Biomimetic design of fibrous composite structures

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Abstract. The paper is devoted to the analysis of the use of Nature’s methods in the design of composite structures, in particular, with the use of optimal curvilinear paths for laying fibers. In the first part models of different structural levels in macro-, mini-, micro-mechanics of composites are noted. The second part includes analysis of the optimal elastic-strength properties of wood and composites for crack stopping by weak interfaces. The third part is devoted to methods for modeling curvilinear fibers trajectories “flowing around the holes”. In the fourth part the technologies for manufacturing joints are analyzed in which holes are formed using curved fiber trajectories. The fifth part describes the “bio-inspired” principles for the optimal design of composite pipe structures which are similar to multilink bamboo stems. In the sixth part examples of the effective use of fiber composites in elastic elements are considered. The seventh part is devoted to the intensively developing additive technologies of three-dimensional printing of parts made from fiber composites with laying the fibers along the calculated trajectories. The role of composite technologies in creating structures in open space is analyzed.

Introduction

There are numerous examples of the use of Natural Solutions in engineering, and particularly in the design of composite structures. The terms biomimetics and «bio-inspired method» are widely used. For example, a question arises: how is the branch-barrel connection arranged? You can break a branch, but no effort can tear the branch off the trunk. The connection is stronger than the part itself. So far, it is only possible to dream about such methods of fastening composite parts.

1. Modeling at different structural levels

Scientific approaches to studying fibrous composites are very diverse. With the same object (composite construction), they can differ in the subject of study which means they can be based on models of different levels. The tasks analyzed in this report relate to composite models that are placed in an intermediate position between “microstructural” and “macromechanical” models.

Micromechanics of wood and composites

Wood, bamboo stem have complex, hierarchical structure [1]. Without going into the details of micromechanical models, we note only a series of scientific works by G.A. Vanin (Fan Fo Fa) [2] and other authors, which set out approaches to the construction of accurate solutions to the problems of the theory of elasticity for periodic fibrous structures. However, the use of gradient models of the moment theory of elasticity of the Kosser-Mindlin-Lurie type in the design of composite structures is extremely
limited, since existing technologies do not allow the production of fibers and binders with a specially
created bio-similar hierarchical structure.

2. Mini-midi mechanics. Optimal properties of components for crack stopping by interface
The main advantages of fibrous composites are not only high strength along the fibers, but also
toughness due to the presence of fragile fiber-matrix interfaces.

Figure 1 shows the crack stopping mechanisms due to the complex stress state near its apex. The
refined analysis [3] allows corrections (figure 1 (b)) to the known Gordon scheme (figure 1 (a)):

\[
\frac{\sigma_{xx}^{\max}}{\sigma_{yy}^{\max}} = \frac{1}{3\sqrt{3}} \approx 0.192
\]

- The ratio of normal stresses equal in the isotropic case is a constant but depends on the anisotropy of the material.
- The largest values of all stress components are achieved on the hole contour, and therefore
  splitting always begins on the hole or crack contour, not in front of it.
- The main role in splitting is played by tangent stresses, since they are significantly more
  transverse, especially in highly anisotropic materials such as wood or unidirectionally
  reinforced plastics, which allows us to formulate the condition for the occurrence of splitting
  before fracturing of fibers in a simple form:

\[
\frac{\tau_{xy}^{\max}}{\sigma_{yy}^{\max}} \geq \frac{\tau^*}{\sigma_y^*}
\]

where \( \tau^* \), \( \sigma_y^* \) are composite shear and tensile strengths along the fibers.

The ability to stop cracks due to the splitting of weak interfaces is one of the main advantages of
natural and polymer composites, which allows to simultaneously increase strength and crack
resistance.

It is interesting to note that equation in (1) is reasonably fulfilled for strong wood varieties: for oak
\[
\frac{\tau_{xy}^{\max}}{\sigma_{yy}^{\max}} = 0.095; \quad \frac{\tau^*}{\sigma_y^*} = 0.091
\]

For unidirectional fiberglass according to equation (1), the shear strength should be about 150 MPa, and
the real strength of the polymer matrix is three times lower, so unidirectional composites are split near
stress concentrators long before they reach limit stress.
3. Methods for constructing biosimilar curvilinear fiber paths
Nature never uses linear reinforcement. Observations of Nature have led to the idea of the need to use an optimal, curvilinear reinforcement structure in composite design, when the fiber trajectories are consistent with stress fields. A large number of works [4, 5 et al.] is devoted to the construction of optimal trajectories of fibers "flowing around" a circular hole.

In [5], a new approach to the construction of fiber paths coinciding with the trajectories of the main tensile stresses is developed. Direct, iterative construction of continuous fiber trajectories makes it possible to directly switch to additive technologies that provide a rational structure of curvilinear reinforcement in the zone of holes or connecting units. The trajectories of the fibers flowing around the hole resemble the structure of wood in the knot area (figure 2).

![Figure 2](https://example.com/figure2.png)

**Figure 2.** (a) structure of pine wood in the knot area, (b) equally stressed structure of fibre laying along trajectories of greatest main stresses near holes and recesses in stretched plate.

The main conclusion of the analysis is that the maximum stress "per fiber" in the optimally reinforced structure becomes about 3-4 times less than with a unidirectional fiber placement which means that the effective stress concentration coefficient decreases from 5 to 1.3, and the fiber overload at the bottom of the hole is only about 30%. At the same time, it is extremely important that shear stresses disappear, causing splits near the holes.

