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RESEARCH ARTICLE

# Crack Bridging and Deflection Toughening Mechanisms of Staggered Hydroxyapatite Lamellar Microstructure in Bone

**Yuxi Liu[1*], Xiaohui He[1], Shuge Li[1], Zhangdong Sun[2]**

*[1]School of Smart Health, Chongqing Polytechnic University of Electronic Technology, Chongqing 401331, China*
*[2]Hubei University of Automotive Technology, Shiyan, Hubei 442002, China*

*Corresponding Author: eyxs28kwio48@163.com

**Abstract:** The observation experiment results of the microstructure of tibial cortical bone show that the cortical bone is a layered bio-ceramic composite material composed of Hydroxyapatite (HAP) and collagen arranged alternately. HAP is a reinforcing phase and accounts for a large proportion in cortical bone. These hydroxyapatites have long and thin sheet-like structures parallel to the outer surface of the bone, forming a unique " staggered structure" with collagen. During the propagation of cracks in the cortical bone of the tibia, crack bridging will occur. Based on the microstructural characteristics of HAP sheets and crack bridging observed in cortical bone, the effect mechanism of staggered structural features and HAP volumetric proportion on tibial fracture toughness was studied. Under a specific variation range, elevated hydroxyapatite proportion and its sheet aspect ratio will lead to obvious growth in the crack deflection coefficient and the dissipated fracture energy. As the volumetric proportion of HAP sheets rises from 0.6 to 0.8, the overall fracture toughness of this staggered composite structure improves markedly. This investigation provides reliable theoretical support for the optimized preparation and structural design of high-strength biomimetic ceramic composites.

**Keywords:** Cortical Bone, Hydroxyapatite, Staggered Structure, Crack Bridging, Toughening Mechanism

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## Introduction

In the long process of evolution, nature has produced numerous biomaterials with complete structures and organizational forms, as well as exceptional mechanical properties. The uniqueness and novelty of their structures far exceed people's imagination [1]. Bones, as an important component of human weight-bearing capacity, are a natural bio-ceramic composite material composed of Hydroxyapatite (HAP) and collagen [2]. This type of composite material, through its intricate multi-level structure and efficient toughening mechanism, can effectively solve the problem of "strength-toughness" balance in engineering materials. Therefore, studying the microstructural characteristics of bone and its fracture toughness is of great significance.

Bone tissue has excellent mechanical properties and a complex multi-layered structure, making it a natural bio-composite material with special mechanical and biological properties. Its multi-layered structure includes macroscopic, microscopic, submicroscopic, nano, and sub-nano [3]. Its internal composition mainly includes organic and inorganic substances. The organic component occupies a volume ratio of 32%-44%, while type I collagen and non-collagen components respectively make up 90% and 10%; meanwhile, HA crystals constitute 33%-43% of the total volume. [4]. Its structural stiffness merely differs by one magnitude from HA crystals. Meanwhile, its mechanical strength reaches 3 to 5 times that of single-component proteins and mineral substances, and it also exhibits superior fracture toughness compared with pure HA crystalline materials [5]. The cortical bone presents a highly ordered multi-level hierarchical structure. At the nanoscale, HA nanocrystals, with a typical size of approximately 5 nm, are embedded within collagen fibers and encircle the outer surface of mineralized collagen fibrils. This unique microstructure enables strong interfacial bonding between the soft organic matrix and rigid inorganic components [6]. The hydroxyapatite layer is composed of many hydroxyapatite sheets arranged in parallel and orderly [7]. At the macro level, cortical bone is composed of 3-5 concentric circular bone plates surrounding the Haversian canal, with the Haversian system (osteon) as the basic unit [8]. This multi-level structure enables cortical bone to effectively disperse stress and resist fracture of different scales.

