Simultaneous improvements of strength and toughness in topologically interlocked ceramics

Mohammad Mirkhalaf*, Tao Zhou*, and Francois Barthelat*†

*Department of Mechanical Engineering, McGill University, Montreal, QC H3A 2K6, Canada

Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved July 23, 2018 (received for review April 27, 2018)

Topologically interlocked materials (TIMs) are an emerging class of architectured materials based on stiff building blocks of well-controlled geometries which can slide, rotate, or interlock collectively providing a wealth of tunable mechanisms, precise structural properties, and functionalities. TIMs are typically 10 times more impact resistant than their monolithic form, but this improvement usually comes at the expense of strength. Here we used 3D printing and replica casting to explore 15 designs of architectured ceramic panels based on platonic shapes and their truncated versions. We tested the panels in quasi-static and impact conditions with stereoimaging, image correlation, and 3D reconstruction to monitor the displacements and rotations of individual blocks. We report a design based on octahedral blocks which is not only tougher (50×) but also stronger (1.2×) than monolithic plates of the same material. This result suggests that there is no upper bound for strength and toughness in TIMs, unveiling their tremendous potential as structural and multifunctional materials. Based on our experiments, we propose a nondimensional “interlocking parameter” which could guide the exploration of future architectured systems.

Significance

Topologically interlocked materials (TIMs) use frictional sliding to generate large deformations and build toughness in otherwise all brittle components. TIMs can be up to 10 times more impact resistant than their monolithic form, but this improvement usually comes at the expense of static strength. Here we report a TIM design based on octahedral blocks which is not only much tougher (50×) than monolithic plates of the same material, but also stronger (1.2×). With no evidence of upper bounds for strength and toughness, TIMs have a tremendous potential as high-performance structural materials. Based on our experiments we propose a nondimensional “interlocking parameter” which could guide the exploration of new TIM designs and other new architectured systems.

Author contributions: M.M. and F.B. designed research; M.M. and T.Z. performed research; M.M. and F.B. analyzed data; M.M. and F.B. prepared the figures; and M.M. and F.B. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Published under the PNAS license.

1To whom correspondence should be addressed. Email: francois.barthelat@mcgill.ca.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1807272115/-/DCSupplemental.

Published online August 23, 2018.
Fig. 1. Fabrication steps for the architectured panels: (A) three-dimensional printing of polymeric building blocks; (B) the 3D printed blocks are transferred to a substrate; (C) silicone is poured to make a negative replica that serves as the mold; (D) the 3D printed blocks are removed from the cured silicone mold; (E) calcium sulfate (CaSO₄) is pressure cast into the silicone mold; (F) the building blocks are assembled and tape-transferred into an aluminum frame.

Mechanical Performance

The response of the panels to a transverse concentrated force was measured in quasi-static and impact loading conditions (Fig. 3A). The panel was simply supported and confined laterally by an aluminum frame. A localized force (or a 1-m/s impact) was applied on the top face of the center block. Fig. 3B shows the responses of an architectured panel made of octahedral blocks in quasi-static and impact conditions together with the behavior of a monolithic calcium sulfate panel of the same areal density. As expected, the monolithic panel produced a linear elastic response immediately followed by a brittle failure at small deflections (~0.1 mm). Failure was catastrophic, with multiple cracks and fragmentation that extended to the edge of the panels (Fig. 3C). In contrast, the architectured panel produced a bell-shaped response typical of tough materials. Compared with the monolithic panel the initial stiffness was in general lower, but the maximum deflection and the energy to failure were an order of magnitude greater. In addition, failure was localized with only the center block missing at the end of the test (Fig. 3C). We also used in situ stereiimaging, image correlation, and 3D scene reconstruction to measure the 3D displacements and rotations of the individual blocks during the tests (see Methods for details). The 3D reconstruction shape obtained from image correlation at six snapshots (points A–F in Fig. 3B) at various times during impact are shown in Fig. 3D. Typical results show that individual blocks rotate and slide on one another near the impact site (the deformation mode in quasi-static was identical). To characterize relative block motion for the entire plate, we computed the total sliding area at the interface and the average block rotation at different time points during the experiment. Taken together, these results point to a well-defined and repeatable deformation mode that follows two distinct stages (Fig. 3B): In the prepeak regime (region I), the average rotation and sliding area between the blocks rapidly increases with panel deflection. As the blocks slide on one another their contact area decreases, which is compensated by an increased geometrical locking so that an increasing force is produced. The slope of the force-deflection curve decreases gradually as the sliding increases, with fluctuations attributed to stick-slip mechanisms which are typical of dry friction (37). At the onset of transition from stage I to stage II, several sharp drops can be observed in the force-deflection curve due to surface cracking and chipping of individual blocks. The force however keeps increasing after each drop as the blocks reinterlock. In this example the maximum force (~180 N in quasi-static and ~190 N in impact) was achieved in this plateau-like region. In the postpeak region (stage II), sliding only occurs at the interface between the center block and its neighbors, so that the total sliding area increases more slowly with deflection. The average rotation of the blocks also
decreases as the deformation of the panel partially recovers (Fig. 3B). The panel finally fails by complete push-out of the center blocks, in this case at a displacement \( \sim 3–4.5 \) mm. The failure is therefore localized, and the panel largely retains its shape and structural integrity, in contrast with the monolithic panel which failed catastrophically with multiple cracks (Fig. 3C).

