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Mechanical Behavior symmetry of mussel shells and numerical method for biomaterial orthotropy directions

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Introduction

Increased levels of Carbon dioxide in the atmosphere triggered a cascade of physical and chemical changes in the ocean surface. Marine organisms producing shell carbonates are regarded as vulnerable to these **physical (warming) and chemical (acidification) changes occurring in the oceans**. The bivalve mussel ***Perumytilus purpuratus*** which is ecologically relevant because forms dense **three-dimensional matrices which constitute a microhabitat for a wide variety of organisms and thus promoting significant effects on coastal biodiversity** [1]. In this work, two hypotheses are tested. Firstly, the **symmetry of the mechanical behavior of left and right valves of the mollusk**; secondly, a method can be developed to characterize the orthotropy of the shell material using computational numerical analysis, so that **orthotropy is obtained by fitting parametric surface to make FEM simulations**. This is done in order to verify that the constitutive model of the material is correct (second hypothesis), and to better **understand the mechanical system of defense against predators**.

Methods

The first study consists of **21 mussels** collected in Huasco (Northern Chile), who are subjected to a uniaxial compression test oriented on three axes: a **normal direction to the surface of the shell (d_n)**, a **radial direction (d_r)** according to the ribs and another **direction tangential to these ribs (d_t)**. A total of **378 tests were carried out** for subsequent comparison between the mechanical properties of the left and the right valve. The second study consists of obtaining the **three directions of orthotropy** prior to a computer simulation, for which the PCL library [2] is used to fit **parametric surfaces to a cloud of points**, which correspond to the barycenter's of the tetrahedral elements of the shell mesh, obtained by the Micro-CT. Finally, the normal directions to the surface are obtained by the GSA method [3], which calculates the **orthogonal projection between a point and a parametric surface**. The other directions are obtained by cross product. These directions allowed to perform simulations of the **flexo-compression test using FEM**.

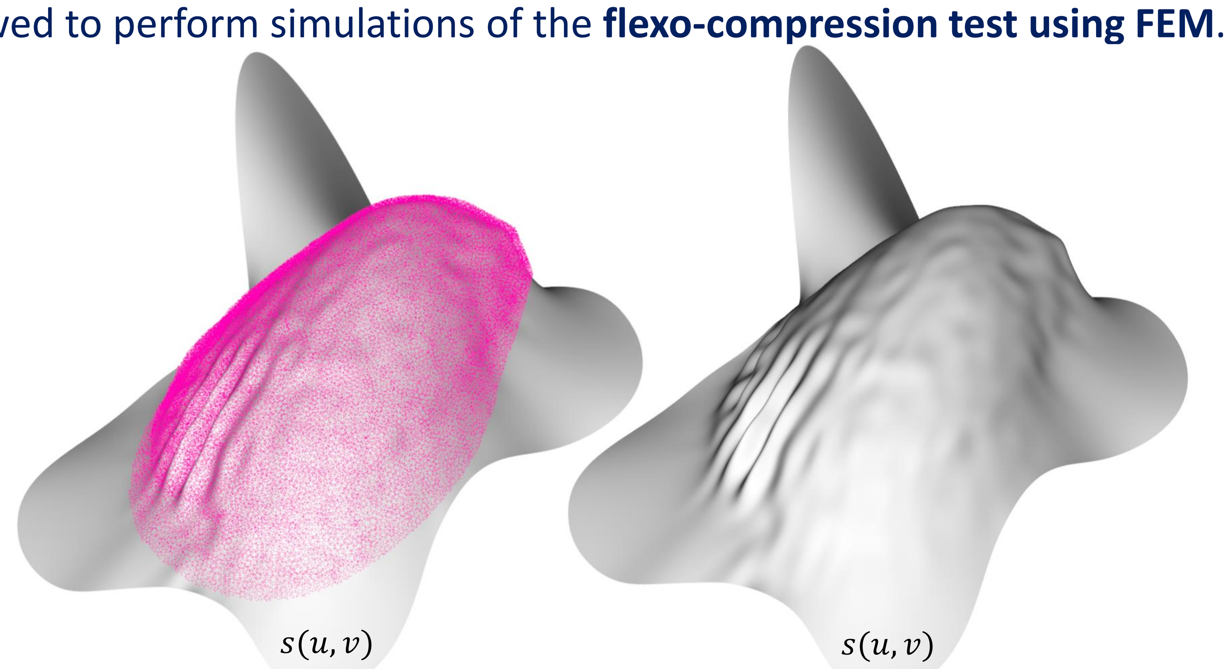

Fig 1. Parametric surface by PCL library [2]

