Geometrical and Loading Influence on Compression Strength of Macadamia Nut

R.R. Loprang, C.Fleck

Abstract— In comparison with other nuts, macadamia nutshell is observed to have a high strength. A quite large amount of force is, therefore, required to crack macadamia. The present paper presents a study of geometrical effects on the compression strength of macadamia nutshell. Geometrical parameters such as wall thickness, diameter and height are evaluated. Compression tests were performed on 80 Macadamia integrifolia nuts with moisture contents of 4 – 5 %. The test data were analysed using two methods: clustering and multi linear regression. The effect of loading axes on the compression fracture force was studied by performing the test in two different loading directions, parallel and perpendicular to the suture. Our results show that wall thickness and loading direction are the most important parameters, while nut size only has a small influence on compression fracture force.

Index Terms— biomaterial, compression, fracture, macadamia nut,

I. INTRODUCTION

Macadamia nut is well known as a tough nut to crack. As compared to other nuts, more effort is needed and normal nut crackers are not able to open it, especially without damaging the kernel. This makes macadamia one of the most expensive nuts. Thus a number of research investigations have been devoted to the nut’s mechanical properties.

In the food industry, nuts are reduced to certain moisture levels to make the shell more brittle and thus reduce the force needed to crack it. Furthermore, when the shell is dry, the kernel will come loose [1, 2] and the risk of crushing the kernel when cracking the shell is reduced. When determining the properties of the shell, a further advantage is that the loose kernel will not affect the fracture strength.

Out of the interest of food industry, studies on the material properties of macadamia nutshell have been performed. For example, Young’s modulus $E$ of macadamia nutshell was reported to be between 4.2 GPa and 5 GPa [3], [4]. However, the number of studies is rather small, and the complex geometry and small wall thickness make the determination of material parameters difficult.

Previous investigations in this laboratory on the microstructure of macadamia nutshell [5] showed that the shells have a layered, hierarchical structure which consists of stone cells and fibre bundles whereby the fibres have a preferred orientation parallel to the suture. The structure of the shell is, therefore, a promising model for a material with high toughness and strength. Up to now, studies on the structure-property-relationship have hardly been performed. Xavier [6] emphasized that size, shape; shell thickness and texture were the most important parameters affecting the kernel extraction quality in macadamia nuts.

This paper presents results from a current study on the influence of geometrical properties and loading direction on the fracture forces needed to crack macadamia nutshell.

II. MATERIALS AND METHODS

There are 9 species of macadamia. The specimens used in this study are Macadamia integrifolia from South Africa, supplied by Nutfields GmbH, with moisture contents of 4 – 5 %. The moisture content was determined according to ASAE S410T [7].

Whole macadamia nutshell were tested under compression using a ZWICK 1475 universal testing machine with a crosshead speed of 5 mm/min (Fig. 1). In order to investigate the influence of loading direction on the compression fracture force the nuts were loaded either perpendicular or parallel to the suture that runs round the shell (comp. Fig. 2). 40 nuts were tested in each of the two loading directions.

As the nuts and shell walls vary strongly in size, the influence of four parameters was evaluated: wall thickness in $x$ and $y$ direction ($t_x$, $t_y$), diameter ($d$) and height ($h$). Figure 2 explains the chosen parameters.

Fig. 1 Compression test of macadamia nut

Fig. 2. Geometry of macadamia nut
III. Results and Discussion

As mentioned above, 40 nuts were tested for each loading direction. Table 1 shows some arbitrarily chosen results of the tests together with the geometrical parameters of the nuts. Even these few results highlight the great variation in size and compression strength of the nuts. Clearly, there is a strong influence of loading direction (see chap. 3.2) which may be explained by the very anisotropic microstructure of the nuts. However, there is also a natural strong variation in geometry and size of the nuts. Accordingly, the forces needed to fracture the nuts vary over a very wide range between about 830 and 3550 N. While it may safely be assumed that size influences the fracture force, it is not clear which size parameter has the greatest influence. In the following, the relative influence of the different parameters will be evaluated by two different methods generally applied to this kind of multidimensional data: clustering method, and multi-linear regression. The results are presented in Figs. 3 to 10. For this analysis, the influence of the four size parameters on fracture force was assumed to be independent.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>tx</th>
<th>ty</th>
<th>d</th>
<th>h</th>
<th>F</th>
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<tr>
<td>1</td>
<td>1.6</td>
<td>2.4</td>
<td>26.6</td>
<td>25.8</td>
<td>3600</td>
</tr>
<tr>
<td>2</td>
<td>2.7</td>
<td>5.7</td>
<td>26.4</td>
<td>25.6</td>
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</tr>
<tr>
<td>3</td>
<td>1.0</td>
<td>1.8</td>
<td>21.8</td>
<td>22.7</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>80</td>
<td>3.0</td>
<td>2.9</td>
<td>22.2</td>
<td>23.3</td>
<td>1796</td>
</tr>
</tbody>
</table>