The shape of the force-deflection curves and these mechanisms were similar for all of the panels (SI Appendix, Figs. S2 and S3). However, the performance of the panels in terms of stiffness, strength, and energy absorption (area under the force-deflection curve) varied across geometries. In general, the stiffness of the architectured panel was about 50–75\% lower than the monolithic panel (SI Appendix, Fig. S4). The strength was on the same order, but the energy absorption was far greater. All properties improved significantly with increasing interlocking angle, up to \( \theta = 20^\circ \) (Fig. 4A–C). Stiffness tripled from \( \theta = 0^\circ \) to \( \theta = 20^\circ \), and maximum force and energy absorption increased by a factor of \( \sim 10 \). These improvements in overall properties were generated by the increased interlocking between the blocks which restricted their relative motion. Interlocking angles higher than \( \theta = 20^\circ \) however generated excessive contact stresses at the interfaces, which damaged individual blocks more extensively. In particular, surface damage to the blocks decreased interlocking strength so that no further improvement was achieved for \( \theta > 20^\circ \).

The stiffness of the panel was similar in quasi-static and impact conditions, but the panels tested in impact produced higher maximum forces and energy absorption. We attributed these rate effects to four factors: (i) the monolithic ceramic was \( \sim 10\% \) weaker (in terms of maximum force) in quasi-static loading compared with impact loading, which can be explained by sub-critical growth of flexural cracks in quasi-static loading, a well-documented effect in the failure of brittle materials (38). (ii) The sliding of the blocks is more extensive in impact loading (Fig. 3B). Indeed, previous studies showed that the static (39) and dynamic coefficients of friction (40) reduce significantly with the slip rate. This reduced coefficient of friction results in lower frictional stresses, which delays surface damage. In turn, delayed damage to individual blocks results in improved strength and in the spreading of sliding to more interfaces, resulting in improved energy absorption. We recently observed that reducing coefficient of friction improves performance in other types of interlocked architectures (35). (iii) The attenuation of elastic waves by the periodic architecture of the panels is another mechanism that can contribute to the improvement of energy absorption in impact (41).
Finally, (iv) the inertia resistance of individual building blocks may contribute to increased resistance to displacement in impact conditions (42). To estimate the inertia of the panel, we used the 3D reconstructed data to measure the velocity of each of the individual blocks at the time of impact. The kinetic energy of each block was then computed and summed over the entire panel to obtain the total kinetic energy. The result, on the order of 3 mJ, was negligible in comparison with the total amount of energy dissipated in the

Fig. 3. Mechanical response of the architectured panels. (A) Schematic of the experimental setup. (B) Force-deflection curves for architectured panels made of octahedral blocks tested in quasi-static and impact conditions. The response of monolithic plate with the same areal density is also shown for comparison. The other two plots show the total sliding area and average rotation of the blocks over the course of the test obtained from stereoimaging and 3D reconstruction. (C) Postmortem samples: Monolithic plates fail catastrophically and by fragmentation, while in architectured panels failure is localized to the central block. (D) Three-dimensional reconstruction of the panels showing the average vertical displacement of the blocks at six points (A–F) during loading.