There are significant differences between artificial high-content ceramic composite materials and natural ceramic materials [9]. A wealth of investigations have demonstrated that the outstanding mechanical performance of natural bone and bone-related biomaterials can be attributed to their distinctive nanoscale architectures, and a variety of toughening mechanisms have accordingly been proposed. A recent study proposed a micro-nano structural analysis model at different scales, and studied the influence of the cross microstructure of HAP fiber sheets and their shape and size on bone fracture toughness [10]. Liu [11] constructed an upgraded version of the tension-shear chain model, which took the interlayer stress heterogeneity of staggered configurations into account. Bar-On [12] proposed a general elastic modulus analytical equation. Casari [13] explored how osseous microarchitecture and hydration conditions affect the microscale strength and toughness of bone tissue. However, the toughening of cortical bone does not rely on a single mechanism but on the synergistic effect of multiple mechanisms. These mechanisms include but are not limited to fiber bridging, deformation of organic matrices, and energy dissipation at interfaces [14]. In the study of the microstructure and toughening mechanisms of bone tissue, various advanced experimental techniques and theoretical models have been adopted. Scanning electron microscopy (SEM) is a key technique for directly observing its microstructure, crack propagation path, and fracture surface morphology [8]. In recent years, atomic force microscopy has been utilized to investigate the nanomechanical properties of bone matrix, which can measure the elastic modulus and hardness of local areas [15]. Nanoindentation testing enables the quantitative characterization of localized mechanical behaviors of materials, including hardness and Young's modulus [16]. These high-resolution experimental techniques provide a powerful tool for understanding the micro-mechanical behavior of bone.

Microstructural observations of fracture surfaces and crack growth paths in tibial cortical bone reveal that this biological tissue is a natural bio-ceramic composite mainly composed of hydroxyapatite and collagen. The lamellar structure of HAP arranged in a staggered manner is approximately parallel to the outer surface of the bone. Each hydroxyapatite lamina is sequentially assembled from elongated, thin apatite sheets. The bone collagen between the layers is an adhesive, forming a unique structure with the staggered arrangement. The analysis of the propagation process of cortical bone microcracks reveals that there is bridging of uncracked ligaments during their propagation. Then, a "staggered structure" analysis model and a crack bridging model were established. Through theoretical analysis, the staggered structure of the hydroxyapatite layer and collagen layer, as well as the mechanism of crack bridging on the fracture toughness of the tibia, were studied. In addition, by introducing the crack deflection coefficient, this work analyzed how the volume fraction and geometric ratio of hydroxyapatite sheets affect the crack deflection coefficient, and further explored the combined impacts of crack deflection and HAP content on bone fracture toughness. Combined with the microstructural features and intrinsic toughening behaviors of tibial cortical bone, this research offers meaningful references for designing and fabricating high-performance biomimetic composites.

## Experimental Materials and Methods

The microstructure of animal bones varies depending on the type and age of bones. In this study, bovine tibia was selected as the research object (bone age: 18 months). Therefore, the observation results of the microstructure of cortical bone in animal tibias in this study may not represent the microstructural characteristics of all animal tibias. Scanning electron

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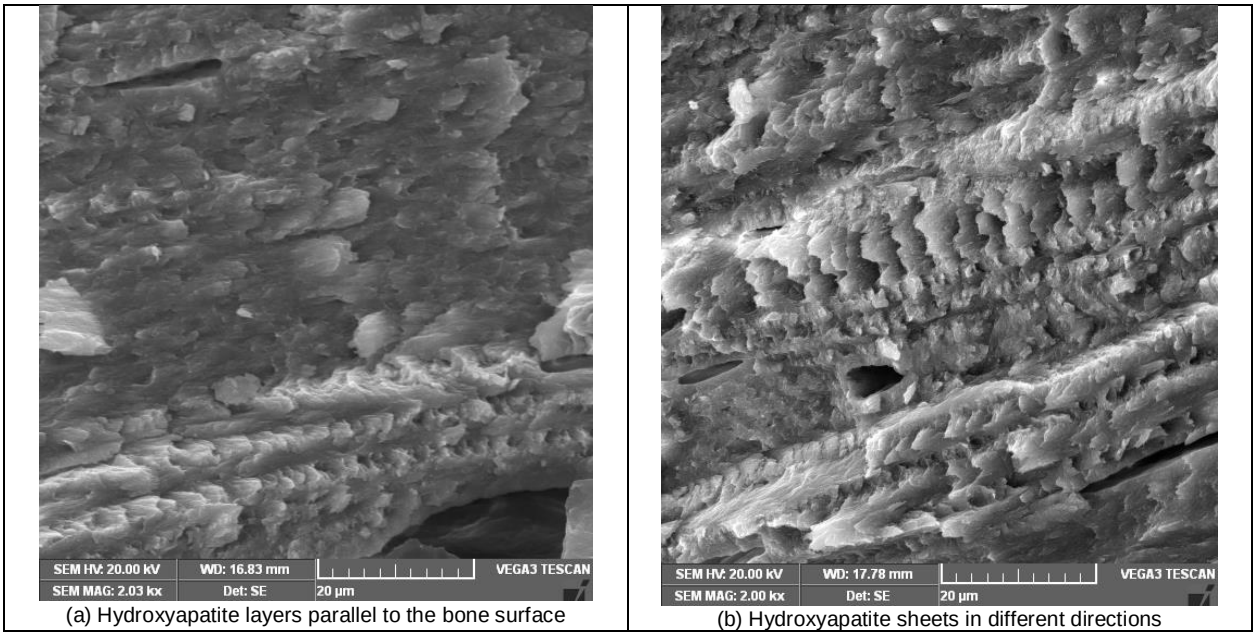
microscopy (SEM) was adopted to characterize the microstructure of the collected tibial cortical bone specimens. The experimental process for sample preparation and observation is as follows:

