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# Mechanical behavior of macadamia nutshells

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**Abstract**

The paper presents the results related to the static mechanical characterization of macadamia nutshells, according to a procedure previously defined on hazelnut shells. Curved specimens were obtained from macadamia nutshells, and they were then subjected to three points bending testing between flat plates of a testing machine. Density, hardness, microhardness, mechanical characterization and microscopic analysis are also presented, related to two macadamia nut varieties. The specimens showed mechanical properties which can be compared with aluminum alloys ones. The behavior of each specimen was also compared with analytical results of equivalent curved beams, monolithic and multilayer.



*Keywords:* Mechanical testing; macadamia nutshell.

## 1. Introduction

The shell of macadamia nut is made of a solid cellular material with low density, but higher than water, and high resistance. Differently from other wooden based materials, macadamia nutshell shows high isotropy and homogeneity, with random oriented 3D cells, as reported in Wang and Mai (1995). This structure is responsible for elevated failure stresses which make shelling a very difficult process.

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**Nomenclature**

| | |
|---|---|
| $A$ | area of cross section |
| $A_m=\int_A \frac{1}{r} dA$ | cross section related parameter |
| $R$ | curvature radius of specimen cross section |
| $r_n$ | curvature radius of neutral axis |
| $e$ | shift of neutral axis from centroidal axis (eccentricity) |
| $h$ | specimen thickness |
| $P$ | loading force during testing |
| $M$ | bending moment |
| $s$ | displacement of testing machine crosshead |
| $\sigma_r$ | specimen failure stress (maximum stress in the specimen during three points bending test) |
| $\sigma_{af\,P}$, $\sigma_{af\,M}$ | average maximum stress for sample in parallel (P) and longitudinal (M) direction |
| $\sigma_a$ | average maximum stress for specific macadamia nut variety |

A description on botanical characteristics of macadamia nuts, on their distribution and use, can be found in Wallace and Walton (2012). Macadamia belongs to the *proteaceae* family, which origins in Australia, and four varieties are present: *integrifolia*, *tetraphylla*, *ternifolia*, and *jansenii*. Commercial edible cultivars come from *integrifolia* and *tetraphylla*, while *ternifolia* and *jansenii* are not edible. Macadamia *integrifolia* is characterized by round fruits, with smooth shell, while *tetraphylla* has more tapered fruits and rough shell. From the botanical point of view, macadamia fruit is a follicle. It is composed of a pericarp, that is the external envelope, the head or shell and the embryo or kernel. Macadamia nut can be eaten raw or cooked. The high oil content makes them good for food and for cosmetics; the kernel is composed by oil for 75-80% in weight.

Macadamia fruits have an ellipsoidal shell. Dimensions may vary. Circumscript sphere diameter varies between 15 to 35 mm (Vock (1998), Wallace and Walton (2012)). The link with the plant is called *hilum* (fig. 1a, point B); the two poles create an external shape variation of a diameter of about 2 mm. Opposite to *hilum* there is the *micropilum* (fig. 1a, point M) featuring a small channel allowing the pollen enters into the flower. *Micropilum* is completely closed in mature fruits and it appears as an ivory shaded point. Macadamia nuts are axialsymmetric around an axis joining points M and B (fig. 1b). Shell cross section features two different colors. Inner side of Point M is coated with an ivory layer of calcium ossalate crystals. Mature fruits are likely to adhere to this layer.

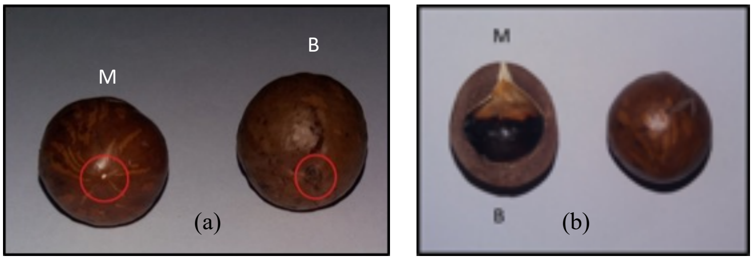



Fig. 1. (a) Micropylum (left) and hilum (right); (b) internal (left) and external (right) aspect of the shell.

Shell matrix appears to be homogeneous, apart some small short fiber (here called primary fibers), randomly distributed in the volume and bigger fibers running from point M to point B (here called secondary fibers) (fig. 2). The external part of the shell is smooth and brown, with variable thickness between fruits and also within the same fruit (fig. 3).

