ABSTRACT

Microscale biological interlocking interfaces often combine features across multiple length scales to enhance mechanical properties of an organism under extreme loading conditions. The elytral suture of the Diabolical Ironclad Beetle *(Phloeodes diabolicus*) is a prominent example, in which its structural integrity arises from a hierarchy of design features. One of them, located at the interface between the elytra, is a surface architecture which provides a significant structural contribution that has yet to be explored. This study investigates how evolutionary processes have developed an asymmetric, "hook-like" shaped microtrichia decorating the elytral sutural blades, proposing a framework that combines experimental, computational and analytical tools to reveal the role of these microscale features within the overall suture structure. Mechanical testing of additively manufactured bioinspired models shows that the overlapping microstructures function as a directional linear ratchet, generating high frictional anisotropy. When integrated into ellipsoidal blade joints, the microtrichia interface increases peak load capacity by 45% and total absorbed mechanical energy by 81% compared to flat controls. Digital Image Correlation and Finite Element Analysis show that the patterned geometry promotes strain distribution across individual unit cells, replacing single catastrophic failure with damage tolerant energy dissipation. Cyclic characterization further confirms that the asymmetric architecture enables repeatable detachment and re-attachment with low resistance during re-engagement and partially decouples stiffness degradation from load-bearing capacity, where stiffness decays after the first three cycles while peak load continues to increase. To further uncover the role of these enhanced interlocking structures, we combined computational and analytical analyses, in which a proposed parametric design grid sweeping the physical variables of the unit cell reveal the effect of each variable for promoting enhanced detachment forces while preserving a smooth re-attachment. Peak force outputs from computational analyses were mapped to analytical models built on simplified representations of four competing mechanisms, which capture the observed trends across the grid. Peak force and energy dissipation data was then used to train a Gaussian Process regression surrogate model that maps the unit cell design variables; by training the model on a small subset of the grid, the surrogate predicts the response of the remaining designs and quantifies the uncertainty of each prediction. These findings can provide insights into scalable, reusable, and damage-resistant bioinspired mechanical fasteners and composite interfaces.