(1) Muscle tissue was removed from the tibia, and its surface was cleaned with 95% ethanol. Then the tibia was processed into SEM specimens with a size of about 5 mm
(2) The prepared specimens were dehydrated, and a palladium coating with a thickness of about 10 nm was sputtered onto their surfaces using an ion sputter coater (KYKY-203)
(3) The sputtered specimens were placed into the SEM. With the voltage maintained at 18 kV, the microstructure observation experiment of the specimens was conducted within a magnification range of 20-9000 times

## Results and Discussion

### Microstructure Characteristics of Tibial Cortical Bone

The microstructure of tibial cortical bone is shown in Fig. 1. As shown in Fig. 1 (a), tibial cortical bone constitutes a layered bio-ceramic composite, which is mainly constructed by collagen and hydroxyapatite substances. Within this composite system, high-strength and high-stiffness hydroxyapatite acts as the rigid reinforcing constituent. In contrast, collagen, which possesses relatively weaker mechanical properties, serves as the flexible bonding matrix. Most inorganic hydroxyapatite components present a layered distribution and align parallel to the outer surface of bone tissue. The organic collagen is also distributed in a lamellar manner between the hydroxyapatite layers and plays a role in adhesion. The lamellar microstructure of hydroxyapatite can cause cracks during the bone fracture process to deflect along the collagen layers, rather than directly penetrating through the hydroxyapatite layers (Fig. 1(b)). In this way, multiple cracks will appear during the bone fracture process, which lengthen crack growth routes and consume more fracture energy, ultimately improving the bone's overall fracture toughness. Through further observation of the hydroxyapatite layer, microscopic characterization reveals that the hydroxyapatite layer is assembled from numerous slender apatite platelets, as illustrated in F. 1(b). These lamellar structures possess a thickness spanning tens to hundreds of nanometers, along with considerably larger length and width sizes.




(a) Hydroxyapatite layers parallel to the bone surface

(b) Hydroxyapatite sheets in different directions

**Fig. 1: Microstructure characteristics of hydroxyapatite layer in tibia**

To investigate the fracture process and the influence of the staggered structure of hydroxyapatite and collagen layers on the fracture resistance of the tibia. From the perspective of fracture energy dissipation, this paper explores how crack deflection behaviors influence the fracture toughness of tibial bone tissue. Hydroxyapatite has a relatively high elastic modulus, and collagen has a relatively low one. Therefore, the load borne by the tibia is mainly carried by hydroxyapatite. However, the most critical region for the tibia is its connecting phase, namely the mineralized collagen between hydroxyapatite

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layers. When the tibia is subjected to external loads, cracks often propagate along collagen. Combining microstructural observations (Fig. 1) and morphological analysis of tibial cortical bone, a schematic illustration was constructed to depict the staggered arrangement of hydroxyapatite platelets as well as the evolving crack propagation routes, which is presented in Fig. 2.

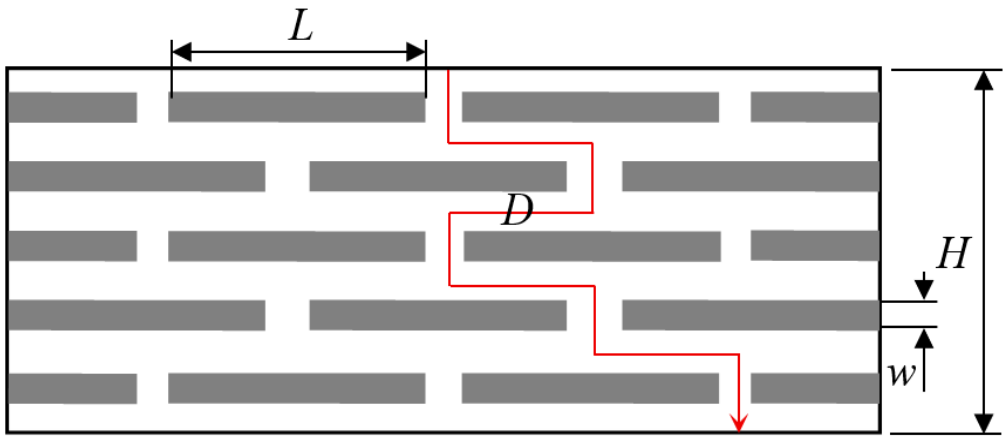


**Fig. 2: Schematic diagram of the staggered arrangement structure of hydroxyapatite sheets and crack propagation paths in cortical bone (The red line represents the crack propagation path, with a total length of *D*)**