A. Geometrical Influence on Compression Strength of Macadamia nut

A.1 Clustering Method

To visualise the influence of each parameter the multidimensional data needs to be reduced to two dimensions. The influence of each parameter may be evaluated by using the so-called clustering method. The idea of this approach is to group the data in a way that, within each group, only one parameter varies while the others are constant. For example, in the present work, from all performed tests, we choose nuts with similar wall thickness tx, height h and diameter d, to evaluate the influence of wall thickness tx on fracture force. This is shown in figs. 3 and 7 for nuts compressed parallel and perpendicular to the suture. Figures 4 to 6, and 8 to 10, show these evaluations for the other parameters. For better comparability, the parameters and the fracture forces are shown as relative changes to the smallest value of the relevant parameter and the respective fracture force.

While before clustering it is extremely difficult to see possible influences of the single parameters, after clustering, the influence of the single parameters on fracture force becomes visible. For example, wall thickness in y-direction does not seem to influence the fracture force, when all specimens loaded parallel to the suture, are considered (fig. 3a). Even more astounding, thicker walls seem to result in smaller fracture forces for some nuts. After clustering, as expected, higher wall thicknesses result in higher fracture forces, even though the influence is small. Figure 6 highlights a further misinterpretation when all nuts are included: diameter seems to have a positive influence on fracture force, when nuts with different wall thicknesses, height, and diameter are observed. After clustering, however, it becomes clear that fracture force decreases with increasing diameter as expected from shell theory. Another example is the influence of height on fracture force when the nuts were compressed perpendicular to the suture (figs.8a, 8b). All these examples clearly show that without clustering the influence of a certain parameter may be extremely misinterpreted.

To evaluate the importance of the single size parameters, regression lines have been fitted to the clustered data. The influence of the parameters is reflected by the slope of the regression line. The bigger the slope, the stronger is the influence (see Table 2). The correlation coefficient R² shows the proportion of variability in a data set that is accounted for by the statistical model. The closer the coefficient is to either -1 or 1, the stronger is the correlation between the variables.

<table>
<thead>
<tr>
<th>without clustering</th>
<th>with clustering</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope R²</td>
<td>slope R²</td>
</tr>
<tr>
<td>Loading parallel to suture</td>
<td></td>
</tr>
<tr>
<td>tx</td>
<td>0.11</td>
</tr>
<tr>
<td>ty</td>
<td>0.57</td>
</tr>
<tr>
<td>h</td>
<td>3.02</td>
</tr>
<tr>
<td>d</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Loading perpendicular to suture

| tx | 1.64 | 0.59 | 2.14 | 0.91 | 0.0009 |
| ty | 0.60 | 0.17 | 1.53 | 0.72 | 0.0161 |
| h  | 6.29 | 0.36 | -9.74| 0.75 | 0.0262 |
| d  | 6.01 | 0.40 | 6.89 | 0.7774| 0.0038 |

As can be seen from Table 2, the R² values of the data without clustering are very small. This means that the parameter is not well correlated with the fracture force, and the regression is not reliable. In contrast, the data sets with clustering show much stronger correlations between the single parameters and fracture force. To further evaluate the reliability of the regressions of the clustered data the p value was calculated. In statistical hypothesis testing, the p-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true. If \( p(i,j) \) is small, say less than 0.05, then the correlation R(i,j) is significant. The calculated p-values show that the regression lines very well describe the influence of the single parameters in the case of the clustered datasets.
a) without clustering  
Fig. 3 Influence of wall thickness ($t_w$) on compression strength of shell compressed parallel to the suture

b) with clustering

a) without clustering  
Fig. 4 Influence of wall thickness ($t_w$) on compression strength of shell compressed parallel to the suture

b) with clustering

a) without clustering  
Fig. 5 Influence of height ($h$) on compression strength of shell compressed parallel to the suture

b) with clustering

a) without clustering  
Fig. 6 Influence of diameter ($d$) on compression strength of shell compressed parallel to the suture

b) with clustering
a) without clustering

Fig. 7 Influence of wall thickness ($t_w$) on compression strength of shell compressed perpendicular to the suture

b) with clustering

$y = 2.1401x - 16.677$

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a) without clustering

Fig. 8 Influence of wall thickness ($t_w$) on compression strength of shell compressed perpendicular to the suture