Results

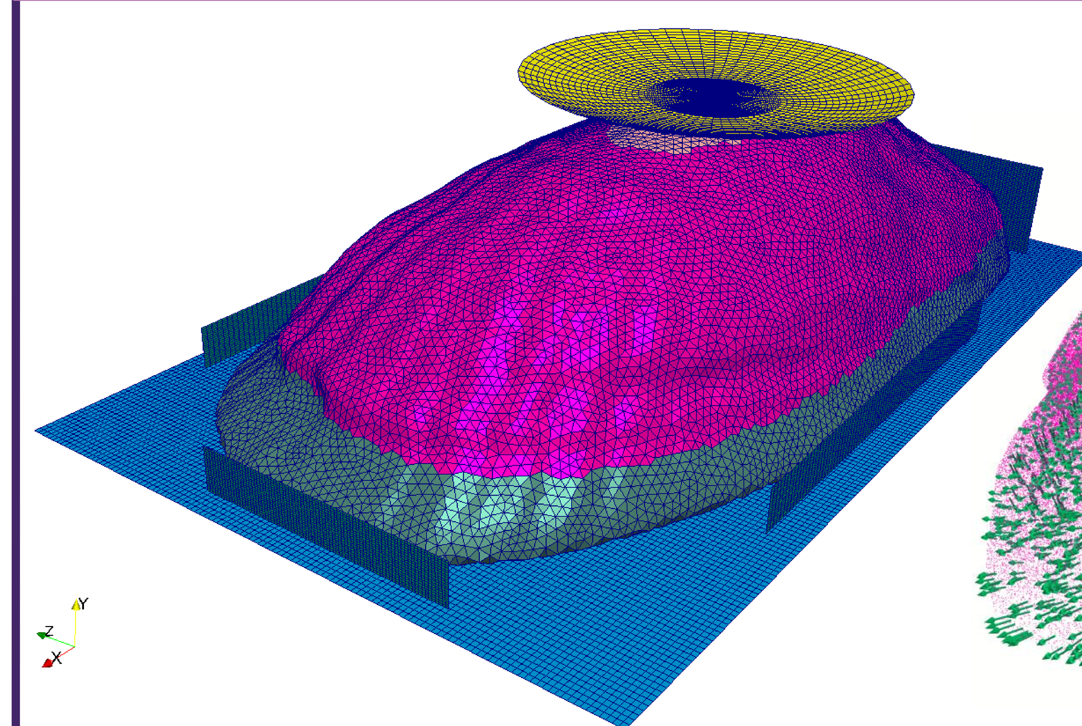

Fig 2. Simulation of flexo-compression test

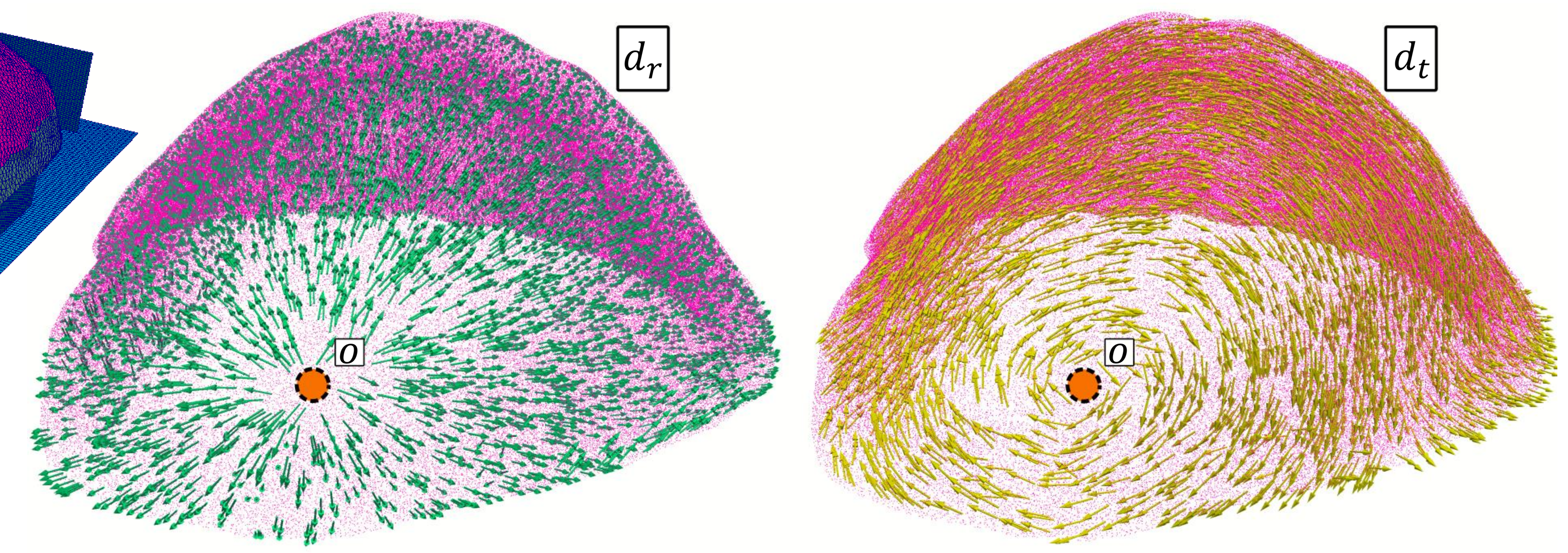

Fig 3. Radial (d_r) and tangential (d_t) direction near the umbo

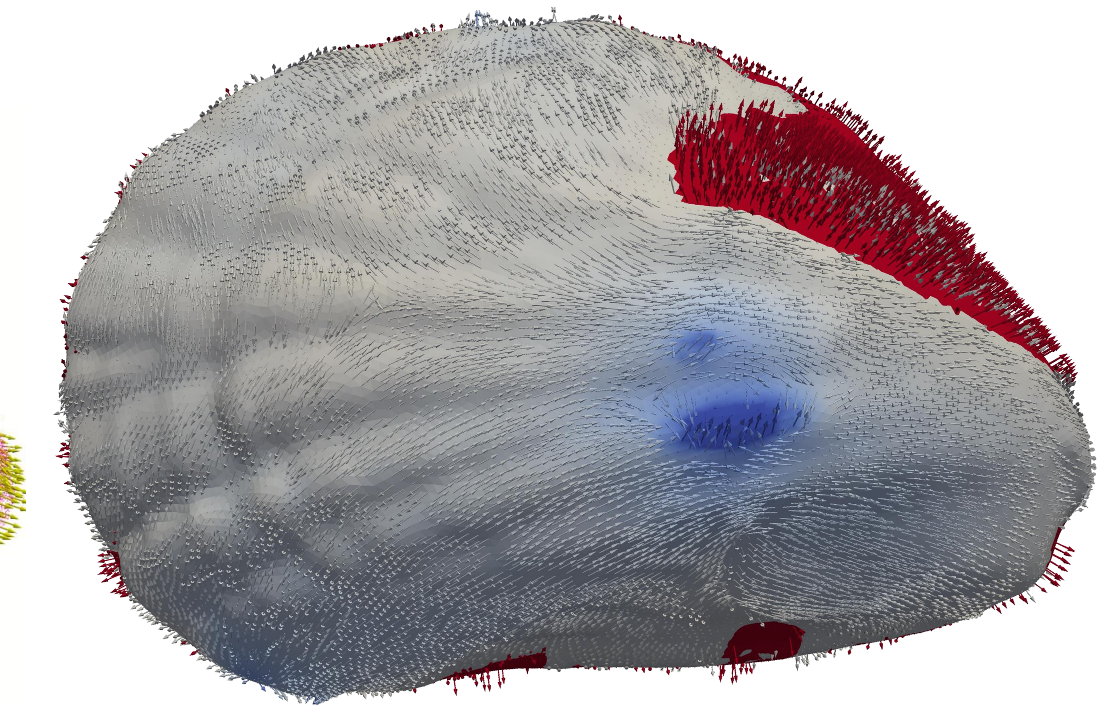

Fig 4. Principal stress 3 (σ_3) in the left valve

The first study determined through statistical analysis by the ANCOVA method, **that both shells (left and right) have the same mechanical behavior of the material**. The second study, considering the point near the umbo as the origin of the ribs, **the three directions are obtained**. This allows to perform the simulation by FEM of the flexo-compression test. By observing the magnitude and direction of the principal stress (σ_1, σ_2, σ_3), it was possible to determine the area, direction and magnitude of load in which the shell reaches the point of rupture, and how the mollusk distributes the stress in its shell when, for example, it is attacked by a predator (gastropods).