## Effect of Microstructure Size Parameters on Fracture Toughness

In accordance with the physical definition of mechanical work, the work produced by a force *F* is determined by multiplying the force magnitude by the displacement of the object along the direction of the force.

$$W = F \times S \tag{1}$$

Where W denotes work (J); F denotes the force acting on the object (N); and S denotes the distance the object travels along the direction of the force (m).

Assuming that the interfacial resistance applied tto collagen when it cracks is τ, the distance at which a crack travels through the hydroxyapatite composite is D; L denotes the length of hydroxyapatite platelets; w represents the width of HAP platelets; H stands for the thickness of the tibial bio-composite, and V indicates the volume fraction of hydroxyapatite platelets (Fig. 2). The distance that cracks pass through the staggered structure composed of hydroxyapatite and collagen layers can be described as follows:

$$D = H + \frac{HLV}{2w} \tag{2}$$

Where *τ* is the interfacial resistance when interlayer collagen protein cracks; *D* is the distance at which the crack passes through the hydroxyapatite composite material; *L* is the length of the hydroxyapatite sheet.

Therefore, the required fracture energy for crack propagation in the tibia is as follows:

$$W = \tau D = \tau(H + \frac{HLV}{2w}) \tag{3}$$

For the comparative investigation on how staggered structures regulate fracture toughness, an ideal hypothesis was proposed that no deflection behavior emerges during crack propagation inside the tibial tissue. The fracture energy required for this scenario is as follows:

$$W_0 = \tau H \tag{4}$$

According to Eqs. (3) and (4), in the process of crack propagation, the fracture energy consumed when the crack deflection is Δ*W* higher than that without bending. The calculation formula is as follows:

$$\Delta W = W - W_0 = \tau \frac{HLV}{2w} \tag{5}$$

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From the above theoretical analysis, increased thickness of the tibial cortical bone composite and elevated volumetric proportion of hydroxyapatite lamellae will strengthen the interfacial resistance of collagen matrices during fracturing. Accordingly, more strain energy can be dissipated in the whole damage and rupture process of bone tissues. In addition, further analytical results demonstrate that a higher aspect ratio of individual hydroxyapatite platelets can effectively promote the dissipation of fracture energy.

Fracture energy dissipation is closely correlated with crack extension distance, where an extended crack path contributes to higher energy consumption. Accordingly, during the failure process of tibial cortical bone, its intrinsic fracture toughness is predominantly governed by crack deflection behaviors induced by the staggered hydroxyapatite structure. More frequent deflection events can effectively prolong crack propagation trajectories, thereby promoting greater fracture energy absorption in the damage process. To quantitatively explore the impact of crack deflection behavior on the anti-fracture performance of tibial tissue, a crack deflection index $\lambda$ is proposed in this research. Herein, parameter $k$ is defined as the aspect ratio of hydroxyapatite lamellar units, and the computational formula of the deflection index $\lambda$ is presented below:

$$\lambda = \frac{D}{H} = 1 + \frac{LV}{2w} = 1 + k\frac{V}{2} \tag{6}$$

Where $k$ and $w$ are the aspect ratio and width of the hydroxyapatite sheet, respectively; $k = L/w$.

According to Eq. (6), the crack deflection parameter $\lambda$ is collectively dominated by the volumetric proportion $V$ of HAP lamellar structures and the geometric aspect ratio $k$ of individual HAP units. Combined with the foregoing theoretical derivation, the correlation curves between the $\lambda$ and the $V$ as well as geometric aspect ratio $k$ of hydroxyapatite lamellae are illustrated in Fig. 3 and Fig. 4. Analytical findings demonstrate that under a fixed volumetric proportion of hydroxyapatite, the crack deflection coefficient $\lambda$ exhibits a linear rising trend alongside the increased aspect ratio $k$ of hydroxyapatite sheets (Fig. 3). With the aspect ratio $k$ maintained at a fixed value, the coefficient $\lambda$ presents a linear growth trend along with the elevation of hydroxyapatite volumetric fraction $V$, as illustrated in Fig. 4.

