

Sep 17th, 12:00 AM - Sep 19th, 12:00 AM

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Recommended Citation

Mirkhalaf, M., Zhou, T., Hannard, F., & Barthelat, F. (2018). Strong and Tough Ceramics Using Architecture and Topological Interlocking. In T. Siegmund & F. Barthelat (Eds.) *Proceedings of the IUTAM Symposium Architected Materials Mechanics, September 17-19, 2018*, Chicago, IL: Purdue University Libraries Scholarly Publishing Services, 2018. <https://docs.lib.purdue.edu/iutam/presentations/abstracts/51>

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Strong and tough ceramics using architecture and topological interlocking

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KEYWORDS:

Bio-inspiration, Architected Materials, Topologically Interlocked Materials, Ceramics, Impact loading, out-of-plane loading

The development of materials with improved combinations of properties and functionalities is critical for technological advances [1, 2]. A practical pathway to address this challenge is to manipulate material architecture [3-5], a strategy which is been used abundantly in nature [6, 7]. In particular, geometrical interlocking between relatively rigid building blocks is a powerful mechanism that adds stability, generates non-linear deformations and delays localization in materials that would otherwise be brittle [8, 9]. The design space for architected materials is vast, and which interlocked architectures are the most effective for specific loading configurations remains an open question.

In this work we developed a fast and inexpensive combination of 3D printing and pressure casting to create architected ceramic panels made of a brittle ceramic (calcium sulfate) to explore the effect of block geometry on performance. We fabricated and testing 15 different interlocking geometries based on convex polyhedral shapes that include platonic solids such as tetrahedron, cube, octahedron, and dodecahedron as well as non-platonic solids such as rhombohedron and truncated versions of platonic shapes. Architected panels were assembled and tested in quasi-static and impact loading (1 m/s) along the out-of-plane direction (Fig. 1a). In order to focus on the effects of geometry, the overall size of the panels (35 by 35 mm), the number of blocks (7 × 7) and the areal density were kept constant for all designs (1.09 g/cm²). Compared to monolithic calcium sulfate which fails catastrophically and at small deformations, the architected panels could undergo large deformations and absorb a large amount of energy by friction between the blocks. Remarkably, some of our designs were also stronger than the monolithic plate, which we attributed to the architecture disrupting the flexural stresses (Fig. 1c). In-situ stereo-imaging was used to reconstruct the three-dimensional deformation of the panel, and to determine the displacements and rotation of individual blocks at different stages during the test. This data revealed the details of a two-step deformation mechanism for the panels that is first dominated by collective sliding and rotation of several blocks around the point force, and then by the displacement of the center block only (Fig. 1c). The best overall performance was achieved with panels made octahedral blocks, which were about 15% stronger than the monolithic panels and could absorb 35-50 times more energy (Fig. 2).

There are several parameters that govern the performance of the architected panels and the mechanics of interlocking is complex, which makes predictions difficult. Here we show that the performance of various architectures can be captured with a single non-dimensional number based on the elastic strain energy stored by individual blocks during interlocking. This number is relatively easy to compute for any arbitrary geometry of building blocks, and it can therefore serve as a predictor for the efficacy of many more possible architected panel geometries and arrangements.

Fig. 1: Mechanical behavior of the architected panels. (a) Schematic of the loading set up. (b) 3D reconstruction of the panels during the test; (c) force-deflection curves for monolithic and architected panels based on octahedron blocks, and average sliding/rotation of blocks during the test; (d) Post-mortem monolithic and architected panel.

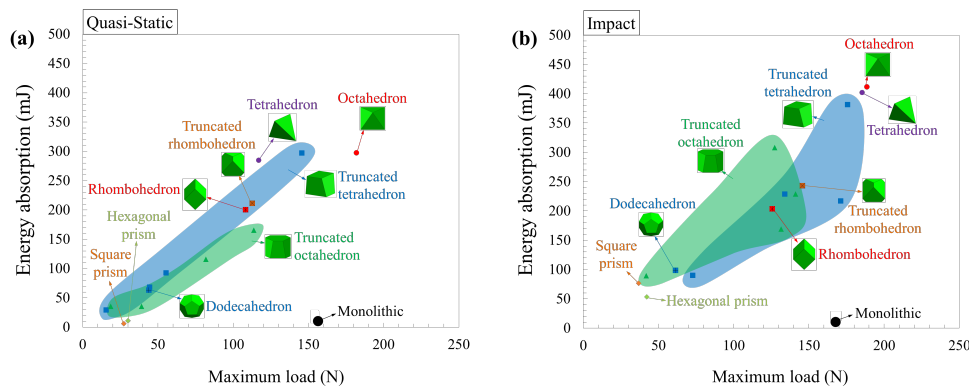
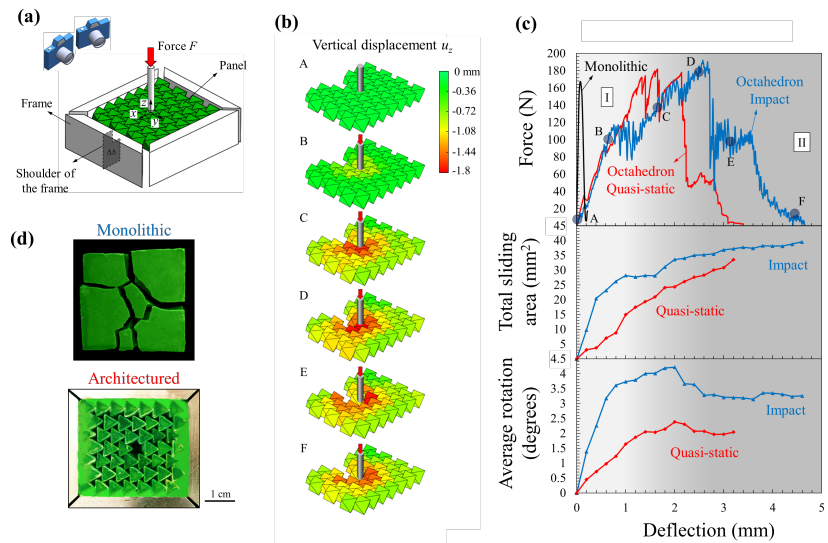


Fig. 2: Material performance charts for different architected panel designs tested in (a) quasi-static and (b) impact conditions.

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