Composite Materials with Helical Inclusions: Theoretical Aspects and Applications Planning Tank Farms for a Pipeline

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There is a whole set of means to essentialy increase energy consumption by a material under dynamic extension. This can be achieved by a special structure including so-called "waiting" elements, curvilinear fibers, and in some other ways which can serve to increase the stability of large strains. In this regard, attention is drawn to mechanics of composites with curvilinear reinforcements. Indeed, curvilinearity provides for greater controlled variation of the mechanical features of the composite than straight fiber composites. Unlike the latter, curvilinear reinforcements lead to rigid nonlinearity of the macro-level stress-strain relation. This can essentially increase the stability of the material under extension, which, in its turn, results in increased resistance to localization of strain and fracture.

Among such structures, composites based on helical inclusions deserve special attention. The helix is a unique perfect curve with constant curvature and torsion. Note that the straight line and the circle are limiting cases with zero curvature (although possibly nonzero torsion) and zero pitch, respectively. Owing to uniformity, translation-rotation symmetry holds, which leads to the existence of simple states of the composite. In such a state, stress-strain fields look invariant to an observer moving and rotating with the triad natural to the helix. Of course, such symmetry occurs only in the case of a unique helical inclusion in an isotropic homogeneous matrix or when such inclusions are placed far enough from one another.

Initial twisting of the fiber was theoretically and experimentally shown to increase the ductility of the composite. Fairly larger ultimate tensile strains were obtained at a small expense of ultimate tensile stresses. It can be mentioned that, along with the problem of a composite material with a helical inclusion, helical systems are relevant to a wide variety of fields in science and engineering. Helical symmetry occurs in a multitude of areas, from mechanical properties of helical DNA molecules and chiral polymers to mechanics of large-scale spatial structures, deployable antennas, etc.

In the present work, some analytical and numerical solutions for quasi-statics and dynamics of helical-inclusion composites are derived. The effectiveness of such composites in composite armor is shown. In this context, two nonlinear problems are considered: a unique inclusion in an elastic space and a plastic matrix with elastic helical reinforcements. The first problem deals with axial and radial extension and torsion of the composite, and internal torsion of the inclusion aligned into a smooth helical canal in the elastic matrix. In a helix-associated coordinate system, due to translation-rotation helical symmetry, the derived stress-strain fields are two-dimensional: they are uniform regarding the helical coordinate. Besides, reflection symmetry is assumed. As a result, the inclusion shape turns out to differ from that corresponding to a global, uniform strain of the composite by a radial displacement only. This displacement, radial force and moment invoked by the matrix on the inclusion are derived, as well as the stress-strain fields in the matrix. The results are obtained, in particular, by superposing fundamental solutions corresponding to homogeneous elastic space under a concentrated force and a moment. Along with exact results, two kinds of asymptotic solutions are derived, one of which presents the entire solution in an analytical form.

In the other problem, penetration/perforation dynamics is studied for a composite armor impacted by a high-speed projectile. The armor consists of a primary, hard metal layer and a flexible back armor. The latter is a multi-ply fabric manufactured of a plastic matrix with elastic helical reinforcements. The role of the primary armor is to decrease the impact energy and to deform the projectile head, while the back armor is intended to consume the remaining energy of the flattened projectile. Various types of such armor based on straight-line filaments are widely used as protection for light combat or cash-carrying vehicles, security doors, superstructures, cabins and control rooms on boats and small ships, etc.

In the presentation, the dynamic extension, fracture and delamination of the multi-ply helical-fiber-composite back armor are studied. In this problem, plastic resistance of the matrix to relative displacements and rotation of the helical inclusions is assumed to be invariant (in the helix-associated coordinate system). The goal of this study is to determine the optimal structure of the composite that would provide maximal energy consumption under impact, and hence maximal stopping power of such armor.

At the Institute for Industrial Mathematics, adequate precise models for these problems have been analyzed and fast computational algorithms were applied towards their solution. Hence a special-purpose software has been developed for simulation of impact and penetration processes. It can also treat unsteady dynamics and fracture of strongly nonlinear structures subjected to an explosion loading. Some examples will be presented of the use of this software for the discussed problems.