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Mechanical properties of *Chamelea gallina* shells

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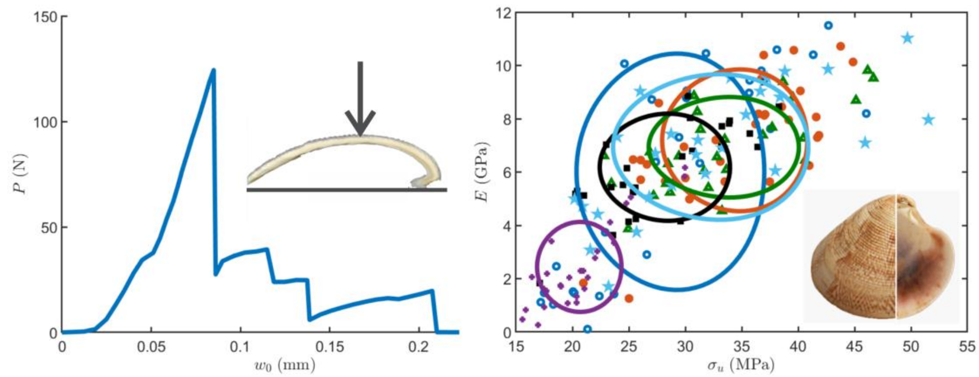
Abstract

In this work we evaluate the mechanical properties of *Chamelea gallina* shells, collected at various locations in the Adriatic Sea, through compression tests. We present an analytical model for the extraction of the material Young's modulus and ultimate strength, based on the approximation of the valves with a simpler geometry. The effect of porosity and the computation of the energy dissipated at fracture are also discussed. Results show a dependence of the mechanical performance on the location at which the samples were collected, i.e. latitude, and thus the environmental factors can affect the rigidity and strength of the shells. These findings confirm and integrate preliminary results published in a previous work.

Graphical Abstract:



Keywords

Clam shells, abiotic factors, aragonite, analytical modelling, fracture.

1. Introduction

It is well known that organisms are able to modify their development and their gene-expression patterns in response to environmental parameters, such as temperature, or to biotic factors, such as food availability or density of predators (Gilbert, 2001). Specifically, the adaptation or acclimation to changing environmental conditions is of extreme interest in developmental biology, also considering the alarming climatic changes of the last decades. Phenotype plasticity is the ability of organisms to produce a range of relatively fit phenotypes, by altering morphology, behaviour or rate of biological activity in response to variations in environmental conditions (DeWitt and Scheiner, 2004).

Calcifying marine organisms, such as corals and molluscs, are among the most susceptible species to changing abiotic factors, since they usually show morphological variations in their skeleton or shell in response to changes in external environmental conditions, e.g. temperature and pH (Watson et al., 2012; Melatunan et al., 2013). These organisms usually employ calcium carbonate ($CaCO_3$) as structural material, which is synthetized through a cascade of biochemical processes referred as biomineralization. In mollusc shells, $CaCO_3$ is found in the form of aragonite and/or calcite, which represent the basic microstructural constituents and are generally assembled within an organic matrix. When co-present, these two polymorphs are differently localized and never mixed in a solid solution (Lowenstan and Weiner, 1989).

The commercial clam *Chamelea gallina* is a common bivalve of the Mediterranean Sea and has a great importance for the fishery in several countries. For instance, the annual yield in Italy is currently about 20,000 metric tons (Romanelli et al., 2008), but it has reached 100,000 metric tons in the late 1970s. The over-exploitation of the resource, therefore, has posed recently growing concerns for the survival of these bivalve communities. In fact, unexpected annual fluctuations in stock abundance, periodic recruitment failures and irregular mortality events can threaten the biological and economic sustainability of this fishery.

The study of the effects of the changing environmental factors on *C. gallina* growth and characteristics, therefore, is of increasing interest also from an economic point of view. In a previous work, samples of *C. gallina* shells were collected at different latitudes in the Adriatic Sea, with the objective to evaluate the effects of solar radiation and sea temperature on the physical properties (e.g. geometry) of the shells. The authors found that the variation of the shell properties along the latitudinal gradient "could be the outcome of phenotypic plasticity, or a genetic adaptation of the populations subjected to different environmental parameters" (Gizzi et al., 2016). These parameters could directly affect the shell morphology and growth (Ramón and Richardson, 1992; Moschino and Marin, 2006; Matozzo and Marin, 2011), or indirectly, e.g. impacting the nutrient concentration and/or predator density.

The present paper is focused on a systematic investigation of the mechanical properties of *C. gallina* shells through compression tests. Starting from the classical theory of shallow spherical shells loaded at the centre, we consider an equivalent spherical geometry and extract the Young's modulus and the ultimate strength of the valves. The effect of the geometry, and specifically the thickness of the shells, on the macroscopic properties is discussed, as well as the influence of porosity. The toughness modulus and the fracture energy of the shells is also quantified from the experimental load-displacement curves. Additionally, we present some Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) analyses of the shells, in order to present an overview of their main composition and microstructural morphology.

2. Experimental tests

2.1 Description of the shells and locations

The clam *Chamelea gallina* (Linnaeus 1758) is a common infaunal bivalve in the family Veneridae of the Mediterranean Sea, where it inhabits well-sorted fine sand biocoenosis at 3-7 m depth (Ramón and Richardson, 1992).

A valve of the *C. gallina* shell appears as a hemi-ellipsoid object, as shown in Figure 1. Its external surface shows a roughness generated by the growth rings, while the internal surface is smooth. In general, the shell thickness, intended as the average distance between the internal and the external surface of the valve, is not constant and increases from the umbo to the periphery. In addition, the shell has usually a constant chemical composition and is made of calcium carbonate in the form of aragonite.

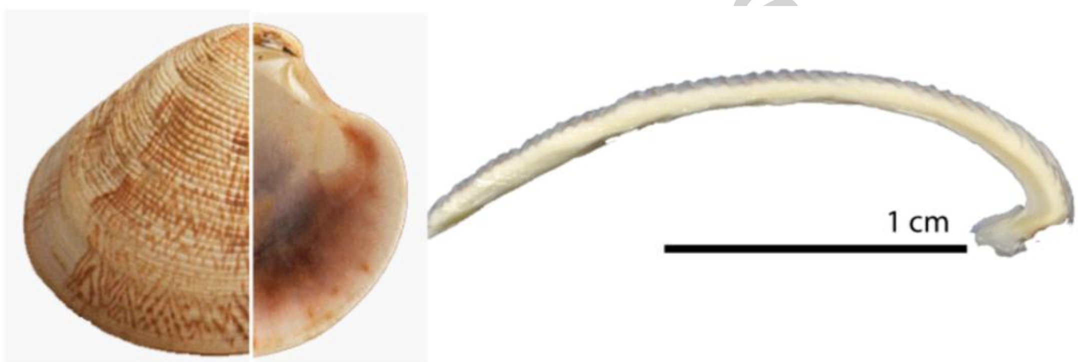


Figure 1 External and internal view (left) and cross section (right) of a valve of *C. gallina*.