It becomes clear that damaging effect of stress concentration in composite joints can be reduced precisely by means of a special reinforcement structure consistent with the stress field.

4. Biomechanical principles of composite parts attachment units design
One of the main fundamental tasks of composite design is the development of connection methods that implement high fiber strength.

The fundamental disadvantages of all known connection methods make it necessary to turn to the Nature for experience, and the "design" of the knot can suggest optimal fiber paths in the connection area through a bolt or rivet (figure 3).

Rational reinforcement leads to a significant reduction in local stresses per fiber, elimination of splits and an increase (at least 50%) in the load capacity of the connection.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Rational fibers trajectories enveloping the loaded hole.
5. Bamboo and composite pipe failure mechanisms

One of the most amazing and perfect works of Nature - the fast-growing stem of bamboo - attracts not only as an indispensable material for scaffolding in Hong Kong, but also as an optimal prototype of composite pipes [6]. The energy criterion of splitting [3, 7] - in the form of a "Chinese flashlight" during compression (figure 4) and with deplanation of the section (figure 5) during torsion of thin-walled unidirectional composite pipes - allows you to indicate rational distances between the rings of a multi-link composite pipe, qualitatively consistent with the dimensions of the bamboo stem.

**Figure 4.** Dependencies of critical stresses on length L during compression of composite pipes for three types of destruction: 1 - local crushing; 2 - "Chinese lantern"; 3 – macro buckling.

**Figure 5.** Torsion split diagram of a thin wall pipe with section deplanation and illustration of the calculation of total shear strain

\[
\gamma = \gamma_1 + \gamma_2 = R \theta + \frac{\partial u}{\partial s}
\]

Increasing torsional stiffness after constrained splitting leads from the energy criterion to an increase in critical torque and to the appearance of significant axial stresses:

\[
M^* = \left( \frac{4 \pi G R_s^3}{h^2 - [3R_s^2 (1 - 2 \rho B_z / \lambda)]^{-1}} \right)^{0.5}; \quad \sigma_{max} = 0.76 \frac{MB_2}{R h^2} \left( \frac{E_s}{G_{yy}} \right)^{0.5}
\]

In (2) \( p \) - sealing factor (\( p = 0 \) - non-shear torsion, \( p = 1 \) - absolutely rigid sealing);

\[
B_z = \frac{\text{ch} \lambda - 1}{\text{sh} \lambda}
\]

\( E_s, G_{yy} \) are Young's and shear modulus,

\[
\lambda = \frac{L}{k}
\]

\[
k = \frac{R^2}{h} \left( \pi^2 - 6 \right) \left( \frac{E_s}{G_{yy}} \right)^{0.5}
\]
It can be understood from (2) that there is such a small length of the pipe link \(L^*\) at which the denominator turns to zero, that is, splitting cannot occur at any torque \(M^+\). This is approximately the length of the bamboo link that Nature "chooses" to avoid premature splitting.

6. Design of bio-similar branching and profiled composite elastic elements

The secrets of the tree crown structure for many centuries have attracted the attention of researchers. Leonardo da Vinci in his notes expressed the following statement: "The sum of the squares of the diameters of the branches is the same before and after branching." The Leonardo Rule suggests how to create branched (figure 6) and profiled (figure 7) composite elastic elements [8-11].

![Figure 6. Diagram of equal-strength branch of rod with circular section.](image)

When acting on a perfectly branching or profiled beam with a variable bending moment:

\[
M(\bar{x}) = M(1)\bar{x}^\gamma; \quad \bar{x} = x/l.
\]

in order to maximize the stored elastic energy, sequential branching on \(1+2\gamma\) of the branches is advantageous, and surprisingly, the maximum possible mass reduction coefficient is also equal to \(1+2\gamma\).

Let us note that in (3) the load of the end force \(P\) corresponds to \(\gamma = 1\), \(\gamma = 2\) for the uniformly distributed load, \(\gamma = 3\) for the linearly varying load.

![Figure 7. Constant-area beam with constant cross-sectional area.](image)

In [11], the reduction in mass of the band spring from the shaped half-rings was analyzed, and it turned out that in the ideal case it is possible to double it, which corresponds to \(\gamma = \frac{1}{2} < 1\), since the change in the bending moment in the diametrically compressible half-ring is proportional to the sine of the polar angle, i.e. it is "slower" than the linear one.

Branching equally stressed composite elastic elements are as effective as profiled beams of the constant area type, but the advantage of branching compared to profiling is the preservation of
continuous linear reinforcement and the possibility of reducing dimensions when collecting "branches" into a bundle.

7. Additive Biomimetic Technologies
The development of additive 3D printing technologies extends the possibilities of creating optimal structures with curved fiber paths [12, 13]. In this way, it is possible not only to design and create products of different shapes, but also to manufacture bio-similar joints [14], which are much more effective than traditional "metal-like" connections.

Since such technologies do not require high temperatures and considerable effort, in the future it is possible to create technological areas for the manufacture and repair of composite elements directly in orbit [15].

Conclusion
In our opinion, the three most promising areas in the mechanics of composites are biomechanics of strength, computer modeling of optimal structures and technological mechanics of composites. It is the modeling of biotechnologies and biomaterials structures that can provide a breakthrough in the creation of composite structures.

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