MSc Eng. Mikołaj Miecznikowski
(professional title, name)

Doctoral School No. 5
(Faculty/Unit)

Warsaw University of Technology
(University)

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ABSTRACT OF THE DISSERTATION

„Application of Artificial Intelligence in Hyperelastic Constitutive Modeling"

dissertation supervisor: DSc Eng. Marcin Gajewski, Prof. WUT

This dissertation concerns the constitutive modeling of hyperelastic materials using machine learning methods supplemented with the constraints of continuum mechanics. Although the work falls within the field of civil engineering, it combines topics of artificial intelligence with classical continuum mechanics. The thesis adopted herein is that incorporating physical constraints into machine learning models is a necessary condition for the correct — physically admissible and extrapolation-capable — reproduction of constitutive relations, and that such physically constrained models make it possible both to discover these relations and to solve boundary value problems, as well as to identify material parameters solely on the basis of displacement data and support reaction forces.

The starting point is a study of classical supervised machine learning methods. Of the thirteen algorithms examined, none met the requirements for constitutive modeling without introducing domain knowledge. Moreover, it was shown that the typical metrics (RMSE, R^2) neither account for satisfying physical constraints nor for extrapolation capability. It was found that methods generating continuous, interpretable regression functions are best suited to this task.

The part devoted to the discovery of constitutive relations presents the identification of parameters of classical hyperelastic models and the discovery of new relations using linear regression and constitutive artificial neural networks (CANN). A regression module was developed that enables the analysis of complete, diverse deformation states, and the concept of a stress feature matrix was introduced. The necessity of accounting for the second invariant of isochoric deformation was demonstrated, and it was shown that regression and CANN lead to different yet correct material models.

The next part of the dissertation concerns the solution of boundary-value problems using physics-informed neural networks (PINN). Using the example of a linear elasticity problem, the equivalence of implementations in pure PyTorch and with the DeepXDE library was demonstrated for Treolar's test data, and an in-depth convergence analysis was carried out, covering the influence of variable normalization, network architecture, the manner of imposing boundary conditions, and the optimization strategy on the accuracy and computational cost.

In the concluding chapter, the PINN approach was extended to a hyperelastic material by solving the boundary value problem of a plate with a hole under tension and then identifying the constitutive parameters of the Yeoh model. To this end, an identification approach described in the literature — in which the material parameters are determined jointly with the network weights on the basis of displacement fields and loading history — was adapted, and a modular, extensible implementation was developed for it, applicable to other constitutive models and boundary value problems. The robustness of the approach to measurement noise at a level of 1 % was confirmed, indicating the possibility of its application to real experimental data, e.g.~obtained from digital image correlation. Moreover, it was found that for forward problems, the PINN method does not outperform the finite element method, and its potential is revealed only in inverse problems.

The dissertation as a whole confirms that physically constrained machine learning methods constitute a valuable tool, consistent with the laws of mechanics, for constitutive modeling and the identification of material parameters.

Keywords: artificial intelligence, machine learning, constitutive artificial neural networks (CANN), physics-informed neural networks (PINN), constitutive modeling, hyperelasticity, continuum mechanics, inverse analysis.

Mikołaj Miecznikowski

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