During the process of crack propagation, the crack deflection coefficient is significantly influenced by the volume fraction and aspect ratio of hydroxyapatite sheets. Increasing the volumetric proportion of HAP can effectively elevate the deflection coefficient. Meanwhile, more energy dissipation will be generated in the evolution of tibial damage, thereby improving the overall fracture resistance performance. In the "staggered structure" constructed by hydroxyapatite and collagen, individual HAP sheets with a higher slenderness ratio deliver enhanced fracture resistance. This mechanical evolution complies with the intrinsic law that slender microscale units present better mechanical robustness.

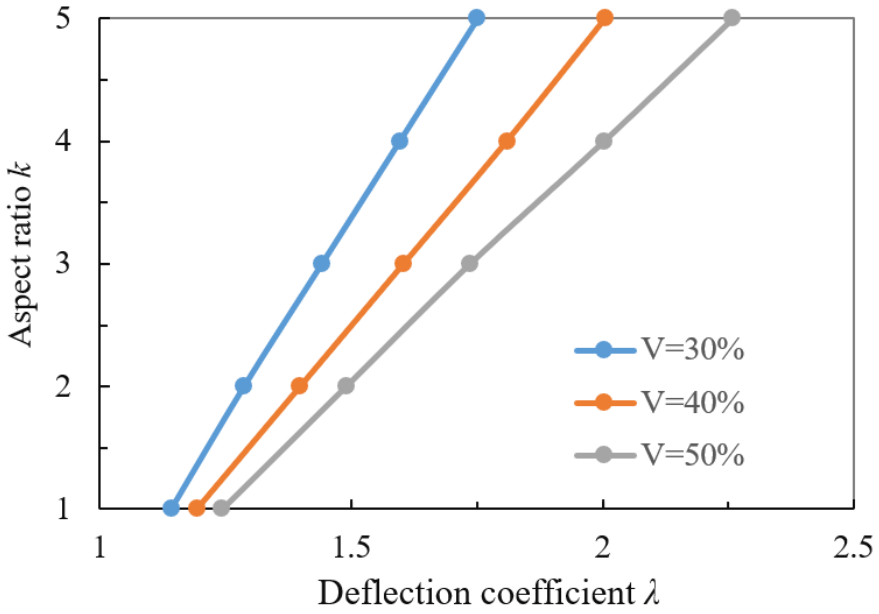


**Fig. 3: Relationship curves between1443-AJBB aspect ratio of apatite flakes and the crack deflection coefficient**

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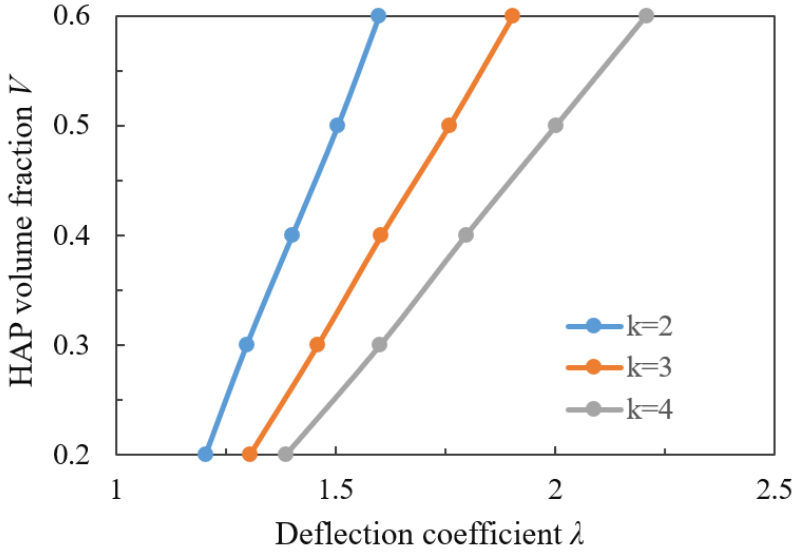
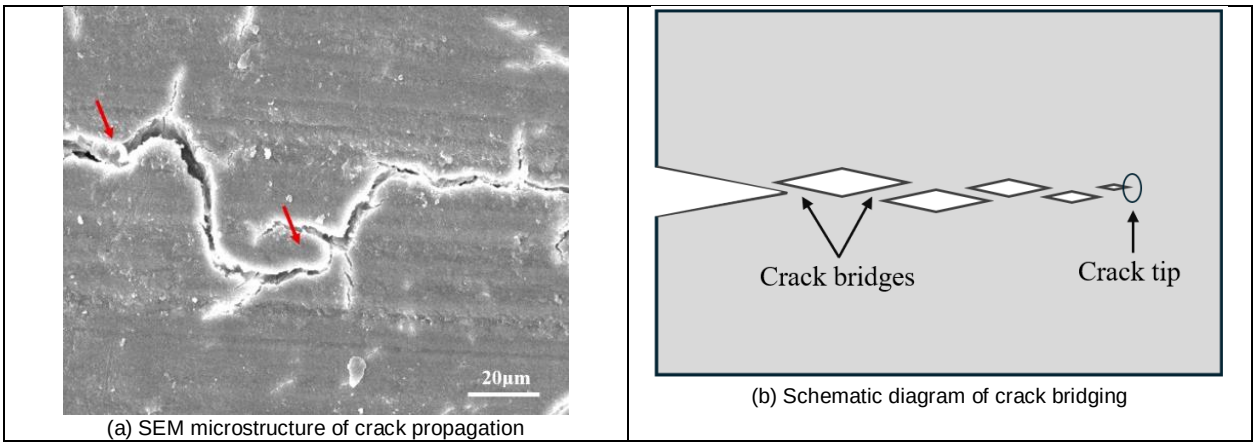