C. gallina samples have been collected at various locations with different latitudes in the Adriatic Sea (see Supplementary Figure 1). In Table 1 we list the two main environmental parameters of the selected locations, i.e. the mean annual solar radiation level and the sea surface temperature, which have been demonstrated to have an impact on the shell biometry and growth, together with the main geometrical parameters used later. The number of samples denotes the number of investigated clams, thus every data reported later is related to the average between the left and the right valve of each clam. The biometric parameters of dry valves have been measured with a pair of calipers (±0.05 mm), while the volume and average porosity of each valve have been extracted by means of the buoyant weight technique, through a density determination kit Ohaus Explorer Pro balance (±0.1 mg; Ohaus Corp., Pine Brook - NJ, USA).

For all the other details concerning abiotic environmental factors and the measurement of biometric parameters, the reader is referred to the previous work on *C. gallina* shells (Gizzi et al., 2016).

Table 1 Location characteristics with average value and standard deviation of the annual solar radiation and sea surface temperature, average value and standard deviation of the main geometrical parameters and number of the investigated samples, ordered by decreasing latitudes. Adapted from (Gizzi et al., 2016).

location characteristics				**main biometric parameters**				
acronym	**latitude** (°)	**solar radiation** (W/m^2)	**sea surface temperature** (°C)	**max Feret diameter** (mm)	**min Feret diameter** (mm)	**height at shell centre** (mm)	**average shell thickness** (mm)	**number of samples**
"MO"	45.7	172.4 ± 2.5	17.90 ± 0.19	26.7 ± 1.3	22.3 ± 0.9	7.4 ± 0.4	1.6 ± 0.2	27
"CH"	45.2	160.8 ± 2.5	16.47 ± 0.19	26.2 ± 1.3	21.5 ± 1.1	6.4 ± 0.3	1.3 ± 0.2	27
"GR"	44.8	163.8 ± 2.6	16.54 ± 0.19	26.2 ± 1.6	21.5 ± 1.4	6.8 ± 0.4	1.3 ± 0.2	27
"CE"	44.2	165.2 ± 2.5	17.05 ± 0.20	26.2 ± 1.5	21.2 ± 1.2	6.4 ± 0.5	1.1 ± 0.1	31
"SB"	43.1	180.4 ± 2.6	18.60 ± 0.17	26.2 ± 1.2	21.6 ± 0.7	6.4 ± 0.4	1.2 ± 0.1	27
"CA"	41.9	180.4 ± 2.6	18.60 ± 0.17	26.0 ± 1.6	21.0 ± 1.2	6.0 ± 0.4	1.1 ± 0.1	27

2.2 Scanning Electron Microscopy (SEM)

SEM observations were carried on the transversal valve sections obtained using a steel saw. Each section was etched with an acetic acid solution (1% v/v) for 1 minute to remove debris and artefacts from cutting. Samples were coated with a gold layer (5 nm) and analysed with a SEM Hitachi S4000.

As highlighted in Figure 2, the SEM observations showed that the microstructure of *C. gallina* shell contains two main layers, according to what observed in most Venerids (Popov, 1986). The boundary region between the two layers (Figure 2a) shows fractures given by the compression tests. These fractures originate from the inner layer, while the outer layer remains nearly unaltered. The pristine sample, instead, shows a continuity of bond between the two layers. In the external layer (Figure 2b) compound prisms are observed. They are formed by an open aggregation of grains having irregular shapes and highly interconnected (Figure 2c). The inner layer is homogeneous and is formed of compact granules which give a spherulitic appearance (Figure 2d,e). Among these grains, having a size around 1 μm, layers of organic material are dispersed. The boundary region between the two layers, when observed at high magnifications (Figure 2g,h) shows a low regularity in the weaving of the particles that show larger dimensions than those observed in the external and internal state.

The lamellar multiscale structure present in *C. gallina* shells is commonly found in nacre (see, e.g., Sun and Bhushan, 2012) and in other seashells (Li et al., 2004; Li et al., 2013). Also the shells of Pectinidae present a complex fracture surface, in which it is possible to identify different layers (Li and Nardi, 2004), namely an inner and an outer part as in our case. Interestingly, the observed spherulitic microstructure (Figure 2d,e), in addition, is found very similar in nacre and conch shells treated at high temperature, where the platelets essentially assume a quasi-spherical shape (Huang and Li, 2009; Li et al., 2015).The macroscopic mechanical performance of the valves are believed to be strongly dependent on the size of the largest microstructural units (Taylor and Layman, 1972), while the organic matrix content essentially influences the Young's modulus and the fracture properties. Specifically, the organic matrix is essentially made of biopolymers that have the capabilities to strengthen themselves during deformation, as demonstrated experimentally (Xu and Li, 2011). Thus the macroscopic mechanical behaviour derives from a complex interplay of several factors, including platelets/lamellae dimensions and shapes, biopolymer content and thus the shear strength of the interfaces. The extensibility of the interfaces, i.e. their ability to sustain deformation, is fundamental for the extreme toughness observed in nacre-like materials (Barthelat et al., 2016).

The presence of two different layers confers to the shell anisotropic mechanical properties, as determined experimentally in previous works (Bignardi et al., 2010) and as we are going to quantify later in terms of toughness modulus and fracture energy.