Fig. 2. Shell specimens showing fibers.

Fig. 3. Shell sections showing how shell thickness varies.

The problem of mechanical characterization was already investigated in Braga et al. (1998), aiming at maximizing industrial shelling processes. The interesting mechanical properties of Macadamia nutshell can be used from the point of view of circular economy, that is for example as charges in structural composite materials, as in Dong et al. (2017) and Cholake et al (2017) with macadamia shell powder.

Aim of the present study is to characterize mechanical properties, and particularly bending resistance, of macadamia nutshells. An experimental testing campaign, run on three varieties of macadamia shell to investigate the influence of variety and specimen cut direction on mechanical properties, is presented. An analytical curved beam model was also applied to estimate stresses in the specimens.

## 2. Theoretical background

The specimens are assumed to be symmetrical and curved on an arc of circumference (fig. 4). In three points bending test, the configuration is symmetrical and so the vertical constraint reactions that are equal to half of the loading force.

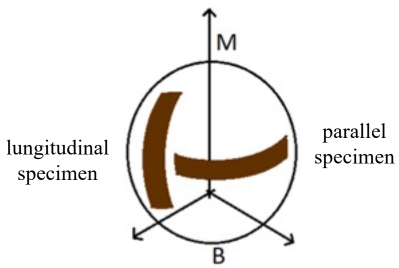



Fig. 4. Sampling directions.

According to Pilkey (2008), in a curved beam the neutral axis is not coincident with the centroidal axis. The stress is not symmetric with respect to neutral or centroidal axes; its maximum value is tensile and it lies in the internal part of the beam. To calculate the value of the maximum stress, the beam slenderness, defined as the ratio between the curvature mean radius *R* and the beam height *h*, is required.

From the beam slenderness, eccentricity *e* and other parameters can be calculated, and in particular:

- If slenderness lies in the range 0.6÷8 then $e = R - A/A_m = R - r_n$;
- If slenderness is higher than 8 then $e \approx I/R/A$.

To calculate $A_m$, two parameters are referred to the mean curvature radius: $c = R + 0.5h$ and $a = R - 0.5h$. Then:

$$A_m = b \cdot ln\frac{c}{a} \tag{1}$$

There are two ways to calculate the normal stress $\sigma_x$ due to bending moment: the traditional method and the $ki$ method. The traditional method does not consider the slenderness value. In Pilkey (2008), the Cook formulation of normal stress reports:

$$\sigma_x = \frac{M \cdot z}{A \cdot e \cdot r} = \frac{M \cdot (r_n - r)}{A \cdot e \cdot r} \tag{2}$$

and then:

$$\sigma_{max,trad} = \frac{M \cdot z}{A \cdot e \cdot r} = \frac{P \cdot \frac{c}{2} \cdot \left(\frac{h}{2} - e\right)}{A \cdot e \cdot \left(R - \frac{h}{2}\right)} \tag{3}$$

In the $k_i$ method, that can be applied if $R/h > 5$, the beam formula is corrected by the parameter $k_i = \frac{h}{6e} \cdot \frac{h-2e}{2R-h}$:

$$\sigma_i = k_i \cdot \frac{M \cdot z_i}{I} \tag{4}$$

where $z_i$ is the distance from centroid, and then:

$$\sigma_{max,ki} = k_i \cdot \frac{P \cdot \frac{c}{2} \cdot \frac{h}{2}}{I} \tag{5}$$

Shear stresses due to shear forces can be neglected, and normal stresses due to normal action can be neglected too. The maximum stress due to bending moment is:

$$\sigma_{b,\max} = k_i \cdot \frac{P \cdot \frac{c}{2} \cdot 0.5 \cdot h}{I} \tag{6}$$

## 3. Materials and methods

Mechanical characterization of shells can be obtained by means of three points bending test, as already described for hazelnuts in Bonisoli et al. (2015), Sesana and Delprete (2014).

In the present paper, three varieties of macadamia nuts were investigated: A16 (*integrifolia*), A4 (*tetraphylla*), and 816 (*integrifolia*) (Vock (1998)). Bending test is run in displacement control by means of MTS QTest 10 testing machine with 500 N load cell and crosshead speed 1 mm/min. Specimens are compressed between two steel plates. A Leica MC 170 HD microscope was used, with magnification lower or equal to 90X.

