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IDENTIFYING PATTERNS OF WALNUT SHELL FRACTURE UNDER COMBINED LOADING IN A RECIPROCATING MILLSTONE SYSTEM

Baurzhan Temov
Master of Technical Sciences*
ORCID: https://orcid.org/0000-0001-8675-5452
Baurzhan Nurakhmetov
Doctor of Technical Sciences, Professor,
First Vice-Rector**
ORCID: https://orcid.org/0000-0002-5064-8687
Ardak Askarov
Corresponding autor
PhD, Assistant Professor*
E-mail: askarov.ardak25@gmail.com
ORCID: https://orcid.org/0000-0001-8813-1336
Ilyas Nurakhmetov
Master of Technical Sciences
Department of Automation and Robotics**
ORCID: https://orcid.org/0009-0003-0934-8257
Galymzhan Nasrullin
PhD*
ORCID: https://orcid.org/0000-0002-0528-3391
*Department of Machines and Apparatuses
of Production Processes**
**Almaty Technological University
Tole bi str., 100, Almaty, Republic of Kazakhstan, 050012

This study explores the process of shell fracture in a locally cultivated walnut vari-ety in a reciprocating millstone setup that implements combined compression, shear, and torsion loading. The task addressed is to enable cracking across the entire shell surface while maintaining kernel integrity, which determines the yield of marketable produce.

In the first stage, shell fracture forces were experimentally determined under local-ized loading from a natural cleft and a whole shell, followed by statistical processing using a two-parameter Weibull distribution. It was found that fracture from the cleft side occurs at lower loads than from the whole shell side, confirming the anisotropy of the shell's mechanical properties.

In the second stage, the effect of roughness pitches of 10, 13, and 16 mm on the fracture force was studied. Experiments have shown that at a 10 mm pitch, fracture oc-curs with the lowest force; increasing the pitch to 13 and 16 mm increases the fracture force due to a decrease in local stress concentration.

A comparison of the two experimental stages revealed that the geometry of the working surfaces determines the conditions for fracture without changing the general pattern: when loading from a natural cleft, lower forces are required. For a fracture probability of at least 0.95 for any nut orientation, a load of approximately 350 N is re-quired. Additionally, the strength characteristics of the kernel were determined using an ST-2 structure analyzer; the average fracture force under direct loading is approximate-ly 1200 grams (≈ 120 N).

The results provide a mechanically sound basis for selecting the parameters of the working parts of a nut cracking machine and a safe range of operating loads

Keywords: walnut, shell fracture, Weibull distribution, strength, walnut shelling machine

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1. Introduction

Walnut processing is a technologically complex operation in the food industry; it requires breaking the shell while maximizing kernel integrity. The yield of intact kernels when separating the broken shell from the kernel directly impacts the economic efficiency of processing and the quality of the finished product. Kernel damage leads to a decrease in market value, while incomplete shell cracking reduces equipment productivity.

The walnut is a composite system consisting of a rigid, thin-walled shell, and a kernel, which is soft compared to the shell.

The shell is characterized by an anisotropic structure and the presence of a natural seam line, which results in directional sensitivity to load. Shell fracture is brittle and is accompanied by a significant spread in ultimate forces due to the natural heterogeneity of the material.

In most industrial nutcracker designs, loading parameters are selected empirically without considering the probabilistic nature of shell strength. This approach does not provide an optimal balance between shell fracture and kernel integrity. Meanwhile, brittle materials are characterized by a statistical strength distribution, which can be described by the Weibull law. This approach allows one to move from estimating the average force to determining the load that ensures failure with a given probability.

An additional challenge is the need to limit the stress transfer to the kernel, which, under direct loading, fails at significantly lower forces. Consequently, the cracking process requires a mechanically justified selection of the working load range, taking into account the probability of shell failure and the kernel strength.