**Fig. 4: Relationships between HAP volume fraction and crack deflection coefficient**

## Effect of Crack Bridging on Fracture Toughness

Crack bridging and a schematic diagram during crack propagation in cortical bone are shown in Fig. 5. The toughening mechanism of cortical bone is relatively complex, and crack bridging is one of its main toughening mechanisms. On the basis of the influence of microstructure size parameters on the fracture toughness of the staggered structure, further investigation was carried out regarding the impact of crack bridging of cortical bone on its fracture resistance performance. In the staggered structure composite material composed of HAP and collagen, its fracture toughness is difficult to predict due to multiple mechanisms that inhibit crack propagation during fracture. However, during crack propagation in cortical bone, there is significant deflection of cracks (Fig. 5) caused by the cracks passing the interface between collagen and hydroxyapatite sheets.




(a) SEM microstructure of crack propagation

(b) Schematic diagram of crack bridging

**Fig. 5: Bridging of uncracked ligaments in cortical bone (The area indicated by the red arrow is the bridging of uncracked ligaments)**

For composite materials with staggered arrangement structures, the pull-out behavior of hydroxyapatite sheets corresponds to the crack bridging mechanism. This extrinsic toughening behavior can effectively improve the mechanical toughness of the surrounding matrix. Nevertheless, the pull-out behavior of hydroxyapatite sheets merely acts as a critical mechanism to maintain interfacial cohesion inside the staggered microarchitecture. Thus, the corresponding strengthening effect should be categorized into the intrinsic fracture toughness mechanism. During crack propagation, the pull-out of HAP sheets (Fig. 6) generates a cohesive zone with a length of $L_n$. This is the result of the closing force generated by each HAP sheet involved in the pull-out.

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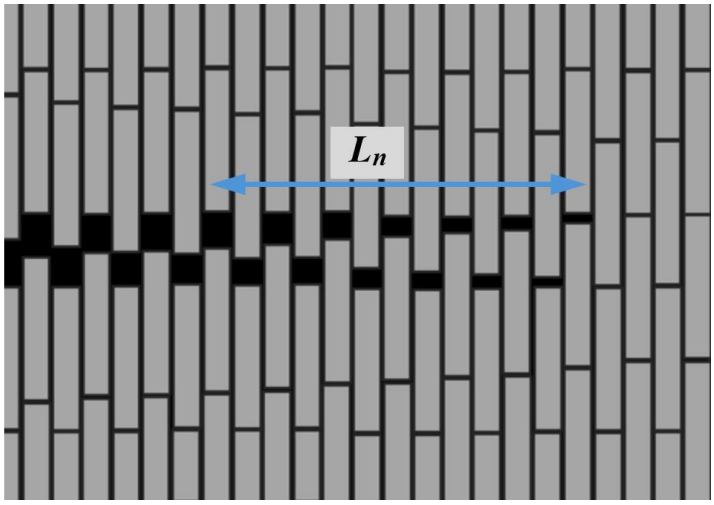


**Fig. 6: Schematic diagram of the pull-out and its cohesive zone of staggered HAP sheets**

The pull-out behavior of hydroxyapatite sheets is predominantly governed by the interfacial shear effect. On the premise that the interfacial shear strength $\tau_s$ remains uniform, the toughness of the interface can be derived by the following formula:

$$J_i = \int_0^{u_{\max}} p(u)\mathrm{d}u = \tau_S \cdot u_{\max} \quad (7)$$

Where $u_{max}$ is the sliding distance of the hydroxyapatite sheet when the interface adhesion disappears; $J_i$ is the interface toughness, and $\tau_s$ is the shear strength of the interface.