For each nut variety two samples of specimens were prepared according to Sesana and Delprete (2014): in parallel, sample P, and in longitudinal, sample M, direction (fig. 4). It is worth noting that, if considering the shell a composite material, its structure is almost isotropic (Wang and Mai (1995)), while the secondary fibers embedded in the matrix give anisotropic properties to the material. Specimens were cut by means of a Micromot Proxxon 50/E NO 28515 and then finished by means of sand paper. With a precision caliper (0.05 mm resolution) the specimen dimensions of fig. 5 were measured. Specimens were weighted by means of a Orma ESB 100S balance (100 g full scale, $10^{-4}$ g sensitivity).

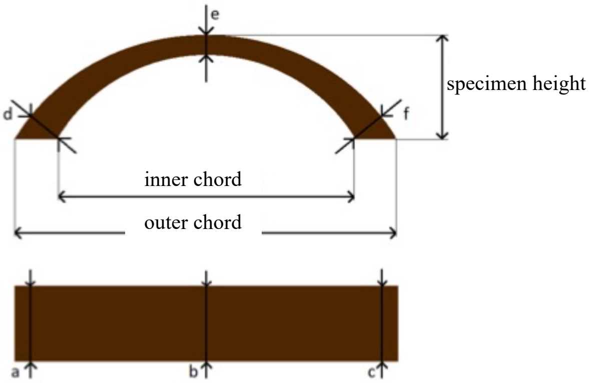



Fig. 5. Scheme of dimensional measurements.

### *3.1. Modelling of curved beams*

In calculation, horizontal forces due to friction between specimens and plates are neglected. In first approximation, neglecting irregularities, the specimens were modelled as curved beams with constant cross section.
The main irregularities are due to three factors. The first one is thickness variability. The thickness varies above all close to poles. The M specimens show the highest variability. To overcome this problem the thickness was measured in three positions: *d*, *e* and *f* (fig. 5). Then, to calculate the specimen volume the average thickness *h* was calculated on each specimen. For the calculation of the resisting cross section, the thickness *e* was considered for each specimen as the most stressed cross section. The second factor of irregularities is the irregular cutting procedure: the average value between *a, b* and *c* (fig. 5), the specimen width *w*, aims at correcting eventual cutting irregularities. The same procedure of the previous point was used for calculating volume and resisting cross section. The third factor is the curved section. The nut is not a perfect sphere. Due to difficulties in cutting the specimens, it is difficult to obtain a negligible curvature in the cross section plane. Then the thickness value was measured parallel to the tangent direction to the curvature in the cross section plane.

Basing on these measurements, other parameters were obtained for modelling the curved beam: specimen curvature in beam axis plane, arch length, radius. By approximating the external and internal edge of each specimen by means of an ideal circular arc, the ideal axis curvature radius and opening angle were calculated. Density was calculated as the ratio between weight and volume, for each specimen. The average density was then calculated for each variety and specimen orientation direction.

## 4. Results

For each sample for each specimen (P and M direction) and each nut variety, dimensions and weight were measured. Then density, curvatures, average thickness for each specimen were calculated. The average dimensions were measured on every specimen and are reported in Table 1; the average densities were calculated for each sample, and reported in the same Table 1. Variety 816 shows density $\rho_{aP}$ in P direction different from other values. This can be due to the fact that real specimen shape is different from ideal circular arc approximation for this sample. Then in following calculation the density in M direction will be used.

Table 1. Average dimensions and density of specimen in M (pedex *aM*) and P (pedex *aP*) direction, and average density (pedex *a*) of all specimens of macadamia nut variety.

| Average height [mm] | variety A16 | variety A4 | variety 816 |
|---|---|---|---|
| $h_{aM}$ | 1,995±0,289 | 1,829±0,223 | 2,171±0,254 |
| $h_{aP}$ | 2,614±0,421 | 2,805±0,477 | 2,606±0,391 |
| $h_a$ | 2,304±0,474 | 2,317±0,616 | 2,388±0,391 |
| Average width [mm] | | | |
| $w_{aM}$ | 4,873±0,710 | 5,604±0,715 | 6,145±0,765 |
| $w_{aP}$ | 5,143±0,694 | 5,822±0,556 | 6,238±0,482 |
| $w_a$ | 5,008±0,697 | 5,713±0,639 | 6,192±0,624 |
| Average density [kg/mm$^3$] | variety A16 | variety A4 | variety 816 |
| $\rho_{aM}$ | 1090±106 | 1089±76 | 1178±69 |
| $\rho_{aP}$ | 1106±109 | 1158±87 | 817±183* |
| $\rho_a$ | 1098±107 | 1123±81 | 1178±69 |

