X-ray Tomography Evaluations of Failure in Additive Manufactured Biomimetic Structures

Curto M.[1a], Kao A. P.[2], Pani M.[1], Bucchi A.[1], Tozzi G.[2], Barber A. H.[3]

[1]School of mechanical and Design Engineering, University of Portsmouth, UK, [2]Zeiss Global Centre, School of Mechanical and Design Engineering, UK,[3]School of Engineering, London South Bank University, UK.

[a] marco.curto@port.ac.uk

Abstract. Biology is adept at producing composites optimized for mechanical function [1]. Understanding the design concepts found within biological structures and reproducing them through manufacturing routes presents significant opportunities in developing novel engineered materials. Additive manufacturing (AM) has recently become prevalent in fabricating bioinspired composites that exhibit high fidelity with their biological source, demonstrating the potential for technology transfer from biology to science [2-4]. Nevertheless, volumetric evaluation of the resulting structural organization and corresponding mechanical performance is lacking. High-resolution X-ray computed tomography (XCT) provides considerable opportunities to assess structural organization manufactured via multi-material 3D printing (MM3DP). In this study we exploit in situ XCT mechanics to resolve a 3D design inspired by the nacreous region of sea shells, manufactured via MM3DP and to evaluate mechano-mimetic effectiveness of the nacre replica.

Introduction

Molluscs presented protective hard shells 545 million years ago, which led to a further 60,000 species using similar structural organization [5]. Hierarchically organized, the protective hard shell is mainly composed at the micro-scale by two layers: a nacreous internal material covered by a hard calcite external layer (Fig. 1). Nacre is perhaps the most interesting due of its ability to dissipate mechanical energy through inelastic dissipation and crack deflection [6].

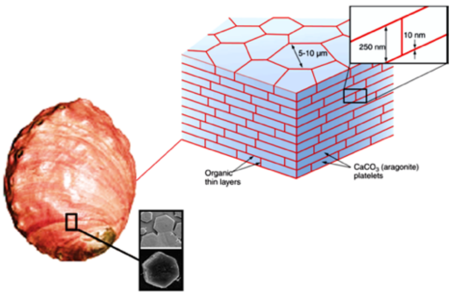

Fig. 1. Representation of the internal nacreous organisation belonging to the nacreous layer of red abalone shell. The thin organic film in red separates the aragonite bricks also covering the others not visible surfaces [6].

Traditional manufacturing techniques do not permit an accurate control of specific material properties in the space and its distribution over very small scale. As result current engineering designs are not able to replicate and take advantage of nature inspired solution. AM shows significant potential in producing engineering materials aiming at replicating nacre shell complexity, especially due to the more recent availability of multi-jetting technology to simultaneously provide 3D printing of hard and soft materials[2][4].

Experimental

In this study the latest state-of-the-art jetting technology is used to produce biomimetic nacre together replicating the contentious, but controlled failure between the hard platelets during mechanical loading. Parametric design is exploited to generate a biomimetic structure made of hexagonal platelets occupying approximately 90 mass% of the hybrid nacre (Fig. 2). A high-resolution multi-jetting material printer (ProJet 5500X, 3D Systems, USA) was used to produce biomimetic structures through deposition of hard plastic for the platelet geometries (VisiJet CR-WT, 3D Systems, USA) and soft rubber materials at the interfaces between the platelets (VisiJet CE-BK, 3D Systems, USA). The materials were chosen from the range available for use in that specific 3D printer model. The printer was operated in XHD mode with a highest 13μm spatial resolution is the z-axis. The hard plastic and soft rubber are produced using a UV curable step and are polymers of similar attenuation under an x-ray probe.

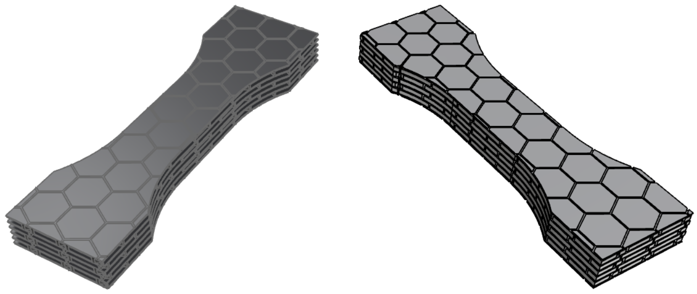

Fig. 2. Design schematic showing (left) the distribution of soft matrix material with the complementary hard counterpart made of platelets (right) from the generative design algorithm.

