THE SKELETON OF EUPLECTELLA ASPERGILLUM AS FOUNDATION FOR THE DEVELOPMENT OF NOVEL COMPOSITE AEROSPACE STRUCTURES

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1 Abstract

Biological materials have long attracted the attention of researchers in different science fields owing to their unique structure and mechanical performance. This paper presents some of the key design strategies, adopted by the hexactinellid sponge E. aspergillum. The laminated configuration of the spicules and silica cement, the periodic lattice arrangement and the fusion strategies play a prominent role in enhancing the structural performance of the skeleton. It is established that the overlapping pattern of the spicules, forming the main framework, is not consistent in all sections of the lattice. Several toughening mechanisms which significantly contribute to the damage tolerance capabilities of the skeleton are identified and discussed. In addition, a novel lattice, inspired by the skeleton of E. aspergillum, is introduced. The performed determinacy analysis of the finite and infinite structures indicates that the lattice experiences pre-stressed behaviour characterised with stiffening the internal mechanisms by the states of self-stress.

2 Introduction

Advanced composite materials for aerospace structures are among those subjected to strict requirements including safety, airworthiness, system integrity, cost-efficiency and environmental compatibility [1, 2].

Along with the major design drivers, such as low weight, strength, stiffness, damage tolerance, durability and thermal stability, multifunctionality is regarded essential for composite structures to be able to simultaneously perform multiple structural and non-structural functions [1, 2]. The quest for lightweight, multifunctional and high-performance structural materials in the aerospace field, has led researchers and industry to work intensively upon improving the performance and load-bearing capacity of composites materials, by calling for novel materials, structures and manufacturing methods [1-3].

The majority of these studies are based on studying biological composites, which have long been recognized as potential sources for developing new ideas [3]. Rigid natural systems, such as bone, teeth, nacre and silica sponge are different in structure and composition, yet they share common design principles. The latter include hierarchical structure from nano to macro levels, adaptation of form and structure to function, a unique inorganic-organic composition from simple, often inferior, elements, and the presence of numerous interfaces, resulting in efficient toughening mechanisms [4]. As a result, biological composites possess high strength, stiffness and toughness, fracture resistance, a combination which is not fully achieved with engineering materials [3, 5]. The fundamental principle, however, is the inherent multiscale structure, functioning as a template for biological composites to surmount the intrinsic weakness of the building elements, and more importantly to attain multifunctionality [6, 7].

The hierarchical organisation skeleton of hexactinellid sponge E. aspergillum (Fig.1) is an excellent example of an effective design strategy for enhancing the performance of an inherently brittle material such as silica. The strength of amorphous silica is determined by the existence of surface flaws, and if its size goes beyond a few microns there is a dramatic loss of strength. Therefore, further hierarchical levels are required to adapt silica as material to a specific function as well as to build structures which are larger than few microns [8, 9].

Recently, Weaver et al. [10] have provided a detailed study on the hierarchical structure of E. aspergillum, concluding that the superior mechanical performance of the three-dimensional cylindrical lattice is based on the complex interactions between the structural levels [10]. They found that the
skeleton is consisted of two independent interwoven square lattices, formed by laminated non-planar cruciform spicules (Fig. 2). The latter are composed of layers of consolidated silica nanoparticles, arranged in concentric manner and separated by thin organic layers. In addition, the lattice framework is reinforced with vertical, horizontal and diagonal bundles of spicules, external ridges and terminal sieve plate and consolidated with laminated silica.

This study deals with measuring the structural efficiency of *E. aspergillum* (Fig. 1) and translating this methodology to develop advanced composite materials and structures for the commercial aerospace environment. The first section concentrates on the characterization of *E. aspergillum* skeleton. The key design principles are executed and discussed as a result of studying the function-property relations, adaption to specific environment and loading conditions. The second section focuses on the determinacy analysis of a lattice, inspired by *E. aspergillum* skeleton. The last section provides concluding remarks and future work discussion.