Fig. 4. Effects of architecture on the mechanical performance. Effect of interlocking angle on (A) stiffness, (B) maximum force, and (C) energy absorption; Maximum force-energy absorption chart and for all of the architectured panels explored in this study tested in (D) quasi-static conditions and (E) impacts. The width of the colored regions is representative of the variations in the experimental results.
The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–400 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–200 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–200 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–200 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–200 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–200 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.

**Summary**

In this study we have systematically explored topologically interlocked panels made of convex ceramic blocks. Under impact or transverse forces individual blocks slide and rotate, providing large deformations and toughness which leads to highly localized failure. In contrast, monolithic panels fracture in a brittle fashion and catastrophically by fragmentation. We have identified an architecture based on octahedral blocks which not only produces a 50–200 mJ. Microinertia therefore plays a negligible role in improving the performance of the panel in impact conditions.

The performance of the panels can be conveniently plotted in an Ashby chart that shows the energy absorption vs. strength in quasi-static (Fig. 4D) and impact (Fig. 4E) conditions. These charts highlight the superiority of the architected designs over the monolithic panels, and the positive effects of increasing the interlocking angle. Square-based and hexagon-based tiling geometries explored here, this geometry provides the most effective balance between interlocking strength and surface damage at the blocks due to contact stresses. These results suggest that the locking parameter could be used as a predictor of material performance for a wider range of designs and geometries, which could guide future explorations without the need for experiments or costly computational models.
other architectures to be explored, with some architectures which could lead to even higher performance (concrete blocks, nonplanar faces). The exploration of this large design space is however difficult because experiments are lengthy and numerical models are computationally costly, if at all possible. To guide this exploration, we proposed a nondimensional interlocking parameter which we show correlates well with the performance of the panel. This parameter can be easily calculated for any geometry, which could greatly accelerate the exploration of new designs (a formal proof that the proposed interlocking parameter is a performance predictor for any arbitrary geometry remains to be established). The variability of our experimental results was similar for the monolithic and architectured panels. However, it is not clear which type of distribution the strength of the TIM panels follows, because we do not have enough experiments for each configuration. The strength of the architectured panels is partially governed by the onset of sliding between the blocks, which may follow a statistical law which is different from the weakest link (Weibull) statistics (44). More experiments and models are needed in this area, and questions related to statistics of failure for TIMs remain largely open.

An important design parameter for the architectured panels is the coefficient of friction at the interfaces, which may be finely tuned by adding roughness on the surfaces of the blocks (24). Interestingly, nature is well ahead of engineers in making use of architectured materials. Materials such as bone, teeth, or mollusc shells are also made of stiff building blocks of well-defined sizes and shapes, bonded together by deformable bioadhesives. The remarkable mechanical performance of these materials (12, 45) can suggest new types of 3D architectures. In addition, the building blocks in natural materials do not simply interact through contact and friction, but also through complex polymers with sacrificial bonds, dynamic cross-links, and viscous behaviors (31, 46) which could also serve as inspiration for interfaces in synthetic architectured materials. The segmentation of load-carrying structures into smaller elements joined by weaker interfaces is a counterintuitive approach to generate mechanical performance, but biological materials and recent studies on architectured materials show that it is indeed a powerful strategy to overcome brittleness while retaining strength. New combinations of properties in these architectured materials and systems can make them attractive for a variety of application including protective panels and armors, structural panels, or high-temperature structures.

**Methods**

Details of the derivation of the interlocking parameter (strain energy model) as well as experimental methods related to fabrication, testing, and data analysis can be found in SI Appendix.

**ACKNOWLEDGMENTS.** This work was supported by Natural Sciences and Engineering Research Council of Canada and by the Fonds Quebecois de la Recherche sur la Nature et les Technologies. T.Z. was partially supported by a Summer Undergraduate Research in Engineering Award from McGill University.