### 4.1. Three points bending test

Force-displacement data were processed to obtain stress-strain data in the hypothesis of curved beam specimens. Each specimen slenderness was calculated and the maximum stress was obtained according to the different hypotheses. In the samples the following values of slenderness were found:

- $R/h < 5$: maximum stress was calculated only by means of traditional method $\sigma_{max,trad}$, Equation (3);
- $R/h > 5$: maximum stress was calculated by means of traditional and $ki$ methods $\sigma_{max,trad}$ and $\sigma_{max,\mathrm{ki}}$, Equation (5);
- $R/h > 8$: maximum stress was calculated following slender beam law; both methods can be applied using the correct values of eccentricity $e$ and parameter $k_i$.

The distribution of $R/h$ groups found within the samples is reported in Table 2.

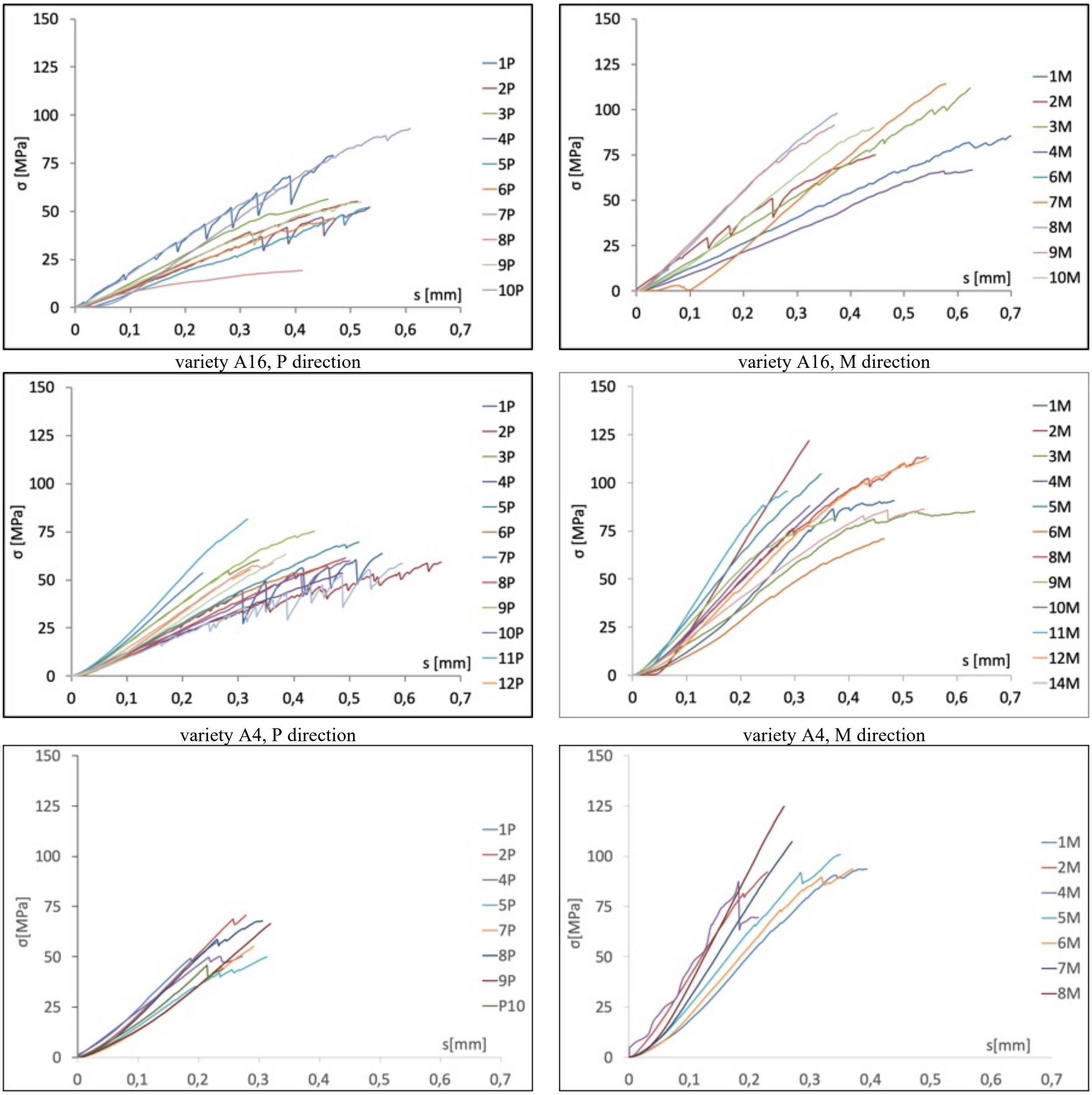
Table 2. Distribution of $R/h$ groups within samples.

