accuracy and computational efficiency.

The versatility and robustness of the developed computational framework are demonstrated by performing extensive comparisons with analytical solutions, available numerical results, and experimental data from the literature. Several benchmark problems and case studies are presented, including isotropic and anisotropic beam and plate multilayered structures subjected to finite strain. The results demonstrate the capabilities of the proposed higher-order approach to simulate complex three-dimensional problems in both compressible and nearly-incompressible regimes. Overall, the proposed high-order finite element approach provides a novel, efficient computational tool for the nonlinear analysis of hyperelastic materials and structures. This research advances the numerical simulation of soft material structures by relying on physically consistent analyses in engineering design, material characterization, and biomechanics.