Design Principles from Glass Sponges for Structurally Robust Lattices

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The hexactinellida sponge *Euplectella Asperguillum* species, commonly known as the Venus' Flower Basket, has received significant attention in the engineering and material science communities because of its remarkable hierarchical design and robustness across many scales. Its basic building blocks are composed of laminated skeletal elements (spicules) that consist of a central proteinaceous axial filament surrounded by alternating concentric domains of consolidated silica nanoparticles and organic interlayers.[1–3] Such spicules are then organized to form a cylindrical glass cage with a a base square-grid architecture reinforced by set of double diagonals that create a checkerboard-like pattern of alternating open-closed cells (see fig. 1). Notably, while the laminar architecture of the spicules has been demonstrated to result in superior resistance to fracture propagation[4] and the shape of the spicules has shown to enhance their overall strength to buckling[5], the functionality of the complex cage macroscale structures is still unknown.

Lattice materials comprising a periodic network of slender members are ubiquitous not only in nature, but also in synthetic structures and devices.[6,7] Lattice materials offer novel and unique properties, including being light weight,[8,9] having high energy absorption,[10] and having the ability to control the propagation of waves[11] as well as heat flow.[12–14] The properties and functionality of such materials are generally dictated by the arrangements of the lattice struts and the node connectivity. In particular, a minimum node connectivity of 6 is required for 2D lattice materials to be stretching-dominated, and therefore, more weight-efficient for structural applications.[15] As such, lattice materials with square architecture (which has a node connectivity of 4) are known to be very unstable when loaded along specific directions, as the only shear resistance arises from the joints.[6] and typically require diagonal bracings to stabilize them.⟹ REF ⟹I wasn't able to find REFs to support this. I will continue looking.

In this paper, we use the anatomy of the hexactinellid sponge species *Euplectella Aspergilum* skeletal system as inspiration for the design of mechanically robust lattice materials with square architecture. First, we use a combination of experiments and numerical analyses to understand the overarching mechanical functions driving the particular and regular alignment of trusses found in the sponge. Then, we utilize an optimization algorithm based on the principles introduced by the sponge, to determine the optimal configuration of reinforced square lattice to achieve the highest mechanical performance. Our results show that we can improve the structure's load bearing capacity by appropriately distributing mass between diagonals as well as choosing a particular spacing between diagonal bracings.

To understand the role of the sponge architecture, we start by comparing its performance to that of other designs. Specifically, we consider four 2D lattices, all based on a square architecture (see fig. 2(a) - see Supplementary Materials for details): *Design #A* which is inspired by the sponge and comprises a set of double diagonals going in opposite directions; *Design #B* which is similar to the sponge design but only contains a single diagonal crossing each of the closed cells; *Design #C* which is similar to bracings found in modern structural engineering and contains a crossing set of diagonal beams in every cell; and *Design #D* which has no diagonal reinforcement. Note that to ensure a fair mechanical comparison between these 4 designs, the total mass is kept constant. Moreover, for *Designs #A, #B, and #C* we also keep the ratio between the mass of the diagonals and non-diagonals struts to be identical (see Supplementary Materials for details). Finally, in all our analyses we constraint the lattices to deform in-plane. To this end, in our experiments we consider specimens sufficiently thick for which out-of-plane deformation is negligible and in the the numerical simulations we assume plane-strain conditions.

We started by testing samples of the four considered designs comprising 6×6 unit square cells. The samples were fabricated with a multi-material 3D printer ⟹(add model @James) using ⟹ name of material ⟹add info here @James. The specimens were fabricated to be 8cm by 8cm in lengths and 3cm in depth. These designs are a tessellation of 6x6 square lattice cells to minimize contributions of edge effects into our results. These specimens where placed on an Instron Model 5969 with 50kN capacity for compression testing (Figure 2(c)). The results reported in Figure 2(d) clearly show that *Design #A* (the sponge design), outperforms the other three considered structures in the amount of load it can bare before the onset of buckling occurs. Once buckling occurs, the structure fails catastrophically and thus is unable to withstand any additional loading. Furthermore, it is also important to note that all designs with diagonal reinforcement (i.e. *Designs A-C*) overlay each other in the linear regime. This is indicative that the different diagonal reinforcement designs considered do not impact the structure's overall stiffness. Design D, as expected has a higher stiffness because