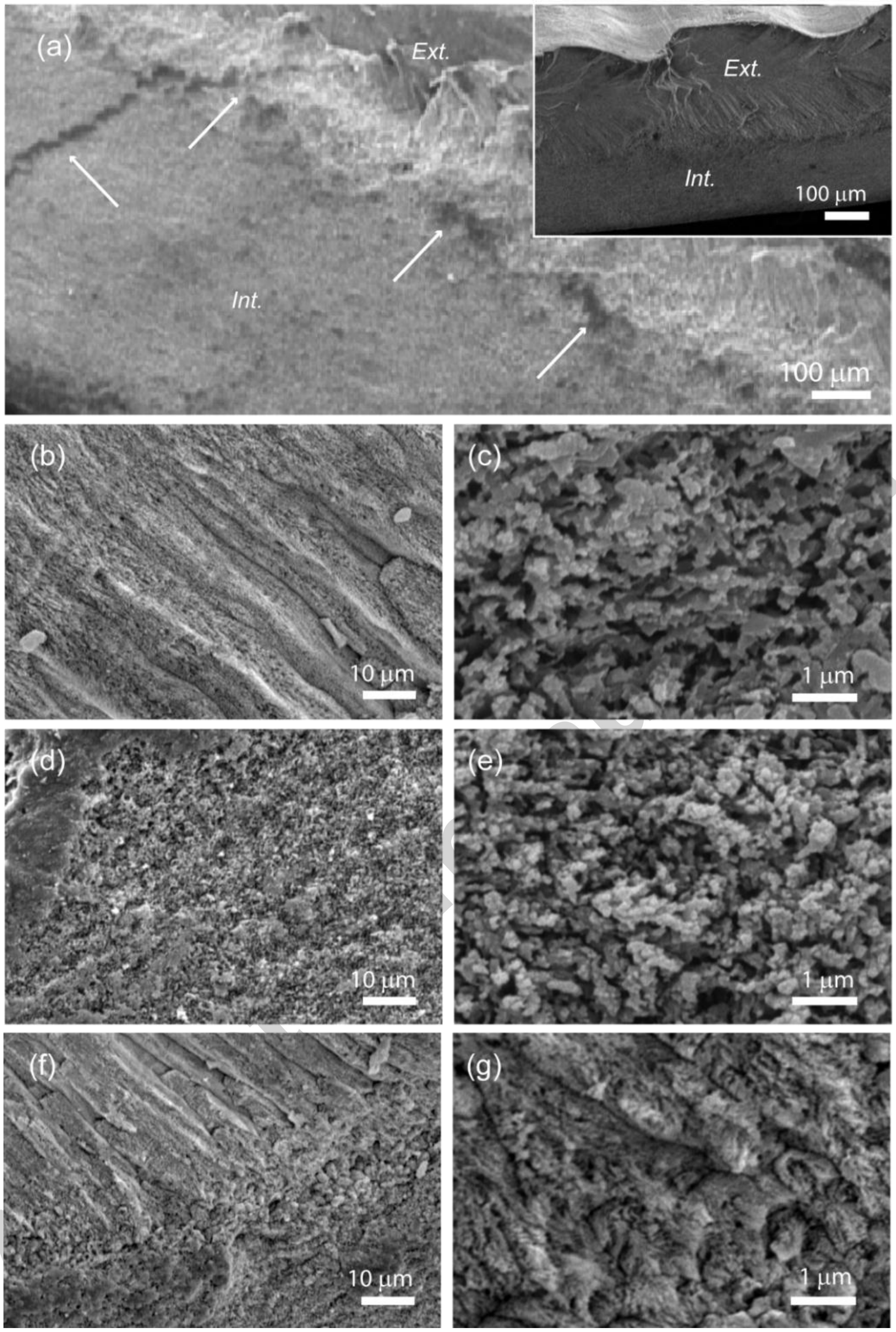


Figure 2 SEM images of the cross section of a valve of *C. gallina*. **(a)** A low-magnification image of a region close to the umbo from a valve that was compressed without fracture. The outer (Ext.) and inner (Int.) layers are observable. The arrows indicate the region were fractures were observed. Inset: cross section of a pristine sample. **(b,c)** Images of the outer layer at low and high magnification, respectively. **(d,e)** Images of the inner layer at low and high magnification, respectively. **(f,g)** Images of the outer-inner junction region at low and high magnification, respectively.

2.3 X-Ray Diffraction (XRD)

XRD analysis was performed after preparing a compact layer of powdered sample in a silica background signal free holder. Diffraction patterns for each sample were collected using an X'Celerator detector fitted on a PANalytical X'Pert Pro diffractometer, using Cu-Kα radiation generated at 40 kV and 40 mA. Data were collected within the 2θ range from 15° to 60° with a step size of 0.02° and a counting time of 1200 s. Fixed anti-scatter and divergence slits of 1/16° were used with a 10 mm beam mask and all scans were carried out in "continuous" mode.

The diffraction pattern is shown in Figure 3, where all the diffraction peaks are indexed according to the structure of aragonite (Pilati et al., 1998).

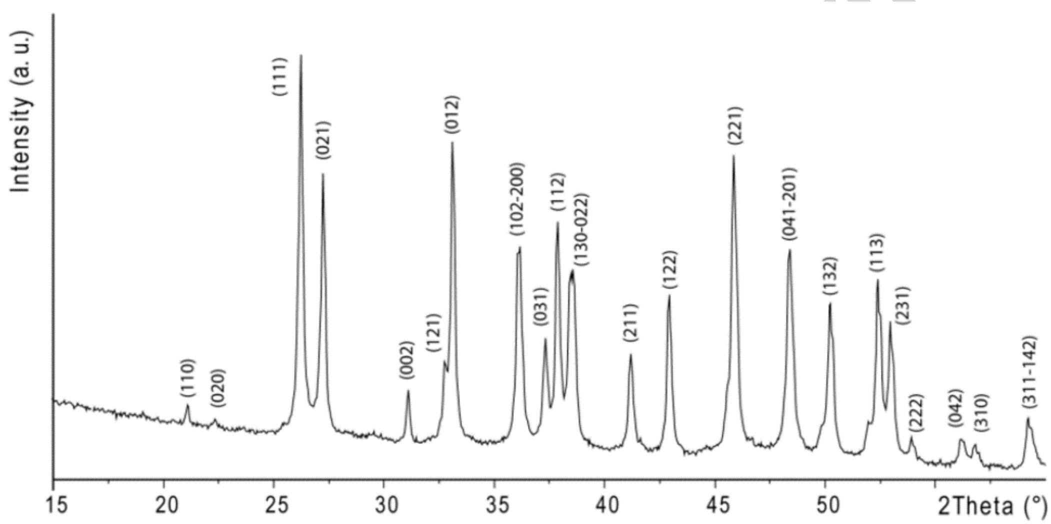


Figure 3 XRD pattern of a sample of ground shell. The diffraction peaks were indexed according to the reference JCPDS card 41-1475 (Keller et al., 1989).

2.4 Compression tests

The compression tests for the evaluation of the mechanical properties of the *C. gallina* shells were carried out in displacement control using an Instron universal testing machine equipped with a 1 kN load cell, as shown in Figure 4. The load using a 3 cm diameter compression platen moved at a constant downward speed of 0.5 mm min^{-1}. Each valve was treated with a 5% sodium hypochlorite solution for three days, in order to completely remove any trace of external organic tissue, and with a 1 M sodium hydroxide solution for one day, for the hydrolyzation of the residual proteic materials from the shell surface. Samples were then rinsed with distilled water and dried at room temperature for one day. We test dry samples because the mechanical response of the shells could be influenced also by their water content, which is believed to be responsible for the viscoelastic behaviour (Mohanty et al., 2006), but this investigation is beyond the scope of the present work.

