Impact Factor: 9.9 ISSN-L: 2544-980X

Modeling of Physically Nonlinear Deformation Processes in Structural Materials

Alisherov Akramboy Alisherovich [1]

Annotation: This scientific article explores the modeling of physically nonlinear deformation processes in structural materials, emphasizing the challenges and methodologies applied in simulating such complex behaviors. By examining the physical basis of nonlinear deformations, various modeling approaches, and their applications in engineering and material science, the significance of accurate predictions for safe and efficient structural design is highlighted.

Keywords: Nonlinear deformation, structural materials, modeling, finite element method, material behavior, engineering applications, computational modeling.

Introduction

At present, structural elements made of modern structural materials with a wide range of mechanical and physical properties are widely used in various fields of technology. The rapidly expanding introduction of structural materials into load-bearing structures for various purposes requires the development of calculation models and methods that take into account the structural features of these materials. These features include their anisotropy, which must be taken into account when calculating the strength of structures. The problem is complicated if the material has physically nonlinear or elastic-plastic properties. Effective implementation of the advantages of structural materials in structures requires solving a set of problems related to determining the rational structure of the material corresponding to the field of external loads and other effects. In connection with the above, the development of numerical modeling of the deformation process of spatial structural elements of complex configuration, made of materials with different physical and mechanical characteristics and subject to external force factors, is relevant. The task is especially relevant when assessing the savings of consumable material while maintaining the strength of structural elements in aircraft construction, automobile manufacturing, astronautics, nuclear power engineering, mechanical engineering, construction, etc. The solution of many engineering and technical problems is, in one way or another, associated with determining the strength and reliability of load-bearing structural elements, which, in turn, comes down to solving problems of physically nonlinear deformation of structural elements made of structural materials. In this work, both homogeneous and composite materials are considered as structural materials.

Methods

In homogeneous structural materials, the integrity of the structure is often violated for design reasons, i.e. various types of holes or recesses are artificially included, leading to the formation of local stress concentration zones. Such inclusions are called stress concentrators. When solving problems of engineering practice, the problem of studying the strength of structures with areas with a sharp stress drop is extremely important. Analysis of the distribution pattern of stresses and strains in such areas makes it possible to determine the presence of plastic zones that have a significant effect on the strength and load-bearing capacity of the structure. To solve the problem of physically nonlinear

[1] Director of Samarkand city specialized boarding school No. 1 Graduated from the master's degree of the The Samarkand branch of the Tashkent University of Information Technologies named after Muhammad al-Khorazmi (2021)

deformation of homogeneous structural materials, the theory of small elastic-plastic deformations proposed by A.A. Ilyushin is used.

Unlike homogeneous materials, fibrous composite materials are obtained artificially from two dissimilar materials with very different properties. In general, the composition has properties that differ significantly from the properties of its constituent components. The mechanical properties of such materials are determined not only by the properties of the fibers themselves, but also by their orientation, volumetric content, and the ability of the matrix to transmit the applied load to the fibers. Composite materials can have a given combination of high specific strength and rigidity, which allows creating previously inaccessible, fundamentally new spatial structural elements. Research conducted in the field of solving problems of nonlinear deformation of composite materials can be conditionally divided into two groups. In the works related to the first group, the composite material based on the averaging method is replaced by a macroscopic homogeneous anisotropic material with effective modules. The second group of studies includes works in which composite materials are studied taking into account the internal properties of the constituent components, that is, from a microscopic point of view. In this paper, fibrous composites are considered from a phenomenological (macroscopic) point of view as transversely isotropic elastic-plastic materials. The method of reducing a medium with a heterogeneous composition to a homogeneous one with effective mechanical parameters makes it possible to use the apparatus of mathematical modeling to solve problems of physically nonlinear reforming of structural elements. Moreover, effective mechanical parameters connect a heterogeneous medium with an equivalent homogeneous medium.

This method allows to describe quite accurately the quasi-static state of composite structures, all geometric dimensions of which significantly exceed the characteristic size of the structural heterogeneity of the composite under study. Mathematical modeling of nonlinear behavior of structural materials allows, based on computational experiments, by selecting effective ratios of volume content and mechanical parameters of fiber and matrix in the composite, to design new composite materials with predetermined mechanical properties. Numerical modeling is a research method that combines mathematical modeling and computational experiment. The developed algorithms for solving the problem and the implemented computing software package also allow to study the behavior of physically nonlinear processes of deformation of structural materials and to obtain a visual picture of the numerical modeling results. Numerical modeling of the solution of physically nonlinear problems of deformation of composite materials includes the following stages: construction of a mathematical model; development of a technique for solving the formulated problem; determination of effective mechanical parameters of the material; construction of a computational algorithm; implementation of the developed algorithms; creation of a software package and calculation on computing systems; processing of calculation results. The purpose of numerical modeling is: to study physically nonlinear processes of deformation of structural materials, their main properties and patterns. Determination of mechanical parameters of the material when designing new composite materials with predetermined parameters; consideration of factors associated with the structural and constructional heterogeneity of materials. To solve the problem of physically nonlinear deformation of structural elements with various geometric features and heterogeneous properties of materials, the finite element method (FEM) is used.