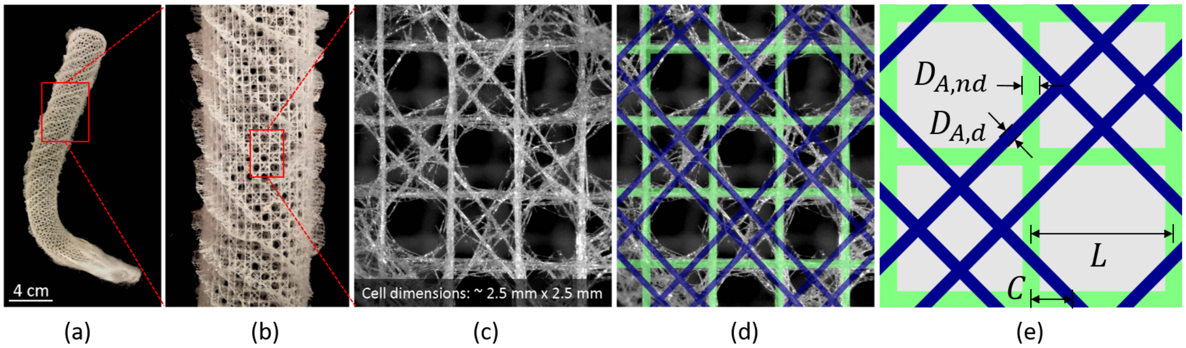

Figure 1: Hexactinellid sponge *Euplectella aspergillum*. (a)-(b) Full-frame photo of sponge. (c) Close up microscope image of the sponge. (d) Comparison between the idealized model (green and blue lines) and the sponge structure. (e) Representative volume element unit cell of the idealized model.

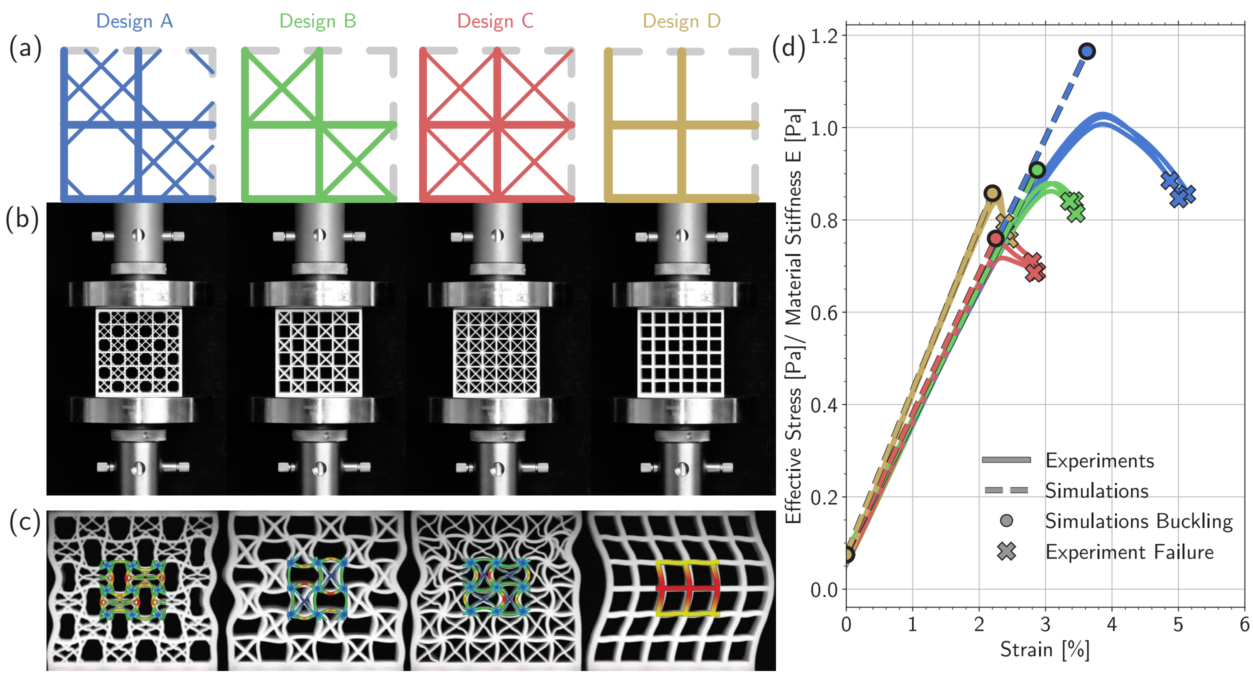

Figure 2: Experimental Results. (a) shows the different designs (Design A-D) considered in this analysis. (b) shows the undeformed experimental setup for the different designs. (c) shoes the post-buckling deformed state for each of the designs. (d) shows the experimental stress-strain curve as well as the overlaid numerical results for linear stiffness and critical buckling for the different designs considered.

of its thicker vertical and horizontal element's, however, it fails much earlier due to a shorter critical buckling strain. As a result, Design A provides the best mechanical performance without compromising the structural stiffness.

To complement the experimental analysis, we have constructed an equivalent finite 6 by 6 cells Finite Element Analysis (FEA) model. In this model we analyze the four different structure's overall linear stiffness and critical buckling strain. In fig. 2 we plot these results over the experimental results and find great agreement between out experiments and numerical model. To reduce the computational cost, we took advantage of the periodicity of the structures and investigated their response by considering a Representative Volume Element (RVE) with periodic boundary conditions along the free edges of the unit cell (more information on this can be found in the SI). For our numerical model we assume Timoshenko beam elements with uniform circular cross-sections and pin-joints at beam intersections. In an effort to create a method for impartial comparison, we maintain a constant total mass (or constant volume as the material is assumed to be incompressible) between all of the designs, as well as a constant mass ratio between diagonal and non-diagonal elements for designs containing these diagonal reinforcement.