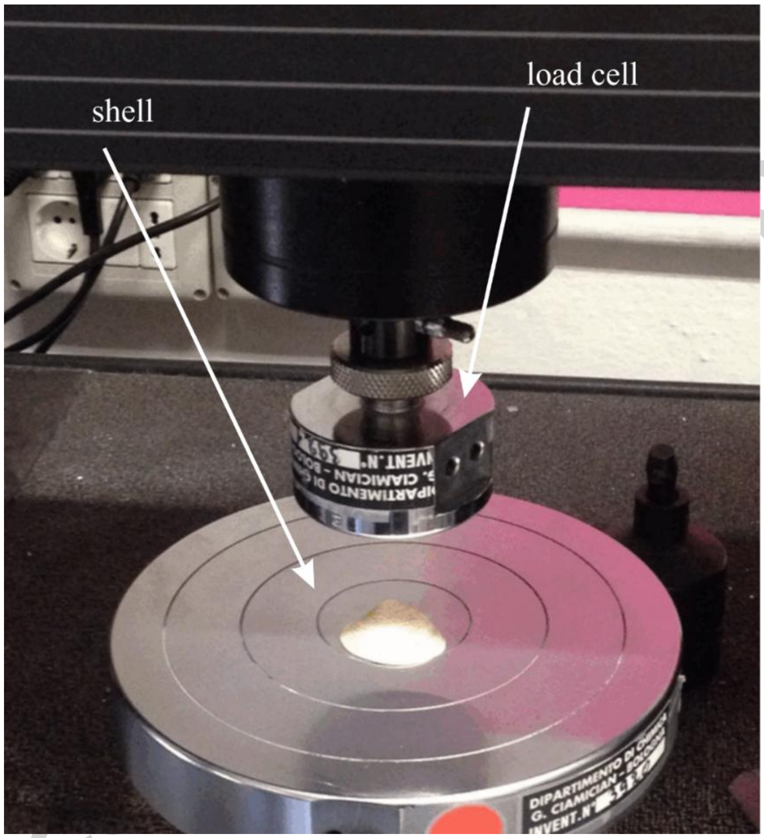


Figure 4 Picture of the machine and setup used for the compression tests.

A typical experimental load-displacement curve is plotted in Figure 5, where it is possible to distinguish two main parts: the first quasi-linear elastic segment, until the maximum load P_{max} is reached, and the subsequent fracture, characterised by irregular rises and drops of the load as the crack grows.

This mechanical behaviour has already been observed and widely studied in the literature (see, e.g., Refs. (Barthelat et al., 2009; Mayer, 2017)) and is typical of natural and artificial laminate composite materials. As anticipated above, the complex fracture behaviour of *C. gallina* shells, emerging from Figure 5, can be attributed to their multiscale architecture, which allow different energy-dissipating mechanisms. As observed also in other seashells (Espinosa et al., 2011; Ji et al., 2017) and nacre-like materials (Kakisawa and Sumitomo, 2011; Huang and Li, 2013; Yuan et al., 2016), on one side one of the core mechanisms is the deformation of the aragonite micro-platelets and their sliding, closely related to the shear strength of the interfaces; while on the other side, the crack propagation between the lamellae (and inside the lamellae at higher loads), which drive the crack path towards the regions with larger stress intensities.

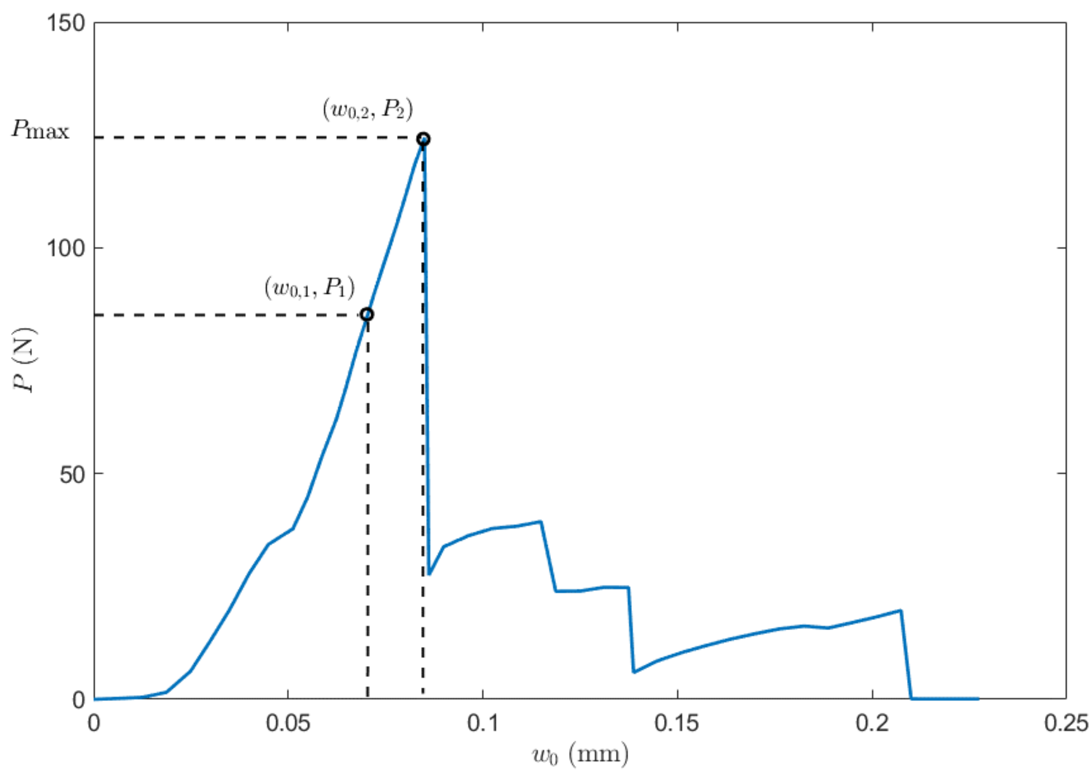


Figure 5 Typical experimental load-displacement curve, with P the total load and w_0 the displacement of the centre of the shell from its natural position. (The two reference points on the linear segment will be used in Section 3 for the extraction of the Young's modulus.)

3. Analytical model

3.1 Description of the shell geometry

The valves present a very complex shape that can be described by four main quantities, as shown in Supplementary Figure 2:

- the maximum Feret diameter $f_{\max}$, i.e. the greatest lateral dimension;

- the minimum Feret diameter $f_{\min}$, i.e. the smallest lateral dimension;
- the thickness h;
- the height of the centre of the shell z_0 from a horizontal plane.

For the purpose of the analytical model introduced later, it is convenient to reduce the geometry described by the quantities above to an equivalent spherical cap. As schematised in Supplementary Figure 3, the equivalent spherical cap can be considered as having the same height and thickness of the shell (i.e., z_0 and h, respectively) and a base radius R, which can be assumed to be:

$$R \approx \frac{f_{\max} + f_{\min}}{2} \tag{1}$$

The radius a of the equivalent sphere can be obtained from simple geometric considerations, i.e.:

$$a = \frac{z_0}{2} + \frac{R^2}{2z_0} \tag{2}$$

3.2 Extraction of the Young's modulus

Considering the experimental setup shown in Figure 4 and the description of the geometry discussed above, we make approximate the system as a shallow spherical shell loaded over a small circular area of radius c, with centre at the apex and with no edge restraint (Reissner, 1946b; Timoshenko and Woinowsky-Krieger, 1959). The shallowness approximation consists in assuming that $R/a \ll 1$ (Reissner, 1946a). Strictly speaking, in our case this approximation is not perfectly fulfilled, because we have simply $R < a$ (and not $R \ll a$ as required) for almost all the samples, but we believe to obtain anyway a good description of the mechanical properties of the shells.