| | variety A16 | variety A4 | variety 816 |
|---|---|---|---|
| Total number of specimens | 20 | 30 | 19 |
| Specimens with $R/h > 5$ | 10 | 22 | 19 |
| Specimens with $R/h < 5$ | 10 | 8 | 0 |
| Specimens with $R/h > 8$ | 20 | 1 | 19 |

In fig. 6 the maximum stress-crosshead displacement curves are reported for each sample and each nut variety. In some specimens, the crack nucleated and propagated instantaneously through the cross section. In other it stopped and a further stress increment was necessary to allow it to propagate, thus the curves show a stepwise trend until final failure. This phenomenon is more frequent in P specimens and it appears in five specimens for A16 variety, five for A4 and four for 816. For these last specimens, the number of oscillations is lower than in A4 and A16 varieties. In M specimens only two for A16, one for A4 and none for 816 show oscillations. Oscillations are less deep in M specimens. In some specimens only one oscillation is present, regardless the cut direction. This behavior seems to be related to secondary fibers. In P specimens, secondary fibers are perpendicular to specimen axis. They are hollow fibers and when present they represent a notch in specimen cross section. On the contrary, in M specimens the secondary fibers can contribute to resistance, as they run continuously along the specimen.

Table 3. Average of the maximum stresses reached for each nut variety; units in MPa.

| | variety A16 | variety A4 | variety 816 |
|---|---|---|---|
| $\sigma_{af\,P}$ | 61±15 | 62±8 | 56±11 |
| $\sigma_{af\,M}$ | 92±16 | 96±16 | 100±13 |
| $\sigma_{a}$ | 76±22 | 77±21 | 87±31 |




variety A16, P direction

variety A16, M direction

variety A4, P direction

variety A4, M direction

variety 816, P direction

variety 816, M direction

Fig. 6. Stress-crosshead displacement curves for each nut variety, directions P and M.

Failure stresses $\sigma_r$ were calculated for each specimen and average values are reported in Table 3. In particular, $\sigma_{af\mathrm{P}}$ is the maximum stress for sample in P direction, average on all the samples, $\sigma_{af\mathrm{M}}$ the maximum stress for sample in M direction, average on all the samples, and $\sigma_a$ the average stress calculated on the variety. These values are consistent with Dong and Davies (2012).

### *4.2. ANOVA*

The factors affecting the failure stress $\sigma_r$ were investigated by means of ANOVA analysis. The influence of the following parameters was investigated: nut variety (keeping the cut direction constant), and cut direction (keeping the variety constant).

In the first case (influence of variety) it results that for both P and M specimens the nut variety is not influent on the failure stress value, this is true with 95% confidence. In the second case (influence of cut direction), it results that for all the three nut varieties, cut direction affects the failure stress; this is true with 95% confidence.

## 5. Conclusion

An experimental testing campaign was run on three varieties of macadamia nutshell to investigate the influence of variety and specimen cut direction on mechanical properties. The investigated varieties are A16, A4 and 816. According to specimen shape, the analytical model of curved beam was applied to estimate stresses in the specimens.

Three points bending test resulted to be a reliable test for investigating mechanical behavior of the nutshell. From the experimental campaign it resulted that macadamia nutshell has relevant mechanical properties, in particular the stress to failure can reach 100 MPa for the investigated varieties.

Mechanical properties of shells are related to their internal structure and, in particular, to the secondary fibers. Their influence is related to their extension and orientation in the point of maximum stress in the specimen. The accuracy in specimen preparation strongly affects result reliability.

The macadamia nut variety is not influencing the resistance properties of the shell for the investigated varieties. The most affecting parameters resulted to be the specimen cut direction. Approximating the shell to an ideal arch is reliable for stress calculation but not for density evaluation.

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