In this regard, the development and experimental study of a mechanical-statistical approach to substantiating the process of walnut shell failure in a reciprocating millstone setup are relevant tasks.

2. Literature review and problem statement

In [1], the fracture patterns of walnut shells are analyzed using a theoretical model of a thin-walled sphere. It was found that the spherical approximation adequately describes the geometry of the object, with localized force exposure causing a gradient stress distribution and material failure occurring predominantly along its longitudinal grain. However, several aspects remained beyond the scope of the study: in particular, the influence of anisotropy and natural heterogeneity of the shell, as well as the stochastic variability of ultimate loads. These limitations stem from the deterministic approach to assessing mechanical properties and the insufficient amount of empirical data, which complicates the practical implementation of the model for verifying operating conditions.

The authors of [2] conducted a comprehensive analysis of the strength characteristics of “Wen 185” walnuts under various compression kinematics. It has been proven that the use of flat, conical, or spherical indenters leads to the formation of fundamentally different stress fields and variations in the breaking force, while maintaining the same fruit orientation. Numerical modeling using the finite element method confirmed that spherical contact is the most effective in terms of minimizing kernel damage. However, issues related to varietal specificity, shell thickness variation, and the correlation between moisture content and breaking energy intensity require further investigation.

Study [3] aimed to experimentally evaluate the mechanical behavior of walnuts under uniaxial loading, taking into account morphometric parameters and load vectors. It was found that the critical force and work of fracture correlate with shell thickness and fruit size, with the minimum fracture resistance recorded under longitudinal compression. The determining influence of the loading pattern on the yield of the whole product was revealed. Unresolved issues include the lack of a volumetric analysis of the stress-strain state and a statistical interpretation of strength, as current conclusions are based on averaged regression models.

Paper [4] examines how moisture level, strain rate, and contact conditions determine the mechanical response of walnuts. It was experimentally confirmed that varying these factors significantly modifies shell rigidity, energy consumption, and kernel yield. It was demonstrated that optimizing raw material parameters and process kinematics enables achieving better technological results. However, the lack of a mathematically formalized probabilistic description of strength and the limited applicability of the data to other varieties and sizes indicate the need for further research.

The authors of [5] examine ways to improve the industrial walnut cracking process to increase the yield of whole kernels. It is shown that controlling humidity and speed, combined with proper positioning of the walnut, significantly outperforms traditional empirical methods. Quantitative relationships between process parameters and the physical and mechanical properties of fracture are presented. The main drawback of this work is the lack of computational modeling of the stress state of the shell and the absence of consideration of the probabilistic nature of the distribution of the material’s strength properties.

The results of simulation modeling of shell fracture using a combined finite and discrete element method (FDEM) and cohesive models are described in [6]. It is established that the configuration and number of contact zones determine the localization of internal forces and the dynamics of crack formation. The advantage of distributed multi-point loading for ensuring controlled shell destruction is demonstrated. Limitations of this approach include the high computational complexity of the algorithms, a simplified representation of the material properties, and the lack of a statistical analysis of strength variability.

The results of the development and refinement of an extrusion mechanism for processing nuts using central compositional planning are reported in [7]. It is revealed that the inclination angle and rotational speed of the rollers are key factors determining the cleaning efficiency (SCR up to 97.24 %) and kernel integrity (WKR up to 92.03 %). The optimal operating parameters were determined: an angle of 0.47° at 108 rpm. High efficiency of the device for fruits with thin shells is noted. Further development of the topic requires improvement of sorting systems and integration into the model of probabilistic destruction criteria taking into account the random location of the nut in the chamber.

The aim of study [8] was to analyze the walnut response to impact for the design of crushing equipment. It was shown that moisture content and the impulse application vector (along different axes) radically alter the energy consumption of the process and the degree of kernel damage. It was found that longitudinal impact, despite its high energy consumption, is the gentlest on the kernel. The use of high-speed video recording made it possible to record the stages of crack initiation and development. Unresolved issues include the lack of a connection between fracture mechanics and shell microstructure and a lack of probabilistic data on strength dispersion.