Let us consider the displacement at the centre of the loaded area, which is given by (Timoshenko and Woinowsky-Krieger, 1959):

$$w_0 = \frac{\sqrt{12\,(1-\nu^2)}}{\pi} \frac{P\,a}{E\,h^2} \left[\frac{1}{\mu^2} - \frac{\pi}{2\,\mu}\psi'_4(\mu)\right] \tag{3}$$

where ν is the Poisson's ratio, E the Young's modulus, ψ'_4 a tabulated function and μ the dimensionless coordinate:

$$\mu = \sqrt[4]{12\,(1-\nu^2)}\ \frac{c}{\sqrt{a\,h}} \tag{4}$$

The radius c of the area of application of load can be derived from the Hertz theory of contact. Considering the experimental setup and the shell geometry, we are in the case of a solid of revolution (i.e., the shell approximated by a spherical cap) in contact with a half-space (i.e., the steel platen through which the compressive load is applied). Thus, according to (Johnson, 1985):

$$c = \left(\frac{3\,P\,a_{\mathrm{eq}}}{4\,E_{\mathrm{eq}}}\right)^{\frac{1}{3}} \tag{5}$$

where $a_{\mathrm{eq}} = a$ and we can take $P = P_{\max}$ and $E_{\mathrm{eq}} = E$, given that the steel platen can be assumed to be rigid with respect to the shell. Strictly speaking, the Young's modulus to employ in the Hertz contact theory is that of a solid sphere, but the theory is still valid during the approach of the two solids, because the indentation depth is negligible with respect to the shell thickness. An analogous reasoning has already been applied in the literature (see, e.g., Ref. (MansoorBaghaei and Sadegh, 2011) where the authors separate the elastic deformation of a spherical shell from the bending deflection).

By taking two reference points $(w_{0,1}, P_1)$ and $(w_{0,2}, P_2)$ on the linear segment of the experimental load-displacement curve, as shown in Figure 5, the Young's modulus of the shell can be derived from Equation (3) as:

$$E = \frac{\sqrt{12\,(1-\nu^2)}}{\pi}\ \frac{a}{h^2}\left[\frac{1}{\mu^2} - \frac{\pi}{2\,\mu}\psi'_4(\mu)\right]\frac{P_2 - P_1}{w_{0,2} - w_{0,1}} \tag{6}$$

where we can assume $\nu \approx 0.16$ for aragonite (Barthelat et al., 2006) and $E = 30$ GPa as the expected value for the computation of c through Equation (5) (see Supplementary Note 1 for details).

Table 2 reports the values of the Young's modulus, which falls in the order of 6 GPa, with the greatest E measured for the "CE" location. The only exception is the "MO" location, whose shells present the biggest size and their load-displacement curves have a smaller stiffness and thus a smaller Young's modulus.

Table 2 Average value and standard deviation of the Young's modulus, from Equation (6), and the ultimate strength, from Equation (10), of the investigated samples ordered by decreasing latitudes.

location acronym	$\boldsymbol{E}$ (GPa)	$\boldsymbol{\sigma_u}$ (MPa)
"MO"	2.44 ± 1.58	20.61 ± 3.74
"CH"	6.93 ± 1.57	33.41 ± 6.65
"GR"	6.18 ± 1.77	28.19 ± 5.77
"CE"	7.19 ± 2.19	34.38 ± 6.43
"SB"	6.94 ± 2.30	32.25 ± 8.65
"CA"	6.01 ± 3.88	28.68 ± 8.32

In Figure 6 we plot the values of the Young's modulus for all the samples as function of the shell thickness: the general trend is that E diminishes for an increasing h. In addition, it is possible to identify a limiting curve that divides the plane in two parts. All the values are located below the curve, i.e., there are no shells with high thickness and simultaneously high Young's modulus. The limiting curve can be described by a best-fit of the type:

$$E(h) = A_1 + B_1\, h \tag{7}$$

By taking the largest value of E for each thickness (see Supplementary Note 2), we find $A_1 = 18.2$ GPa and $B_1 = -7.8$ GPa mm^{-1}, with R^2-value 0.9185.

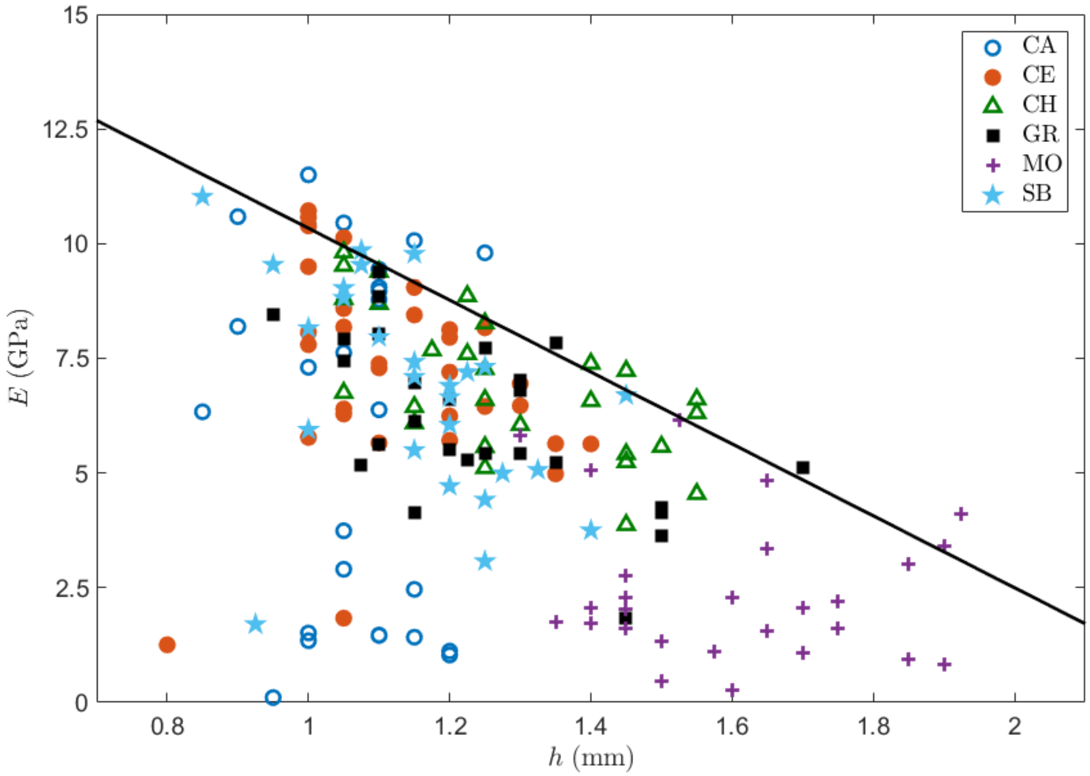


Figure 6 Young's modulus as function of the shell thickness, computed through Equation (6), of the investigated samples divided by location. The solid line represents the curve described by Equation (7).