### 3 Investigation of E. aspergillum skeletal lattice

#### 3.1 Material and Methods

The specimens under investigation, originating from the Philippines, were received as dry skeletons. Numerous sections from different parts of the skeleton of the specimen were excised with a razor blade, cleaned with 10 wt. % solution of H$_2$O$_2$ and rinsed with distilled water. The excised portions of the specimens were first examined by optical microscopy and then mounted on 9 mm individual aluminium stubs using conductive carbon tabs. Subsequently, all samples were sputter coated with gold and examined with Zeiss EVO-MA10 scanning electron microscope.

#### 3.2 Results and discussion

The skeleton of *E. aspergillum* is characterised with an elaborate hierarchical organisation, ranging from nano to macro levels. We concentrated on investigating the higher hierarchical levels, identifying the key design concepts that contribute to the excellent performance of the skeleton. The main strategies, observed in the investigated specimens are described in more details in the following sections.

#### 3.2.1 Laminated structures

Laminated structure is the underlying design strategy adopted by the sponge to overcome the brittleness of its constituent material. The former is observed not only in the principle spicules of the skeleton but in the secondary silica deposited over the entire lattice (Fig. 3 A and B). The structural efficiency of the laminated arrangement has already been reported in the literature [8]. It is considered crucial for enhancing the damage tolerance of the individual spicule under bending. Such arrangement creates numerous weak interfaces which provide the foundation for the formation of efficient crack stopping mechanisms and leading to gradual rather than brittle failure of the spicules.

#### 3.2.2 Lattice framework

The lattice configuration is formed by overlapping the horizontal and vertical rays of the tetractine spicules in a way that there is alternation of nodes, containing of the axial centre of the spicules (Fig. 3C, white arrow) and nodes that do not (Fig. 3C, black arrows). In this study, the former will be referred as fixed nodes and the latter, which are positioned at the intersection between the vertical and horizontal rays, will be identified as free nodes.
Fig. 3. SEM images of the laminated structure of (A) fractured tetractine spicule and (B) laminated silica matrix; Lattice framework (C) formed by the overlap of large tetractine spicules and reinforced with bundles of smaller size spicules and (D) a splitting zone in the horizontal elements of the lattice; Fusions strategies (E) Joint on the surface of a main spicule and (F) an area of the same zone indicating the presence of several toughening mechanisms.

The resultant lattice, shown in Fig. 2 is characterised with a substantial degree of flexibility, allowing the nodes to slide past each other when external force is applied. The effect of this independence, however, is diminished by the deposition of secondary silica matrix, the reinforcing bundles of spicules and external ridges. The node pattern, however, is not consistent and this is reported here for the first time. Two neighbouring nodes comprising the spicule centre can be seen in Fig. 3D (white arrows). This configuration does not occur isolated, it can also be observed in several sections of the lattice of a different specimen (Fig. 2, white circles).

One possible explanation is the occurrence of the splits in the horizontal elements of the lattice (Fig. 3D). These splits were observed in all specimens as well as in vertical direction. The splitting could be necessary to attain a regular cell size, needed for efficient water filtration, since there is change in diameter and curvature of the skeleton from the base to the upper parts.

**3.2.3 Fusion strategies**

The principal spicules of *E. aspergillum* are fused with silica matrix to form a rigid lattice framework. The process, secondary after skeleton formation, starts from the base and extends upwards to cover the entire skeleton and the terminal sieve plate [11]. The layered silica matrix, which follows the features of the lattice, contributes for the enhanced strength of the lattice in several ways.

**Spot Soldering**

The presence spot soldering joint in areas of close contact between neighbouring elements (Fig. 3B, white arrow) instead of continuous joints along the length of the lattice leads to significant reductions in weight, since these joint are observed over the entire skeleton. In addition, the alternation of fused and empty areas may act as an effective crack stopping mechanism, impeding crack propagation further along the length of both vertical and horizontal components of the skeleton thus increasing the damage tolerance capabilities of the whole system.