According to the mechanism of crack bridging, the fracture toughness $J_0$ of crack bridging can be calculated as follows:

$$J_0 = \frac{1}{2} \cdot k \cdot J_i \quad (8)$$

Where $J_0$ is the fracture toughness of crack bridging; $k$ is the aspect ratio of the HAP sheet; $J_i$ is the interface toughness. Eq. (8) shows that the toughness of the interface is magnified by 0.5$k$ times by the bridging.

According to the pull-out mechanism of hydroxyapatite sheets, the length $L_n$ of the adhesive region associated with crack bridging can be calculated as follows:

$$L_n = \frac{\pi}{16} \cdot k \cdot \frac{V^2}{1-V} \cdot \frac{G_j \cdot J_i}{\tau_s} \quad (9)$$

Where $G_j$ is the interfacial shear modulus between HAP and collagen; $V$ is the volumetric proportion of hydroxyapatite sheets; $J_i$ is interface toughness; $\tau_s$ is shear strength of the interfaces; and $V$ is the volume fraction of HAP.

As derived from Eq. (9), the cohesive zone length exhibits a functional dependence on the aspect ratio and volumetric fraction of HAP lamellae, as well as the interfacial material properties. Under constant interface parameters, the length of the cohesive zone increases linearly with the aspect ratio of HAP lamellae and nonlinearly with the volume fraction.

During the process of small-scale crack propagation, assuming that the length of crack propagation is enough to produce a uniformly wide tail, the energy dissipated by the staggered structure composite material during loading/unloading can be relatively easily calculated. Under this condition, the derived result exhibits negligible dependence on the geometric morphology of the crack front, and the global fracture toughness can be formulated using the following equation:

$$J = \frac{J_0}{1-\alpha} \quad (10)$$

Where $J$ is the overall toughness; $\alpha$ is the parameter of the process zone, which is composed of the crack front and tail. $\alpha$ is calculated as follows:

$$\alpha = \frac{1}{4} \cdot \left(\frac{1}{t} \cdot \frac{V^2}{1-V} \cdot \frac{G_j \cdot J_i}{\tau_s} - 1\right) \quad (11)$$

Where $t$ is the thickness of HAP lamellae within the staggered structure.

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For composites featuring staggered microarchitectures, the toughness enhancement is primarily dictated by the process zone parameter $\alpha$, and using a larger $\alpha$ will result in greater overall toughness. However, according to Eq. (10), the steady-state crack propagation assumption breaks down when $\alpha \geq 1$. Under such conditions, the predicted fracture toughness values lose physical validity, as this scenario yields a negative toughness amplification factor.

Moreover, transient cracks must be considered when $\alpha \geq 1$, as the width of the crack tail varies with the propagation of the crack. According to Eq. (11), the threshold condition for non-steady-state crack formation is presented below:

$$5t \cdot \frac{1-V}{V^2} - \frac{G_j \cdot J_i}{\tau_S^2} \leq 0 \tag{12}$$

In the unsteady-state propagation regime, determining the process zone's toughening contribution poses greater difficulties compared to the steady-state case, as the resultant fracture toughness is inherently governed by the crack tip geometry. When $\alpha<1$, the material's fracture toughness converges to a well-defined steady-state plateau. Conversely, when $\alpha>1$, the fracture toughness exhibits unbounded monotonic growth with crack extension and never attains a stable equilibrium value.