3.3 Extraction of the ultimate strength

Within the approximation of shallow spherical shells, the maximum bending stress can be computed as (Timoshenko and Woinowsky-Krieger, 1959):

$$\sigma_{b,\max} = \pm \frac{3\,(1+\nu)}{2} \frac{P_{\max}}{h^2} \frac{\psi'_3(\mu)}{\mu} \tag{8}$$

where ψ'_3 is another tabulated function, depending on the dimensionless coordinate introduced through Equation (4), and is negative in the considered range of μ. Thus, in Equation (8) we take the negative sign in order to have a positive maximum bending stress. The maximum membrane stress arising in the compressed shell, instead, is given by (Timoshenko and Woinowsky-Krieger, 1959):

$$\sigma_{m,\max} = \frac{\sqrt{12\,(1-\nu^2)}}{2\,\pi} \frac{P_{\max}}{h^2} \left[\frac{1}{\mu^2} - \frac{\pi}{2\,\mu}\psi'_4(\mu)\right] \tag{9}$$

and we take it as positive in the case of compression.

Finally, the ultimate strength of the shell σ_u is given by the sum of Equations (8) and (9), i.e.:

$$\sigma_{\mathrm{u}} = \sigma_{b,\max} + \sigma_{m,\max} = -\frac{3\,(1+\nu)}{2}\,\frac{P_{\max}}{h^2}\,\frac{\psi'_3(\mu)}{\mu} + \\ + \frac{\sqrt{12\,(1-\nu^2)}}{2\,\pi}\,\frac{P_{\max}}{h^2}\left[\frac{1}{\mu^2} - \frac{\pi}{2\,\mu}\psi'_4(\mu)\right] \tag{10}$$

where, according to signs assumed above, the (positive) compressive membrane stress has been added to the (positive) bending stress. Note that we get $\sigma_{m,\max} \ll \sigma_{b,\max}$ for all the samples, thus we can assume $\sigma_u \approx \sigma_{b,\max}$.

In the same Table 2, we list the ultimate strengths of all the tested shells computed through Equation (10), obtaining a value in the order of 30 MPa. As observed for the Young's modulus, also the ultimate strength depends slightly on the location, with the shells with a smaller E presenting also a smaller value of σ_u (i.e., "MO"). The relation among the Young's moduli of the shells from the different considered locations, is almost verified also for the ultimate strength, despite a larger scattering of the experimental data does not allow a precise discrimination.

As done before for the Young's modulus, in Figure 7 we plot the computed ultimate strengths as function of the shell thickness, showing a similar decreasing trend of σ_u for increasing h. Again, we can divide the plane through a curve of equation:

$$\sigma_u(h) = A_2 + B_2\,h \tag{11}$$

being A_2 and B_2 fitting parameters. By taking the largest value of σ_u for each thickness (see Supplementary Note 2), we find $A_2 = 78.3\ \mathrm{MPa}$ and $B_2 = -31.2\ \mathrm{MPa\ mm^{-1}}$, with R^2-value 0.9090. The impossibility to have a simultaneous large thickness and large strength is typical of brittle materials, e.g. ceramics, as in the case of aragonite. For larger h, there is a larger probability to have defects (for instance, larger pores), which degrade the mechanical strength of the shells.

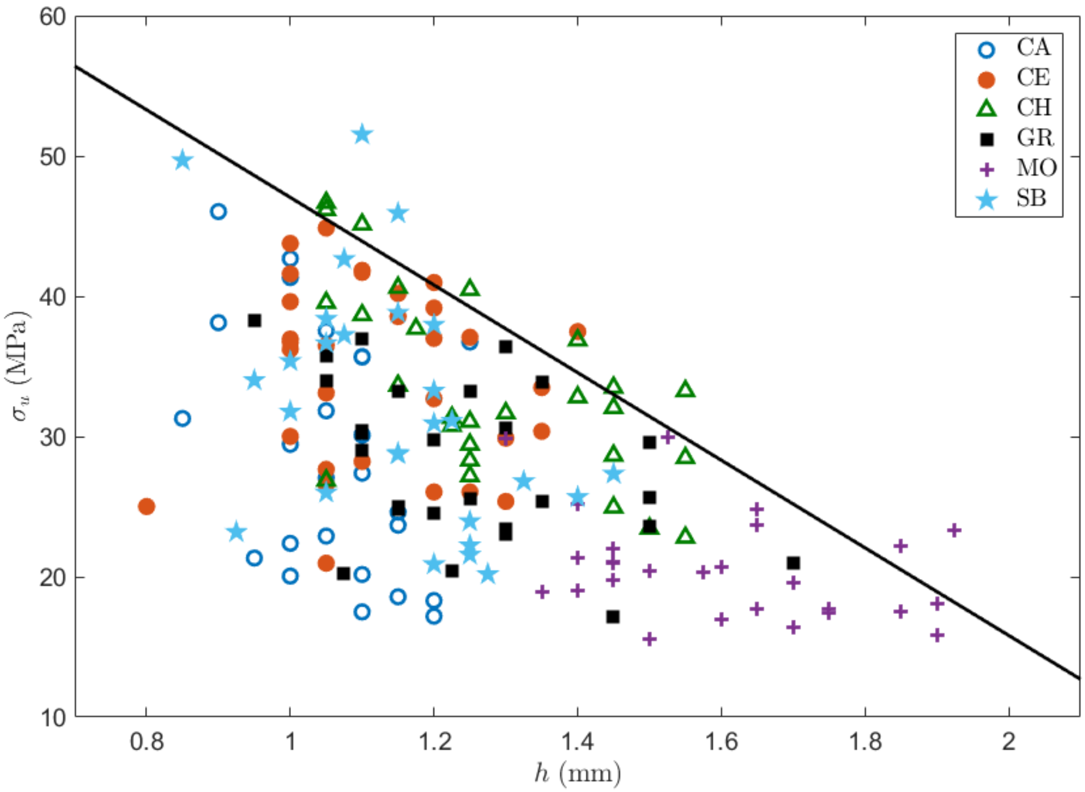


Figure 7 Ultimate strength as function of the shell thickness, computed through Equation (10), of the investigated samples divided by location. The solid line represents the curve described by Equation (11).

The values of the Young's modulus and the ultimate strength, computed through Equations (6) and (10) respectively, can be plotted on the two axes of a single graph, as we attempt to do in Figure 8. In the obtained Ashby plot (Ashby, 1992) it is evident the large scattering of the experimental data, with the shells collected at the "MO" location occupying the bottom left corner, because of their small values of E and σ_u.