**Fusion between the principle spicules**

These joints are effectively a unidirectional fibre-reinforced composite with small spicules embedded in silica matrix (Fig. 3B and E, black arrows). They occur in the junction between the load-bearing tetractine spicules and between the latter and the reinforcing bundles (Fig. 3E white arrows). In contrast to engineering composites, it is evident that the junction (Fig. 3E) is characterised with low fibre volume fraction which leads to the assumption that the silica matrix and the small spicules (fibres) might be equally responsible for the strength of the joint. While the spicules (Fig. 3E, black arrow) act as a crack deviating mechanism, the silica matrix exhibits toughening mechanisms which are typically observed in bone. The microcracking (Fig. 3F) of the matrix is a process of plastic
deformation responsible for the development of extrinsic toughening mechanisms such as crack bridging and crack deflection (white arrows) [12]. In addition, the formation of fracture lances (Fig. 3F, black arrow) contributes to the overall fracture resistance of the joint, by increasing the energy required for the crack to propagate. Such unstable fracture mechanisms lead to mixed loading conditions which are considered to be an efficient strategy for enhancing the resistance of a structure without introducing other material systems [13].

The above discussion is just an indication of the strategies adopted by *E. aspergillum*. Its structural efficiency results not only from merging material and structure, but is also due to the synergy between all hierarchical levels, each characterised with specific functional properties. Nevertheless, to be able to understand the multiscale aspects of *E. aspergillum* design strategies and translate them to engineering concepts, further extraction and investigation on the individual features at each length scale is required.

4 Analysis of a novel lattice structure, inspired by the skeleton *E. aspergillum*

Depending on the stresses that control the microscopic failure mode, the periodic lattice structures can be grouped into bending and stretching-dominated structures. The latter are characterised with high nodal connectivity at the cell vertices and microscopic stretching-dominated mode resulting in collapse of the cell elements by axial stresses, thus increasing the strength and stiffness per unit mass [14]. Finite stretching-dominated frameworks are distinguished from bending-dominated by using Maxwell’s stability criterion, which states the minimum number of struts for lattice framework to be rigid, i.e. statically and kinematically determinate [15]. Calladine and Pellegrino extended Maxwell’s stability criterion by including the states of self-stress and the state of internal mechanisms [16-18]

Since a lattice structure is a periodic framework, whose unit cell is tessellated into infinite space, the formulation of a complete determinacy necessitates extending the analysis to an infinite structure [19]. Hutchison and Fleck [20] studied the determinacy of infinite lattice structures with any Bravais lattice symmetry applying Bloch’s theorem. The study, however, concentrated on lattice structures whose end points of unit cell elements coincide of the cell envelope [20]. Elsayed and Pasini employed matrix-based method, applying Bloch’s theorem for determinacy analysis and Cauchy-Born hypothesis to calculate the macroscopic properties of lattice materials with any arbitrary topology. In addition, they applied the Dummy Node Scheme to obtain the nodal periodicity within the unit cell for lattices whose unit cell elements intersect their cell envelop [19, 21].

In this study, the methodology, developed by Elsayed and Pasini [21] was implemented to analyse a novel lattice structure based on *E. aspergillum* skeleton and more specifically at the level where the cruciform spicules are arranged to form quadrate lattice, reinforced with horizontal, vertical and diagonal bundles of spicules (Fig. 3C and 4). The diagonal bracing intersect (Fig.4) the vertical and horizontal components approximately at ¼ length of the square cell. Moreover, the ± 45° beams are grouped in pairs intersecting with each other inside the square cell of the grid framework, thus forming a lattice with open and closed cells (Fig. 4). Such configuration is beneficial not only for the water-filtering functions of the skeleton, but also represent an optimised and lightweight structural design concept.

Nevertheless, it should be noted the novel lattice structure, analysed in this study, incorporates only certain features of *E. aspergillum* skeleton, owing to the extreme structural complexity of the native skeleton. In addition, all the nodes in the lattice are assumed to be pin-jointed since the latter provide an excellent basis for predicting the performance of their rigid-jointed counterparts [18].

