3D Printing of Bio-inspired Helical Composites with Enhanced Failure Resistance

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The arrangement of stiff helicoidal fibers into a soft matrix is a fundamental construction principle used by nature to enhance the mechanical behavior of biological materials. Considering wood, the basic load-bearing component is the cell wall, traditionally described as a three-layer cylindrical structure. Each layer features a compliant matrix of hemicellulose and lignin reinforced by stiff helicoidal microfibrils of cellulose. The middle layer is the thickest and the angle its microfibrils form with the cell axis is pivotal in modulating stiffness and failure strains. The biomechanical role of the other two layers, whose thickness count for about 15% of the total cell wall, is much less understood. Here, we combine computer simulations, multimaterial 3D printing and experimental testing to characterize the mechanical behavior of synthetic composites mimicking the multilayer helicoidal structure of wood. We considered single-layer cylindrical motifs made of a rubbery matrix reinforced by stiff polymeric spiral fibers. The 3D-printed structures showed variations in stiffness up to 4 times when increasing fiber winding angle from 0 to 45 deg. We investigated the biomechanical consequences of adding outer and inner layers either with vertical or horizontal thin fibers, i.e. 75% smaller than fibers in the middle layer. The highest failure resistance was achieved when the added layers had horizontal fibers (perpendicular to the cylinder axis), which is also the arrangement seen in wood. The reinforcing rings, albeit thin, could restrain failure of the larger fibers, leading to a 200% increase in strength. Finite element simulations elucidated the interplay between matrix and fibers in absorbing deformation energy. Besides revealing basic biomechanical properties of the wood cell, our work should demonstrate that construction principles observed in biological composites can be exploited to boost mechanical performance of 3D printed bio-inspired structures.