Technological biomechanics of fibrous composites

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Abstract. There are numerous examples of using Natural solutions in technology, especially, in design of composite structures [1]. Bio-inspired methods (suggested by Nature) are widely used in human activity. For instance: how does branch-trunk connection work? You can break a branch, but nearly impossible to tear the branch off the trunk. The connection turns out to be stronger than the part itself. So far, designers of composite products can only dream of such methods of joining.

1. Methods for constructing biosimilar curvilinear fiber trajectories
Nature never uses right linear reinforcement. Nature observation led to the idea of the need to use an optimal, curved reinforcement structure in composite design, when the fiber paths are consistent with the stress fields. A large number of works [2, 3, etc.] are devoted to the construction of optimal trajectories of fibers "flowing around" a circular hole.

In [3] the new approach to the construction of fiber paths coinciding with the trajectories of the main tensile stresses is developed. Iterative continuous fiber tracing makes it possible to go directly to additive technologies that provide a rational structure of curvilinear reinforcement in the area of holes or attachment points. The fibers trajectories flowing around the hole resemble the structure of wood in the knot zone (figure 1).

Figure 1. (a) structure of pine wood in the knot zone, (b) uniformly stressed structure of fibers laying along the trajectories of the maximum principal stresses near holes and undercuts in a plate under tension.

The main conclusion from the analysis is that the maximum stress "per fiber" with an optimal reinforcement structure is about 3-4 times less than with a homogeneous rectilinear laying, that is, the effective stress concentration factor decreases from about 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 the shear stresses that cause splitting near the holes disappear.

It is obvious that the harmful effect of stress concentration at the composite parts joints can be reduced precisely by using a special reinforcing structure, consistent with stress field.

2. Biomechanical design principles for composite parts joining
One of the fundamental tasks of composite design is the development of joining methods that achieve high fiber strength.

The fundamental disadvantages of all known joining methods force us to study Nature experience, and the knot "design" can suggest the optimal fibers trajectories in the composite joining with a bolt or rivet (figure 2).

Rational reinforcement leads to the significant reduction in local stresses per fiber, elimination of splitting and the increase (by at least 50%) in the bearing capacity of the joint.

3. Design of bioinspired branching and profiled composite elastic elements
The secrets of the tree crown structure have attracted the attention of researchers for many centuries. Even Leonardo da Vinci in his notes made the following statement: "The sum of the squares of the branches diameters is the same before and after branching". The “Leonardo’s Rule” suggests the way to create branched (figure 3) and profiled (figure 4) composite elastic elements [4, 5].

![Figure 2. Rational trajectories of fibers envelop a loaded hole.](image1)

![Figure 3. Scheme of equal-strong branching of a circular cross-section rod.](image2)
When loading a perfectly branched or profiled beam with a variable bending moment:

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

(1)

to maximize the stored elastic energy, sequential branching into an integer number of branches is advantageous \( 1 + 2\gamma \), and the maximum possible mass reduction factor is also equal \( 1 + 2\gamma \). Let’s note that loading by the end force \( P \) corresponds \( \gamma = 1 \) in (1), \( \gamma = 2 \) corresponds to a uniformly distributed load, \( \gamma = 3 \) corresponds to a linearly varying load.

Branching uniformly stressed composite elastic elements are as effective as profiled constant-area beams. The advantage of branching over profiling consists in conservation continuous rectilinear reinforcement and in the possibility of dimensions reducing when collecting "branches" into a bundle.

4. Additive biomimetic technologies

The development of additive 3D printing technologies expands the possibilities for creating optimal designs with curved fiber trajectories. On this way, it is possible not only to design and create products of various shapes, but also to manufacture bio-inspired joints [6], which are much more efficient than traditional "metal-like" joints.

Since with such technologies there is no need for high temperatures and significant molding efforts, in future it is possible to create technological sections for manufacturing and repairing composite elements directly in orbit [7].

Conclusion

Let us point out the three most promising, in our opinion, directions in the composites mechanics: strength biomechanics, computer simulation of optimal structures, and composites technological mechanics. It is the modeling of biotechnology and biomaterials that should provide a new breakthrough in the creation of composite structures.

References

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