b) with clustering

$y = 1.5362x - 36.548$

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a) without clustering

Fig. 9 Influence of height ($h$) on compression strength of shell compressed perpendicular to the suture

b) with clustering

$y = -9.7399x + 127.19$

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a) without clustering

Fig. 10 Influence of diameter ($d$) on compression strength of shell compressed perpendicular to the suture

b) with clustering

$y = 6.8867x + 4.2553$
The presented slopes of the regression lines for the clustered data show how big the influence of each parameter to the fracture force is. For both loading directions, the influence of the single parameters is similar. Height and diameter of the nuts showing the parameters that influence the fracture force the most while the thicknesses in x- and y-direction are the least influential parameters. Concerning height and diameter, the size of the nut in the loading direction would be a more appropriate expression. This means, when the nuts are compressed parallel or perpendicular to the suture, height or diameter, that is the size in loading direction, is the most important parameter. It further has to be kept in mind, that the present evaluation is based on the percentage of changes. Hereby, all parameters are changed to the same scale.

A.2 Multi Linear Regression

Additionally to the clustering of the data, a multi-linear regression analysis was performed to model the relationship between all four size parameters and the response variable “fracture force”. Hereby, a linear equation was fitted to the observed data.

Equation 1 gives the formula for the multi-linear regression:

\[ A \cdot x + B \cdot y + C \cdot h + D \cdot d + E = F \]  

(1)

Hereby, the constants A, B, C, and D represent the linear correlation between the single size parameters and fracture force F; E is the intercept.

For all tests performed, this gives a set of 40 equations which may be written in matrix form:

\[
\begin{bmatrix}
  t_{x1} & t_{y1} & h_1 & d_1 & 1 \\
  t_{x2} & t_{y2} & h_2 & d_2 & 1 \\
  t_{xn} & t_{yn} & h_n & d_n & 1 \\
\end{bmatrix}
\begin{bmatrix}
  A \\
  B \\
  C \\
  D \\
  E \\
\end{bmatrix} =
\begin{bmatrix}
  F_1 \\
  F_2 \\
  F_n \\
\end{bmatrix}
\]

(2)

Hereby, \( N \) is the number of tests performed for each loading direction. Equation 2 can be rewritten in a simpler form:

\[ [C] = \text{inv}[P]x[F] \]

(3)

\( P, C \) and \( F \) are the parameters, the constant and the force matrix, respectively. To solve this set of linear equations, matrix \( P \) has to be inverted:

\[ [C] = \text{inv}[P]x[F] \]

(4)

However, as 40 tests were performed, \( P \) is not a square matrix and therefore cannot be inverted. To obtain a square matrix, \( P \) is multiplied by \( P \) transpose. Hence, it is possible to invert it and the solution is derived as follows:


(5)

Hence:

\[ [C] = \text{inv}[P]^T x[P]x[F] \]

(6)

As results, two linear combination equations are obtained for the two loading directions. Equation 7 shows the correlation for the first loading case when the nut is compressed parallel to the suture:

\[ F = 0.37 \cdot t_x + 0.42 \cdot t_y + 2 - 27 \cdot h - 2.5 \cdot d + 27 \]

(7)

Equation 8 describes the correlation for the second loading case (perpendicular to the suture):

\[ F = 1.32 \cdot t_x + 0.21 \cdot t_y - 1.7 \cdot h + 0.7 \cdot d + 13 \]

(8)

B. Influence of Loading Direction on Compression Strength

Figure 11 shows the fracture forces of all nuts, for both loading directions. Even if all nuts – which strongly differ in size, as was outlined above, are considered – a clear trend of higher fracture forces can be seen if the nuts are loaded perpendicular to their sutures. To better investigate the influence of loading direction on fracture force, specimens with similar size parameters were chosen from all experiments for the two loading directions. The result is shown in fig. 12.

These results are in good agreement with the work of Braga et al. [10]. A possible explanation is that the fibres end at the hilum; therefore, cracks are easier introduced there, even though the wall thickness in the loading contact area is higher than under compression parallel to the suture.
IV. SUMMARY AND CONCLUSION

Summarising, it may be stated that the relative influence of different size parameters of macadamia nuts can very well be evaluated statistically by clustering method and multi-linear regression. The strongest influence factor is the size of the nut in loading direction while thickness plays a minor role. The most important parameter, however, is loading direction. Macadamia nuts that were compressed perpendicular to the suture exhibit approximately 1.5 to 2.5 times higher fracture forces in comparison with nuts that were compressed parallel to the suture, even though their wall in contact loading area is thinner. This result is most probably due to the fibre reinforced microstructure.

REFERENCES