Results and discussion

The use of FEM leads to clear and simple algorithms that allow to significantly reduce the number of operations performed, minimize the amount of memory used by the computing system and significantly reduce the amount of input information. To calculate the effective mechanical parameters of unidirectional fibrous composites, expressions obtained by applying asymptotic methods for calculating composite materials are used. They allow to take into account the radial interaction of the components caused by the difference in the Poisson ratios of the matrix and fiber. The computational algorithm for solving the problem includes the following stages: constructing a finite element representation of the structural elements; calculating the effective mechanical parameters of the composites; forming and solving a system of linear equations; determining the components of the stress state; solving an elastic-plastic problem; visualizing the calculation results. The division of the algorithm into the above stages corresponds to the FEM calculation scheme and is caused by the need to automate the processes of packaging, processing and storing a large volume of data used in the calculation process. In addition, such a division of the computational algorithm allows to reduce the solution of the problem to solving a sequence of simple independent problems. A specialized software package has been developed for numerical modeling of physically nonlinear deformation processes in structural materials and for conducting a computational experiment. The software package includes: a system part for organizing the functioning of the package; functional content, which is a set of programs implementing a specific task from the subject area of the package; software for constructing a finite element representation of the geometry of the structure and visualizing the calculation results; an interface that provides a user dialogue with the program package.

Conducting computational experiments with variation of the percentage volume content and mechanical parameters of the fiber and matrix of composite materials allows determining the mechanical parameters of the material with predetermined properties. To date, the problem of developing numerical modeling, computational algorithms and software packages for solving physically nonlinear deformation of structural materials cannot be considered complete. Insufficient attention has been paid to issues related to the development of a numerical model, effective computational algorithms and a specialized software package for solving problems of nonlinear deformation of structural materials. In the scientific literature, issues related to conducting computational experiments on the design of new structural materials, determining the impact of structural features such as material anisotropy, volumetric fiber content in materials, the presence of cavities, holes and their mutual influence are poorly studied and covered. In this regard, this paper proposes a method for automating the process of solving problems of physically nonlinear deformation of structural materials, starting with constructing a discrete model of the configuration of the studied structural element and ending with the visualization of the calculated parameters.

In the realm of materials science and structural engineering, understanding the deformation behavior of materials under various loading conditions is paramount. Structural materials often exhibit nonlinear deformation characteristics due to microstructural changes, stress levels, and temperature effects. These nonlinear deformations can manifest as elastic, plastic, or viscoelastic behaviors that challenge traditional linear modeling approaches. Consequently, accurate modeling of physically nonlinear deformation processes is essential for predicting material behavior, ensuring the integrity of structures, and optimizing material performance.

Modeling physically nonlinear deformation processes has significant implications across various fields, including:

- Civil Engineering. Ensuring the safety and resilience of structures under extreme loading conditions (e.g., earthquakes, wind loads) involves accurate predictions of material behavior.
- Aerospace Engineering. Structural components must withstand severe dynamic loadings and deformations; proper modeling helps enhance material design and performance.
- Automotive Industry. Understanding nonlinear deformations allows for better crash simulations and optimizations for safety performance in vehicles.
- Biomedical Engineering. Nonlinear models at the tissue scaffolding or cellular level help in the design of implants and understanding biological responses to mechanical stimuli.

Conclusion

In conclusion, accurate modeling of physically nonlinear deformation processes in structural materials is essential for advancing material science and engineering practices. As materials exhibit increasingly complex behaviors under various loading conditions, advanced modeling techniques such as FEM and multiscale approaches become integral to predictive simulations. Challenges remain, particularly surrounding computational demands and the intricacies of calibrating models against real-world behavior. Nevertheless, overcoming these hurdles will enable safer and more efficient structural designs, paving the way for innovation in numerous engineering applications. Future research and development in modeling methodologies will play a crucial role in addressing evolving engineering challenges and optimizing the performance of structural materials.

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