Fig. 3 shows XCT evaluations of the resultant biomimetic nacre structure with an emphasis on maximizing contrast between the similar polymeric materials. Subsequent XCT imaging of the biomimetic nacre is performed in situ under mechanical deformation to failure. Fig. 3 provides direct evidence of the dominant failure mode through crack deflection between platelets. Curves are reported to demonstrate the effects of the parametric control over the fibre's aspect ratio.

Conclusion

Regular hexagonal platelets in a repeating organization are clearly identified in Fig. 3 as well as the lower volume fraction rubber material between the hard platelets. Our results demonstrate considerable interfacial failure within the biomimetic nacre confirmed by XCT that is comparable to the failure found in biologically formed nacreous regions of shell. This failure is highlighted as being effective for enhancing the toughness of additive manufactured structures. The incorporation of XCT into workflows to assess additively manufactured parts is powerful especially when composite structure incorporating multiple polymeric materials are used for biomimetic design.

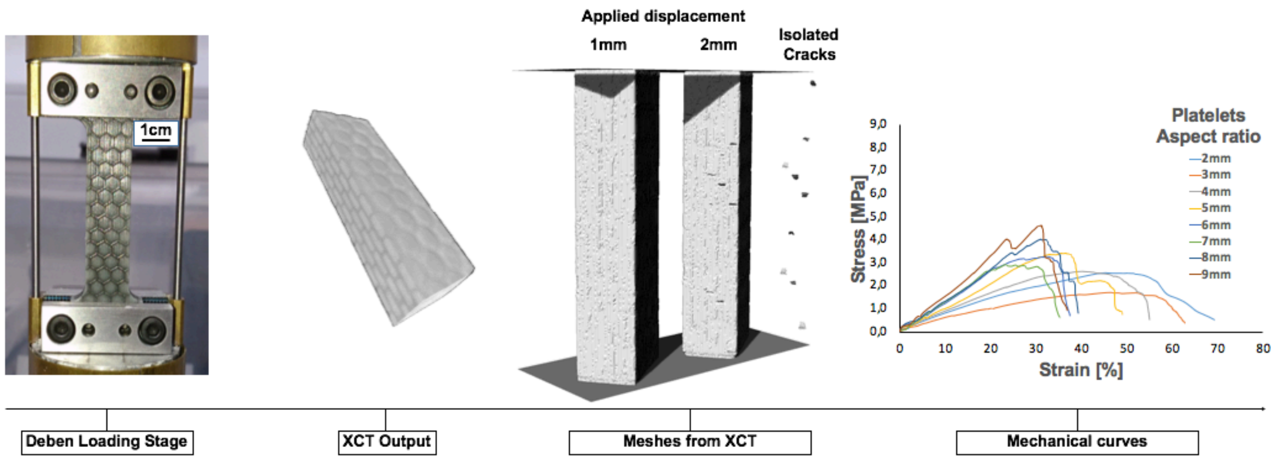

Fig. 3. Crack development within the Hybrid Nacre composite when a load is applied while preforming high-resolution XCT.

References

[1] Dunlop, J. W. C.; Fratzl, P. Biological Composites. *Annu. Rev. Mater. Res.* **2010**, 40 (1), 1–24.
[2] Dimas, L. S.; Bratzel, G. H.; Eylon, I.; Buehler, M. J. *Adv. Funct. Mater.* **2013**, 23 (36), 4629–4638.
[3] Parwani, R., Curto, M., Kao, A. P., Rowley, P. J., Pani, M., Tozzi, G. and Barber, A. H. *ACS Biomater. Sci. Eng.*
[4] de Obaldia, E. E., Jeong, C., Grunenfelder, L. K., Kisailus, D. and Zavattieri, P. *J. Mech. Behav. Biomed. Mater.* **2015**, 48, 70–85
[5] Sarikaya M. and Aksay I A 1995 Polymers and complex Materials Biomimetics, Design and Processing of Materials
[6] H. D. Espinosa, A. L. Juster, F. J. Latourte, O. Y. Loh, D. Gregoire, and P. D. Zavattieri, "Tablet-level origin of toughening in abalone shells and translation to synthetic composite materials," *Nat. Commun.*, vol. 2, no. 1, pp. 173–179, 2011.