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Review

# Mechanical effects of microchannels on fiber-reinforced composite structure

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ABSTRACT

Microchannel networks embedded within fiber-reinforced composites provide empty spaces and pathways to store and transport a functional fluid to the desired location within a structure to execute one or more tasks of sensing, healing, and cooling at the same time. This addition to structure is anticipated to enhance the performance, safety, and reliability of the structure. Besides these benefits, these embedded channels alter the microstructure and fiber volume fraction of the composite that ultimately affect the load-carrying capacity of the composite structure. This paper seeks to review the effect of microchannel addition on the mechanical properties of fiber-reinforced composites. This effect may be positive or negative; slight or significant largely depends upon channel diameter, location, inter-channel distance, shape, and orientation, which also play a great role in the multifunctional performance of the composites. Therefore, depending upon the application these parameters must be wisely selected to manufacture the most suitable microchannel network that can lead to optimum multifunctional composite structures.



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## 1. Introduction

The development of advanced tools and manufacturing techniques lead to the origination of a new class of functional materials that essentially comprise a variety of embedded microchannel networks. This concept mimics the biological microvascular systems, and shows promise to provide smart solutions to long-standing problems within structural materials. In living organisms these channels transport fluids from one place to the other to execute many tasks, such as to sense, control, or heal damage, increase or decrease temperature, supply food and discard harmful materials. Similarly, polymers and polymer composites are incorporated with synthetic microchannels to provide additional functions of sensing [1–3], enhanced damage visibility [4,5], self-healing [6–13], and active-cooling [14–16]. The basic principle behind these functionalities is the flow of functional fluids, either assisted by pump or capillary forces. Microchannel-based self-sensing systems employ the use of fluids at different pressures (in adjacent channels), connected to the monitoring system. The damage event links the two channels at different pressure that causes a change in pressure of the system [17,18]. Microchannel-based damage enhancement systems deliver X-ray or Ultra Violet (UV) opaque fluids to the damage site. These fluids improve the visibility of that hidden damage, connected with the microchannels [19,20]. Similarly, microchannel-based self-healing systems transport a healing agent to the damage zone that polymerizes there to restore the lost strength [21–23]. On the other hand, microchannel-based active-cooling systems circulate a coolant to absorb and remove excess heat [24,25]. Regardless of the application, many factors such as the design of microchannels network, properties of fluids, matrix, and the distribution method can significantly affect the overall functionality of the composite structure. These effects have been thoroughly studied by many researchers by employing different experimental and numerical approaches [26]. Keeping in view these effects and structures' application, polymers and polymeric composites embedded with synthetic microchannels have been fabricated by a range of manufacturing techniques [27]. However, no matter what type of processing approach is used to create microchannels, they take the place of load-bearing material, which eventually impinge on the load-carrying capacity of the structure. In contrast to synthetic microchannel networks, many biological microchannel networks within tissues are quite robust in achieving multifunctions as well as maintaining higher mechanical performance.

### *1.1. Biological examples*

Wood and dentin are excellent examples of microvascularized materials that have higher toughness and strength than their primary constituents. In these materials, microchannel networks play a positive role in maintaining structural integrity, such microchannel networks can be applied to engineering applications with higher strength requirements.

Wood is a natural, biocomposite of cellulose fibers in the lignin matrix with lengthy, parallel and isolated vascular network (Fig. 1(d)), connecting roots to the canopy. These long channels further physically split into thin channels through hierarchical links (see Fig. 1(b and c)) to distribute the flow to wider areas via multiple paths. These redundant flow paths enhance the reliability of the channel network, so if one channel fails or blocks, others are available for fluid flow [28]. This vascular design also does not affect the structural integrity of wood [29].

Conversely, dentin is a calcified biocomposite and a major component of animal teeth. It comprises of microvascular network of cylindrical tubules roughly parallel to one another (as shown in Fig. 1(e)). These tubules connect the interior pulp layer to covering enamel layer. The sizes of tubules range from 0.8 mm at the dentin-enamel junction to 2.5 mm at the pulp and tubules' densities are 2.5% at the dentin-enamel junction and 22.5% near the pulp [30]. The Young's modulus of dentin increases from 25 GPa for tubular circumference (with 0.1 mm radius) to 29 GPa for peritubular dentin region (with 0.9 mm radius). Microvascular network within dentin causes a 60% higher fracture toughness due to collagen fibril bridging effect [31].

These vascular structures not only efficiently transported the fluids for sensing and healing, but also maintained the mechanical integrity of the structure. Likewise, researchers proposed numerous optimized synthetic network architectures for specific applications that offered balance among different functionalities.

### *1.2. Microchannels network design*

Not any microchannel network design can be fabricated due to manufacturing limitations and they impose certain restrictions on the design of the network. However, diameter, spacing, position, and channel orientation are some of the variables that can be varied for a network design by most of the manufacturing methods, yet their ideal values largely depend upon their ultimate usage.

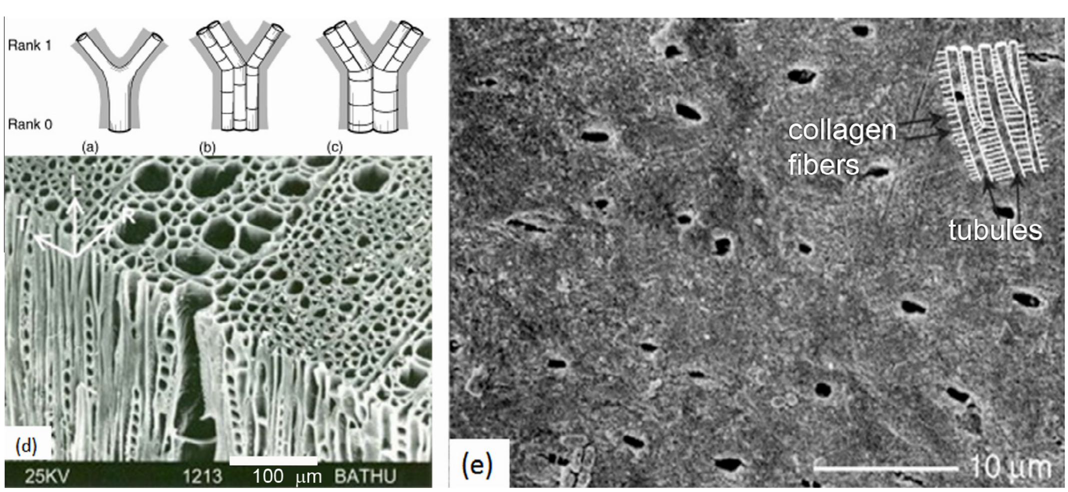


**Fig. 1.** Vascular networks in (a) animals; a single continuous tube divides to form two daughter tubes (b, c) plant xylem; the tubes are not continuous, but divided into individual conduits [28], SEM images of (d) English wood, illustrating extensive longitudinal vascular structure [32], and (e) elephant tusk dentin, showing long axis of tubules [31].