4.1 Determinacy analysis of the unit cell

The lattice (Fig. 4A) is characterised by a unit cell (Fig. 4B), defining its structural periodicity. The latter is achieved through translation of the primitive vectors $\vec{a}_1$ and $\vec{a}_2$ [19]. Since the mechanical performance of pin-jointed frameworks is dictated to

Fig.3. SEM image of the skeletal lattice
a great extent from their statical and kinematical
determinancy, the formulation of the kinematic and
equilibrium matrices of the finite structure is
essential [18]. They are given [18] as:

\[ A \cdot t = f \quad (1) \]
\[ B \cdot d = e \quad (2) \]

Where \( A \) and \( B \) are the equilibrium and kinematic
matrices, respectively, \( t \) and \( e \) are bar force and
deformation vectors and \( f \) and \( d \) are the joint force
and deformation vectors, respectively.

Dummy nodes (Fig. 4B) were created at the
points of intersection of the cell elements and the
cell envelope and the real and dummy nodes bases
and bar bases were formulated to generate the
kinematic and equilibrium matrices for the lattice.
The degrees of freedom related to the dummy nodes
were eliminated and the determinancy analysis of the
cell was performed by implementing the four
fundamental subspaces of the generated kinematic
and equilibrium matrices [19, 21].

The determinacy analysis showed that the unit
cell have no states of self-stress but internal
mechanisms. Thus, the finite structure is statically
determinate and kinematically indeterminate and
according to extended Maxwell criterion, is regarded
as a bending-dominated structure.

**4.2 Determinacy analysis of the infinite lattice structure**

The analysis of the infinite structure is based on
the Bloch’s theorem to define the propagation of
wave-functions through infinite lattice structure
[20]. The theorem is used to obtain the reduced
equilibrium and kinematic matrices in order to
determine the sets of periodic self-stress (SSS) and
periodic internal mechanisms (SIM) from the four
fundamental subspaces of the reduced matrices. The
sets (Table 1) were formulated at different wave
numbers (\( \omega_1 \) and \( \omega_2 \)), which are derived from the
irreducible first Brillouin zone of the reciprocal
lattice [22].

<table>
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<tr>
<th>Wave numbers</th>
<th>SSS</th>
<th>SIM</th>
<th>PFV</th>
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<tr>
<td>( \omega_1 )</td>
<td>( \omega_2 )</td>
<td>SS</td>
<td>SIM</td>
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<tr>
<td>0.2500</td>
<td>0.5000</td>
<td>0</td>
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<td>0.5000</td>
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The results (Table 1) indicate that the lattice
structure changes its behaviour. While the unit cell
contains no states of self-stress but internal
mechanisms, the infinite structure is statically and
kinematically determinate at all of the wave numbers
but one. This is due to the effect of the geometrical
stiffness, superimposed to material stiffness. The
former is usually negligible, but of substantial
importance in under-constrained systems, which are
kinematically indeterminate. In this case, the internal
mechanisms are regarded as first-order infinitesimal. They are stiffened by the states of self-stress as it can be noted from last two columns of Table 1. The determinacy analysis is extended to account for the geometrical stiffness of the infinite lattice structure [23]. The Product Force Vector (PFV) approach is used to detect the stiffening effect of periodic states of self-stress on the periodic internal mechanisms. Such internal mechanisms are classified as first order infinitesimal mechanisms accompanied by higher order strains.

5 Conclusions

The skeleton of E. Aspergillum was considered as a promising structural system for the development of novel aerospace structures. The skeletal lattice incorporates all underlying design strategies in engineering: laminated structures, beams composed of bundled spicules, fibre-reinforced composites, employing longitudinal, horizontal and diagonal stiffeners and transverse diaphragms to prevent ovalisation. Nevertheless, the effective realisation of such concepts is dependent to a great extent upon the fusion strategies. The determinacy analysis of the lattice, showed that its behaviour changes from bending dominated, at most wave numbers, to more stable one when accounting for the microscopic geometrical stiffness. Pre-stressed mechanisms are commonly observed in both nature [24] and structural engineering. This study, however, shows that such behaviour is also experienced by a periodic structure in which the pre-tension is contained in a set of bar elements. Ongoing research is concentrated on the calculation of homogeneous stiffness and strength properties of the lattice, the effect of geometrical stiffness on both microscopic and macroscopic performance and finite element simulations of lattice behaviour.

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