DAMAGE PROPAGATION IN OSTEON-INSPIRED STRUCTURES: THE ROLE OF THE CEMENT LINE

Timothy Volders (1), Laura Zorzetto (2), Hajar Razi (3), Richard Weinkamer (2), Davide Ruffoni (1)

1. University of Liege, Belgium 2. Max Planck Institute of Colloids and Interfaces, Germany 3. ETH Zurich, Switzerland, and WoodTec Group, Cellulose & Wood Materials Laboratory, Empa, Switzerland

Introduction

Bone is well known for its ability to tolerate and repair damage. Damage propagation is hampered by several toughening mechanisms at different length scales, providing high strength and toughness. Damage repair is enabled by bone remodeling, which relies on an intricate multiscale porosity to house blood vessels and osteocytes with their processes. In cortical bone, blood vessels are accommodated in the central canals of osteons, and surrounded by several concentric layers of bone lamellae. Osteons are usually bordered by thin interphases called cement lines, which are believed to interact with damage by crack deflection. Because composition and mechanical properties of cement lines are not well known, the interplay between cement line properties and damage propagation is usually explored with computer models [1]. In our study, we use computational modeling combined with multimaterial 3D printing to investigate damage behavior of osteon-inspired systems, with the specific aim to understand how damage could be deflected or trapped inside the cement line (CL).

Methods

We designed 2D osteon inspired systems featuring a central hole (Haversian canal), a circular interlayer (cement line) and a homogenous matrix containing a notch, with scaled-up dimensions compatible with 3D printing (Fig. 1A). A damage-based finite element (FE) analysis, previously used to model damage in lamellar bone [2], was used. The model assumes that a critical equivalent plastic strain is needed to initiate damage and that damage evolution is controlled by a specific energy. Increasing damage decreases material stiffness and strength. We systematically varied the initial notch position with respect to the hole as well as CL material properties (stiffness and yield stress) keeping matrix properties constant. After finding the critical notch position that causes a crack to reach the hole, we introduced the CL around the hole and we investigated damage behaviour. Specifically, we determined the contrast in material properties (defined as material contrast) between matrix and CL, which was needed to influence damage pattern at different notch positions. For each scenario, small perturbations in the notch position were considered. We then used 3D polyjet printing to prototype selected models with interlayers printed using different materials than the matrix. The models were tested under mechanical conditions representable of the FE simulations.

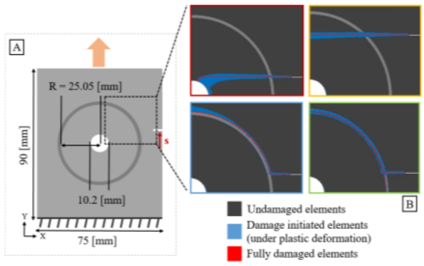

Fig. 1: FE model and main damage patterns.

Results

Different damage patterns were observed depending on CL properties and notch position (Fig. 1B): damage crossed the CL and either reached the hole or went straight, damage was trapped inside the CL or damage was deflected along the matrix-CL interface. In the two last cases, the hole was shielded. Decreasing CL stiffness and yield strength trapped damage inside the CL, whereas increasing both parameters led to damage deflection. The variation in material properties required to deflect damage was always higher than the one needed to capture damage (Fig 2). When damage met the CL at decreasing angles, the required material contrast decreased. The 3D printed samples had a qualitatively similar damaging behavior.

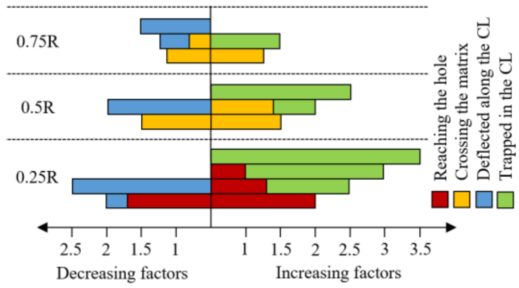

Fig. 2: Material contrast and damage behavior.

Discussion

Our results indicate that a thin interlayer can have a large influence on damage propagation. Trapping damage into the CL is less challenging than deflecting it. Cracks meeting the CL at high incidence angles may require a quite large increase in material property to be deflected (up to 3.5) which is probably challenging to be obtained in bone. This work also shows that 3D-printed synthetic materials can benefit from strategies used by bone to increase damage tolerance.

References

1. Gustafsson A. et al., Biomech Model Mechanobiol, 18, 1247–1261, 2019.
2. Razi H. et al., Bone, 130, 115102, 2020.