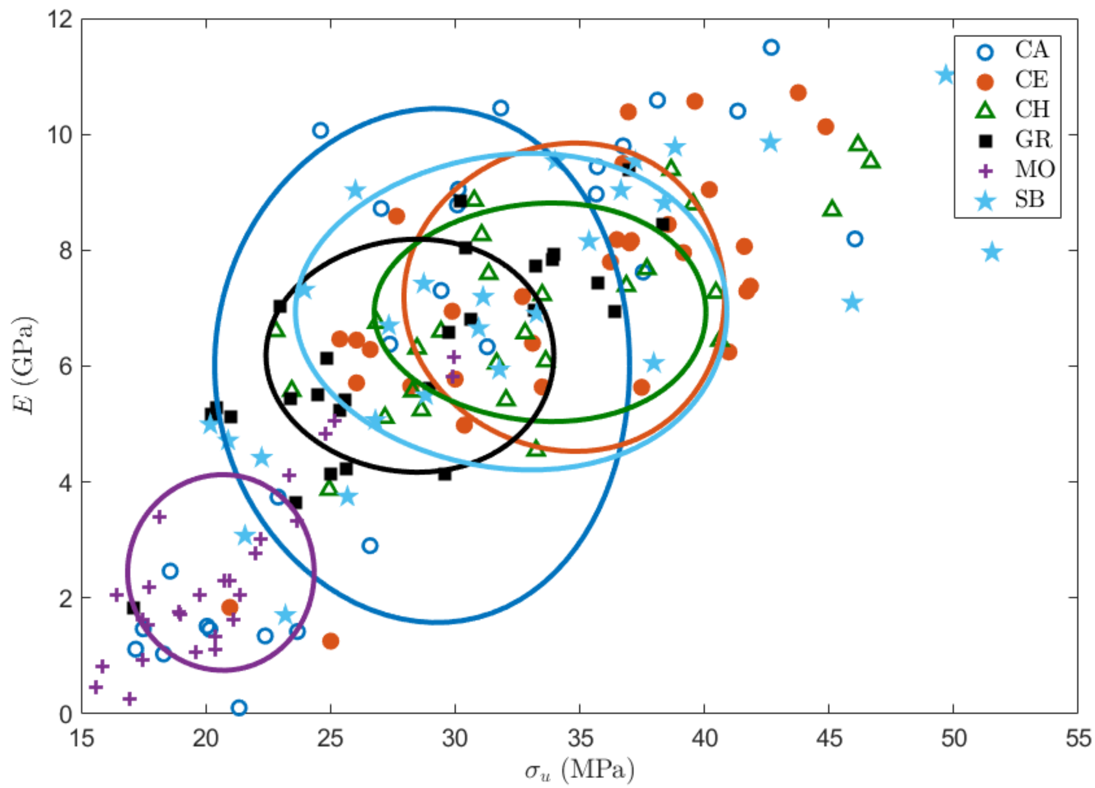


Figure 8 Ashby plot of the Young's modulus and the ultimate strength of the investigated samples divided by location. Each ellipse has centre in $(\sigma_{u,m}, E_m)$ and horizontal and vertical semi-axes $\sigma_{u,std}$ and E_{std}, respectively. The subscripts "m" and "std" denote the average value and the standard deviation, respectively, of the considered quantity as reported in Table 2.

3.4 Effect of the shell porosity

As already observed in biological structural materials (Seto et al., 2012; Fantazzini et al., 2015), also *C. gallina* shells presents a certain amount of porosity, which can affect the mechanical response and the fracture properties. In order to take into account the shell porosity, here denoted by the volume fraction φ, it is possible to rescale the computed values of E and σ_u according to the rules of mixtures employed for the mechanics composite materials (Jones, 1999), respectively:

$$E = E_{\text{mat}}\,(1-\varphi) + E_{\text{por}}\,\varphi \quad (12a)$$

$$\sigma_u = \sigma_{u,\text{mat}}\,(1-\varphi) + \sigma_{u,\text{por}}\,\varphi \quad (12b)$$

where E_{mat} and $\sigma_{u,\text{mat}}$ are the properties of the matrix, E_{por} and $\sigma_{u,\text{por}}$ the properties of the pores, and E and σ_u the macroscopic properties of the shell computed before. By assuming $E_{\text{por}} =$

0 GPa and $\sigma_{u,\mathrm{por}} = 0$ MPa (i.e., there is no material in the pores), we can extract the actual properties of the matrix, i.e. the microscopic properties of the shells, as:

$$E_{\mathrm{mat}} = \frac{E}{(1-\varphi)} \tag{13a}$$

$$\sigma_{u,\mathrm{mat}} = \frac{\sigma_u}{(1-\varphi)} \tag{13b}$$

The values of E_{mat} and $\sigma_{u,\mathrm{mat}}$ for all the samples are reported in Table 3, together with the average shell porosity. In general, we observe a slightly increasing porosity for a decreasing latitude and thus a larger effect on the mechanical properties of the shells. As the latitude decreases, the porosity generally increases and thus the difference between E and E_{mat}, and between σ_u and $\sigma_{u,\mathrm{mat}}$, increases. Anyway, being φ always in the range 2÷5%, the difference between the mechanical properties computed through Equations (6,10), and reported in Table 2, and those obtained by considering the porosity through Equations (13a,13b), is always below 5%.

Table 3 Average value and standard deviation of the Young's modulus, from Equation (13a), and the ultimate strength, from Equation (13b), of the investigated samples ordered by decreasing latitudes, considering the shell porosity.

location acronym	φ (%)	E_{mat} (GPa)	$\sigma_{u,\mathrm{mat}}$ (MPa)
"MO"	2.97 ± 0.48	2.51 ± 1.63	21.24 ± 3.86
"CH"	2.97 ± 0.69	7.15 ± 1.62	34.42 ± 6.76
"GR"	3.85 ± 0.79	6.43 ± 1.83	29.32 ± 6.00
"CE"	3.97 ± 1.01	7.48 ± 2.27	34.75 ± 6.35
"SB"	3.71 ± 0.88	7.20 ± 2.38	33.51 ± 9.04
"CA"	4.03 ± 0.90	6.26 ± 4.04	29.88 ± 8.61

3.5 Extraction of the toughness modulus and fracture energy

Here we attempt to extract the energy dissipated from the fracture of the *C. gallina* valves, assuming that each shell breaks into two parts and the fracture involves the entire cross section in Figure 1. The fracture pattern could be also very complex involving the rupture in multiple pieces. However, the main objective here is to discriminate between the properties of the inner and outer layer, defining nominal/effective rather than real/complex mechanical properties.