The results presented in fig. 3(a) show that all of the structures containing diagonal reinforcement behave the same way for varying loading angles. This illustrates the fact that the structural stiffness is independent of design, but instead depend on the amount of material allocated to the perpendicular aligned beam elements. This is further supported by the graph for Design D, where all of the material from the diagonal beams is removed and allocated to the non-diagonal elements, giving the structure a higher stiffness at 0° and lower stiffness at 45°. Any stiffness at 45° in Design D is strictly a result of the bending resistance due to the pinned joints between the non-diagonal beams.

The results shown in fig. 3(b) indicate that the structural buckling strength is clearly dependent on the design and alignment of the beam elements. From this figure, we can see that Design A, the sponge design, has the highest buckling strength compared to the other designs containing diagonal reinforcement. At 45° loading, Design A improves the buckling strength by a factor of 2.5 times that of Design C, which is the commonly used truss systems.

In summary, the investigation of the *Euplectella Aspergillum's* intricate and regular structure has lead to macro-scale design principles that can be applied to general square lattice materials and structures. When compared with other diagonally reinforced square lattice designs, the sponge design has experimentally and numerically proven to provide a superior mechanism for withstanding loads prior to onset of buckling. By controlling the number of diagonals, diagonal separation and mass ratio between diagonal and non-diagonal elements, a structure's design can be optimized to withstand buckling load caring capacity.

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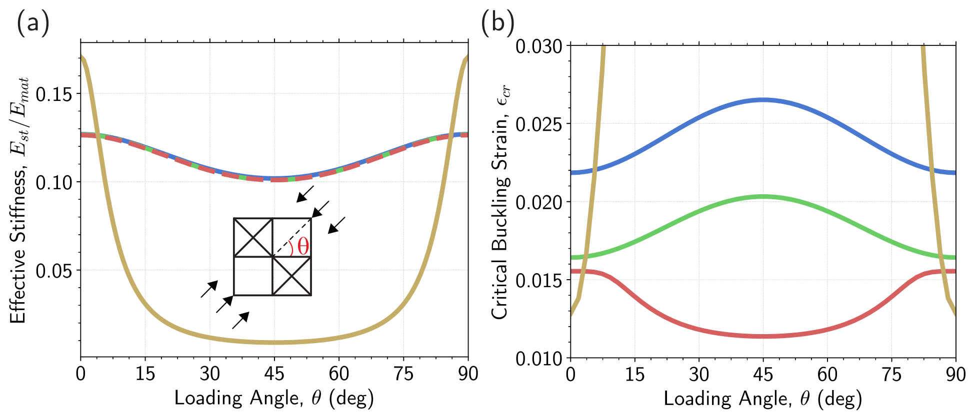

Figure 3: Structure Mechanical Response Figure showing (a) the structural stiffness for the different designs and (b) the buckling resistance for the different designs. The designs considered are depicted below as Design A-D.

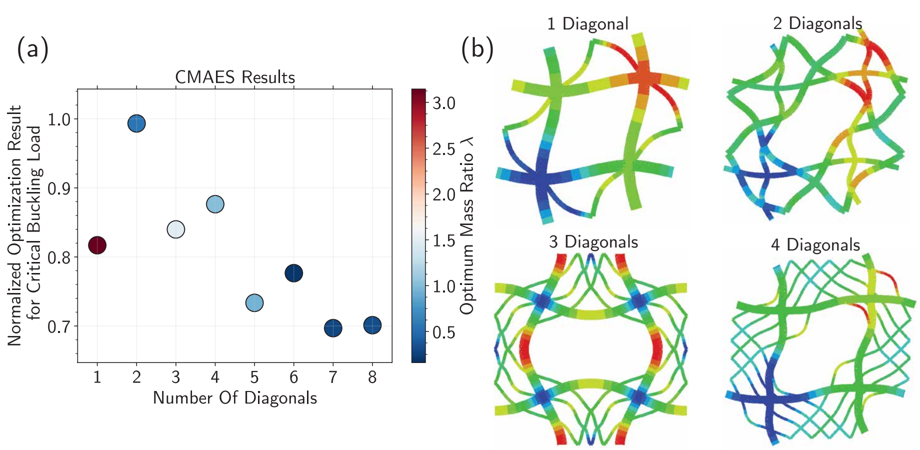

Figure 4: Critical Buckling Load Optimization Results. (a) shows the optimal value of critical buckling load for varying number of diagonals. The color of each point represents the optimal mass ratio λ parameter for that configuration. Note, we do not explicitly show the other optimal values for the diagonal spacing parameters. (b) shows the resulting deformed geometries for designs including one to four diagonals.