GEOMETRIC CHARACTERIZATION OF SCAFFOLD BUILDING BLOCKS FOR TISSUE ENGINEERING

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INTRODUCTION

Minimization schema in nature affects the arrangement of material in all objects regardless of the scale of magnitude. Be it minimal energy expenditure (soap bubbles) or structural integrity (honeycombs, bone), these rules give rise to highly ordered systems with defined, repeated architecture. The field of cellular solids has focused heavily on the elastic and plastic properties of two dimensional architectures, such as the honeycomb. Few studies, however, have investigated the effects of these minimization schemes in the formation of complex, three-dimensional architectures, such as bone. Even fewer studies have attempted to characterize the architectural properties of these shapes for the determination of the effect of material arrangement on structural integrity.

The goal of this study was to characterize the difference in mechanical properties of a group of architectures as the result of material arrangement between different shapes. Through geometric characterization of regular polyhedra, we determined quantitative differences in grossly different architectures. This research presents the first step towards developing rules which govern the effect material arrangements exert upon the specific properties of a material. This research is immediately applicable for the design of tissue engineering scaffolds which require either a specific loading conditions or are needed in load bearing applications.

METHODS

The polyhedra subset was chosen from the Platonic and Archimedean solids, which are the simplest three dimensional shapes in nature exhibiting symmetry. Four shapes were chosen for this characterization schema, displayed here in their wireframe approximations for illustrative purposes. A hexahedron (Fig 1A) and a truncated hexahedron (Fig 1B) were chosen to represent the simplest approximations of beam structures. A rhombitruncated cuboctahedron (Fig 1C) and a truncated octahedron (Fig 1D) were chosen as more complex shapes to compare to the hexahedron and octahedron. Additionally, the truncated hexahedron and the truncated octahedron contain the same number of struts and vertices, with varied material arrangement. Table 1 illustrates the differences in the polyhedra in terms of struts and vertices.

DISCUSSION

The shapes were then evaluated with a prescribed displacement finite element simulation for cases of both confined and unconfined compression. Stiffness and elastic modulus were calculated at each porosity. Material property definitions used were the same for each shape, further aiding in the calculation of effects due solely to arrangement. Elastic modulus was averaged from the confined and unconfined compression results. Elemental principle stress distribution was evaluated for each polyhedra as a method to characterize the loading on each architecture as a result of the spatial arrangement of the building material. Von Mises stress was also calculated as a method to localize any stress concentrations and stress-free elements.

RESULTS

For all polyhedra, strut length and strut diameter were linearly related, but only between each polyhedra. Additionally, the surface to volume ratio increased exponentially with increasing porosity, as expected. Interesting results were seen in the change in surface area as a result of porosity. The simplified architectures (hexahedron, truncated hexahedron) exhibited a decrease in surface area with increasing porosity. The complex shapes however, exhibited a maxima for surface area at or around 65% porosity (Fig 3). The truncated octahedron demonstrated considerably lower surface area at the low porosities when compared to the three other polyhedra. These differences are remarkable because the truncated hexahedron and the truncated octahedron both contain the same number of struts with the same diameter and it is solely a material arrangement difference.

Finite element analysis illustrated that the shapes, although containing the same material volume and enclosed within the same bounding box, exhibit considerably different mechanical properties. The modulus of the truncated hexahedron was twice that of the truncated octahedron, a shape with the same number of struts and edges. Also, there is a marked reduction in the bending of beams in the more complex shapes as a result of the material arrangement. An increase in the number of beams in an architecture results in a decrease in the high stress concentrations at the interface between the matching of beams.

Table 1. Geometric properties of polyhedra.

<table>
<thead>
<tr>
<th></th>
<th>Hexahedron</th>
<th>Truncated Hexahedron</th>
<th>Rhombitruncated Cuboctahedron</th>
<th>Truncated Octahedron</th>
</tr>
</thead>
<tbody>
<tr>
<td># struts</td>
<td>12</td>
<td>36</td>
<td>72</td>
<td>36</td>
</tr>
<tr>
<td># vertices</td>
<td>8</td>
<td>24</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>Connectivity Index</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

The chosen polyhedra were generated as wireframe approximations using computer aided design (CAD) (Fig 1). Each polyhedra was created in four volumetric porosities (50, 60, 70, and 80) and a constant material envelope (bounding box), allowing for a direct comparison of only the specific arrangement of material in each shape in comparison with each other. Geometric characterization of the architectures was completed following the generation of the architectures. Surface area, strut length, strut diameter, and porosity were used to quantitatively compare the architectures.