Considering Figure 5, we define the total dissipated energy U_{TOT} as the area below the force-displacement curve, i.e.:

$$U_{TOT} = \int_0^{w_{0,\max}} P(w_0)\,\mathrm{d}w_0 = \sum_{i=1}^{N} \int_0^{w_{0,i}} P_i(w_0)\,\mathrm{d}w_0 \tag{14}$$

being $w_{0,\max}$ the fracture displacement and we have introduced the summation because the overall curve can be approximated by a piecewise function of N continuous functions. Thus, we can define the total toughness modulus as:

$$T_{TOT} = \frac{U_{TOT}}{V} = \frac{1}{V} \int_0^{w_{0,\max}} P(w_0)\,\mathrm{d}w_0 = \frac{1}{V} \sum_{i=1}^{N} \int_0^{w_{0,i}} P_i(w_0)\,\mathrm{d}w_0 \tag{15}$$

where V is the volume of the shell, taken as average between the right and left valve of each sample.

The fracture energy, instead, is defined with reference to the fracture area A, which here we can assume equal to the cross section of the shell (see Figure 1 and Supplementary Figure and 3), i.e.:

$$G_{c,TOT} = \frac{U_{TOT}}{A} = \frac{1}{A} \int_0^{w_{0,\max}} P(w_0)\,\mathrm{d}w_0 = \frac{1}{A} \sum_{i=1}^{N} \int_0^{w_{0,i}} P_i(w_0)\,\mathrm{d}w_0 \tag{16}$$

As anticipated above, we can assume that the internal layer of the shell is the first one that undergoes fracture, followed by the external layer. Therefore, if from Figure 5 we assume that the peak of the force is reached when the internal layer fails, we can easily compute the toughness modulus of the internal layer (T_{int}) and that of the external layer (T_{ext}) of the shell. The integral in Equation (15), consequently, must be divided into two parts:

$$T_{int} = \frac{1}{V_{int}} \int_0^{w_0|_{P_{\max}}} P(w_0)\,\mathrm{d}w_0 \tag{17a}$$

$$T_{ext} = \frac{1}{V_{ext}} \int_{w_0|_{P_{\max}}}^{w_{0,\max}} P(w_0)\,\mathrm{d}w_0 \tag{17b}$$

being $w_0|_{P_{\max}}$ the displacement at which the maximum load occurs and V_{int} and V_{ext} the volumes of the internal and the external layers, respectively.

Similarly, we can compute the fracture energy of the internal and the external layer, by dividing the corresponding integral in Equation (16) as done above for the toughness modulus, i.e.:

$$G_{c,int} = \frac{1}{A_{int}} \int_{0}^{w_0|_{P_{\max}}} P(w_0)\, \mathrm{d}w_0 \tag{18a}$$

$$G_{c,ext} = \frac{1}{A_{ext}} \int_{w_0|_{P_{\max}}}^{w_{0,\max}} P(w_0)\, \mathrm{d}w_0 \tag{18b}$$

Given the availability of the actual volume V of the shells, measured experimentally as described before, for the values of V_{int} and V_{ext} we do not make use of the spherical shape approximation introduced earlier for the computation of the mechanical properties. Instead, we notice that $V_{int} \approx V_{ext} \approx V/2$, thus we use the experimental value $V/2$ for the extraction of the toughness moduli in Equations (17). Note also that we have introduced the fracture areas of the internal and the external layers, A_{int} and A_{ext} respectively, assuming that each layer covers half of the cross section (see Figure 2a), i.e. the thickness of the internal layer is assumed equal to the thickness of the external layer, and using the spherical shape approximation. See Supplementary Note 3 for the detailed computation of A_{int}, A_{ext}, V_{int} and V_{ext}.

In Table 4 we list the computed values of toughness modulus and fracture energy for the internal and external layers of all the samples. It is difficult to observe a clear dependence of these quantities on the location (i.e. latitude) of collection of the samples, but interestingly the sums $T_{int} + T_{ext}$ and $G_{c,int} + G_{c,ext}$ are almost the same for every location. On the other hand, a strong difference between the two layers can be observed: the internal layer presents always a much higher toughness modulus and fracture energy.

Table 4 Average value and standard deviation of the toughness modulus and the fracture energy of the internal and the external layers of the investigated samples ordered by decreasing latitudes.

location acronym	internal layer		external layer	
	T_{int} (kJ/m^3)	$G_{c,int}$ (kJ/m^2)	T_{ext} (kJ/m^3)	$G_{c,ext}$ (kJ/m^3)
"MO"	12.32 ± 2.92	0.20 ± 0.05	8.34 ± 4.26	0.13 ± 0.07
"CH"	16.30 ± 6.14	0.27 ± 0.10	6.98 ± 3.78	0.11 ± 0.06
"GR"	11.06 ± 4.54	0.18 ± 0.07	8.86 ± 3.92	0.14 ± 0.06
"CE"	14.96 ± 4.28	0.26 ± 0.08	7.32 ± 4.44	0.12 ± 0.08
"SB"	13.44 ± 6.38	0.23 ± 0.12	10.52 ± 6.10	0.17 ± 0.10
"CA"	11.64 ± 4.54	0.19 ± 0.07	9.80 ± 7.38	0.16 ± 0.12

4. Conclusions

We have presented an experimental investigations of *Chamelea gallina* shells, collected at different locations in the Adriatic Sea. Microscopy investigations on the cross section of the shells have highlighted the presence of two main layers of different microstructure, which interact with the propagation of cracks during mechanical loading.

Compression tests have been performed to extract the main mechanical properties of the shells, namely Young's modulus and ultimate strength, which have been derived through an analytical model based on the shallow spherical shell approximation. Results have shown a certain dependency of the mechanical performance on the latitude of collection of the samples, and these findings are essentially preserved when the shell porosity is considered. These results confirm that the preliminary outcomes of a previous work (Gizzi et al., 2016) for a variety of physical properties, are consistent also for the mechanical properties of the shells. The latitudinal gradient has been demonstrated to not affect significantly the internal microstructure of the shells, but only their macroscale morphology. Thus, we can conclude that the values of the Young's modulus and the ultimate strength depend on the latitude due to the change in shell morphology (e.g. thickness).Finally, we have investigated the fracture properties of the considered shells, which present a complex fracture growth as usually observed in natural and artificial composites. We have computed the toughness modulus and the fracture energy for the two layers (i.e. internal and external) that fail progressively under compression: the extracted properties are nearly independent from the latitude, but highlight a different mechanical behaviour of the two layers, with the internal one being able of absorbing more energy at fracture.

Our findings can be of interest for the estimation of the future yield of the clam fisheries in the Adriatic Sea, by correlating the mechanical properties of the shells to e.g. the mortality events. From the mechanical point of view, instead, the measured properties can be of interest for the design and optimization of new bio-inspired composite materials (Libonati et al., 2016; Gu et al., 2017; Pugno and Valentini, 2019), e.g. multilayer composites for shell structures.

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Highlights:

- Clam shells collected at various latitudes are tested under compression.
- An analytical model is employed to extract the Young's modulus and the strength.
- The fracture energy and toughness of two microstructural layers is estimated.
- The main mechanical properties depend on the latitude of collection of the samples.