For the purpose of quantitatively investigating the impacts of microstructural dimensional parameters and volumetric fraction of HAP lamellae on the fracture resistance of staggered structure composites, $k$=5, 10, 15, $G_j$=1 MPa, and $\tau_s$ = 25 MPa are taken respectively for calculation. Assuming $t = G_j \cdot J_i/\tau_S^2$, the impacts of geometric aspect ratio and volumetric content of HAP lamellae on the fracture resistance of staggered-architecture composites are systematically presented as shown in Fig.7. As the aspect ratio of hydroxyapatite sheets increases, the fracture toughness of the staggered structure composite increases significantly. However, geometric aspect ratio is not always good as it increases, an excessively large aspect ratio will cause the hydroxyapatite sheets to be pulled apart, which is not conducive to increasing fracture toughness. In addition, when the volume fraction of HAP sheets is less than 0.6, the increase in fracture toughness is relatively small as the volume fraction (Fig. 7) increases. When the volume fraction of HAP exceeds 0.8, the fracture toughness increases rapidly and enters a non-steady-state toughening state. The above analysis indicates that the toughening of crack bridging in composite materials with staggered structures is affected by the volume fraction and structural parameters of hydroxyapatite sheets. In the steady-state toughening state, the toughening effect of crack bridging on staggered structural materials increases as the hydroxyapatite volume fraction and aspect ratio increase. Through an analysis of the effects exerted by bridging structures during crack propagation, the bridging mechanism of staggered microarchitectures in bone tissue contributes to enhancing the fracture resistance of bone. Specifically, crack bridging can significantly elevate the fracture toughness of the bone tissue.

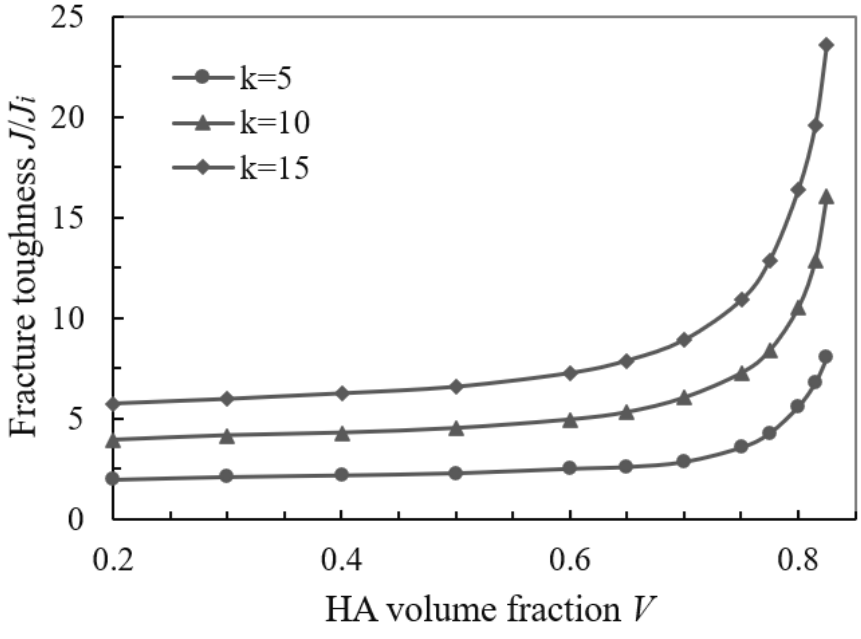


**Fig. 7: Relationship between mineral volume fraction and fracture toughness**

## Conclusion

Based on detailed microstructural observation and analysis of the tibia, this study demonstrated that it is a natural composite material consisting of HAP and collagen matrix, wherein the mineralized hydroxyapatite lamellae are organized in a staggered structure. The staggered and bridging structure analysis models were established. Through theoretical analysis, the influence mechanisms of the staggered structure and bridging of hydroxyapatite and collagen layers on bone fracture toughness were investigated:

(1) Comparing the energy dissipated during crack propagation with deflection and that without deflection, the tibial cortical bone, as a composite material, has a staggered structure formed by hydroxyapatite and collagen in it. This structure can effectively prolong the crack propagation trajectory and enhance the overall fracture energy dissipation capacity

(2) The crack deflection coefficient is directly affected by the volume fraction and aspect ratio of hydroxyapatite. The analysis results indicate that higher volumetric fractions and aspect ratios of hydroxyapatite lamellae correspond to elevated crack deflection coefficients and concomitantly increased fracture energy dissipation

(3) The crack bridging can effectively enhance the fracture toughness of tibial cortical bone. According to the crack bridging toughening mechanism operative during the fracture of staggered structure composites, progressive increases in the aspect ratio and volumetric fraction of HAP lamellae lead to a pronounced enhancement in the material's overall fracture toughness

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## Author’s Contributions

Yuxi Liu and Shuge Li: Designed and performed the experiments, analyzed the data, and prepared and revised the paper. Xiaohui He and Zhangdong Sun: Designed the experiments and participated in collecting the materials related to the experiment.

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