Fatigue of self-healing hierarchical soft nanomaterials: The case study of the tendon in sportsmen

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One of the defining properties of biological structural materials is self-healing, i.e., the ability to undergo long-term reparation after instantaneous damaging events, but also after microdamage due to repeated load cycling. To correctly model the fatigue life of such materials, self-healing must be included in fracture and fatigue laws, and related codes. Here, we adopt a numerical modelization of fatigue cycling of self-healing biological materials based on the hierarchical fiber bundle model and propose modifications in Griffith's and Paris' laws to account for the presence of self-healing. Simulations allow us to numerically verify these modified expressions and highlight the effect of the self-healing rate, in particular, for collagen-based materials such as human tendons and ligaments. The study highlights the effectiveness of the self healing process even for small healing rates and provides the possibility of improving the reliability of predictions of fatigue life in biomechanics, e.g., in sports medicine.

I. INTRODUCTION

One of the distinctive characteristics of biological structural materials is their ability to autonomically repair progressive damage, or in other words to achieve self-healing.[1,2] Typical examples are skin, bone or tendons, where the long term reparation occurs as a result of an initial damaging event.[3] Drawing inspiration from these natural systems, self-healing artificial materials have also been designed and produced, using diverse approaches and various constituents, from systems based on "microcapsules" containing a healing agent,[4,5] to "vascular-based" systems,[6,7] to "molecular-based" systems.[8,9] In particular, self-healing was found to be particularly effective in increasing the fatigue life of composites[8,10] and polymers,[11] where up to 90% recovery of fracture toughness was achieved. A review of approaches to self-healing in artificial materials can be found in Ref. 12, while a review of numerical modeling methods applied to such systems is given in Ref. 13.

In biological materials, damage generally evolves as a consequence of cyclic loading during the whole lifetime of a particular tissue. Tendons and ligaments are typical examples. Their function is to transmit forces between bones and muscles or bones and other bones, and are constituted essentially by type I collagen fibers.[1] As for other biological structural materials, they display a hierarchical structure that encompasses various size scales, ranging from collagen molecules (nanometer scale), to microfibrils, to fibrils, to fibers, to fiber fascicles, and to the final tissue itself (at cm scale).[14] Thus, tendons and ligaments can be considered an example of "soft nanomaterials". From a mechanical point of view, they can be modeled as bundles of viscoelastic fibers organized in a hierarchical structure, cyclically loaded in the fiber direction in uniaxial tension. Thus, a fiber bundle model-like approach[15] with the inclusion of hierarchy and self-healing is ideally suited to simulate the mechanical behavior of these biological structures. In previous work, we introduced such a hierarchical fiber bundle model (HFBM)[16,17] coupled with self-healing[18] to study the effects of material regeneration on the strength and toughness of hierarchical composite materials.

As mentioned above, damage to tendons and ligaments can be caused by macrotraumas but more often by

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