Conclusions

- The first study was able to determine that in the right left shell of the mollusk there are **no significant differences in their mechanical properties** (elastic modulus, stress and strain before the rupture of the material). In addition, it was determined that the shell material **supports a lower stress when the individual ages**.
- The first part of the second study gives excellent results by **giving orthotropy to the material in the mechanical simulation**, a method that can be used in **different biomaterials** that, like shells, are not trivial to give orthotropic directions to the material with **complex geometries**.
- The second part determined that, due to geometrical conditions, **the shell bears a greater load as the mollusk ages**. This is achieved by not concentrating the compression stress due to the length of its shell; therefore, it is useful for the mollusk, **considering that its material is deteriorated by age according to the first study**.

Numerical method

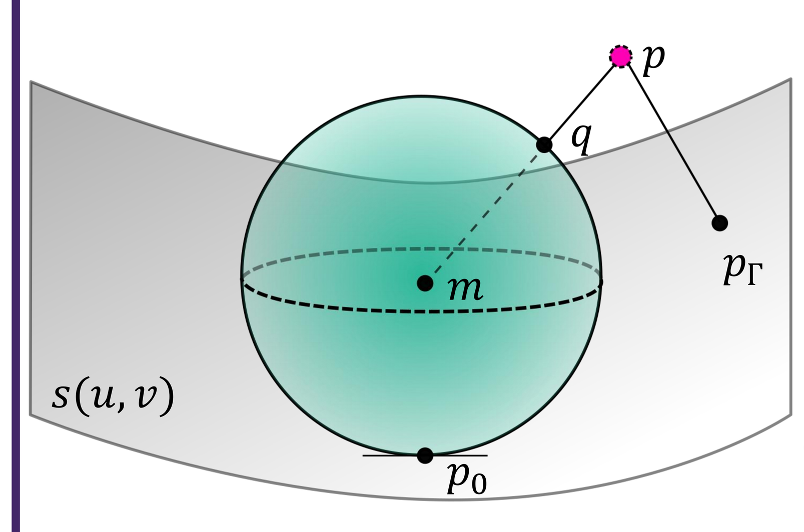

Fig 5. GSA Method [3]

The GSA algorithm [3] calculates the minimum distance between a point in space ($\boldsymbol{p}$) and a parametric surface ($\boldsymbol{s(u,v)}$), giving the closest point belonging to the surface ($\boldsymbol{p_\Gamma}$) with its corresponding parameters. The method consists in creating a sphere normal to the parametric surface (fig. 5), specifying its radius and center of the sphere **m**, **determined by the curvature of the surface itself**. When the method finds the orthogonal projection ($\boldsymbol{p_\Gamma}$) of all barycenter's ($\boldsymbol{p}$), the normal direction ($\boldsymbol{d_n}$) is calculated as: $\boldsymbol{d_n = p - p_\Gamma}$

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