The authors of paper [9] investigated a methodology for non-destructive quality testing of nuts using X-rays and a modified Faster R-CNN architecture. The integration of FPN, ROI Align, and Softer NMS structures significantly improved defect recognition performance (mAP increased by 5.86 %). The system demonstrated high accuracy in identifying empty and shriveled nuts (over 91 %). However, the influence of the orientation of the object in the image, the limited sample (only thin-skinned varieties), and the lack of correlation between the inspection results and the subsequent fracture mechanics require further research.

Study [10] considers the development of an automated classification algorithm for peeled kernels based on deep learning and physicochemical markers. It was found that the colorimetric lightness index L* serves as an indicator of the degree of lipid oxidation. The constructed ResNet152V2-SA-SE model demonstrated an accuracy of 92.2 %, thereby outperforming standard architectures. Despite its success, the method is limited to analyzing already extracted kernels, does not take into account the mechanical causes of defects during the cracking process, and does not link quality parameters to the loads applied to the shell.

Despite the advances in the design of nutcracker mechanisms and in the studies on fracture mechanics, our review of the scientific literature reveals a number of critical gaps. Firstly, most studies are based on the analysis of deterministic characteristics (average values of deformation work and critical forces), while the stochastic nature of the strength of the shell as a brittle natural material remains poorly understood [1–4]. Secondly, current research is often disjointed: theoretical modeling of the stress state of the shell is rarely integrated with practical engineering solutions within a single calculation algorithm [1, 2, 6, 7]. Thirdly, the potential of the Weibull distribution, which is the standard in the mechanics of brittle media, is practically not used to describe the probabilistic nature of walnut fruit destruction.

The construction of a comprehensive mechanical-statistical model remains poorly understood. Such a model should combine approximation of the walnut by a thin-walled sphere, calculation of stress fields under various contact patterns (including multipoint loading), and probabilistic interpretation of strength properties using Weibull's law.

Implementation of this approach could enable a transition from empirical selection of equipment parameters to scientifically based design of working elements that ensure effective shell fracture while maximizing kernel preservation.

The above suggests the merits of conducting a study to identify patterns of walnut shell fracture under combined loading in a system with a reciprocating millstone. Our study takes into account the influence of the geometry of the working surfaces, the orientation of the walnut, and the probabilistic distribution of its strength properties.

This study is necessary to devise a mechanical-statistical approach that combines experimental determination of fracture forces, analysis of the shell stress state, and strength interpretation based on a two-parameter Weibull distribution. This will enable a transition from the empirical selection of nutcracker parameters to a scientifically based design of their working elements.

3. The aim and objectives of the study

The objective of our study is to provide a mechanistic and probabilistic justification for the walnut fracture process in a reciprocating millstone system based on experimental determination of the fracture force and the use of the Weibull distribution to estimate the probability of crack formation. This will allow us to determine the calculated range of contact loads that ensure guaranteed shell fracture with minimal damage to the kernel, and to justify the design parameters of the installation's working area.

To achieve this goal, the following objectives were set:

– to experimentally determine the fracture force of walnut shells under various loading orientations with an indenter with a contact pad diameter of 10 mm;

– to determine the influence of the roughness pitch of the working surfaces on the fracture force of the shell from the crack side and the intact shell, perform statistical processing of the results, approximate the strength using the Weibull law, and compare the data from the two stages;

– to determine the strength characteristics of walnut kernels under mechanical loading;

– to mechanically interpret the walnut shell fracture process;

– to establish a safe load range that ensures walnut shell fracture while maintaining kernel integrity.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is the process of breaking the shells of a locally cultivated walnut variety in a reciprocating millstone milling system, which implements combined compression, shear, and torsion loading.

The walnut shelling and breaking system is shown in Fig. 1.

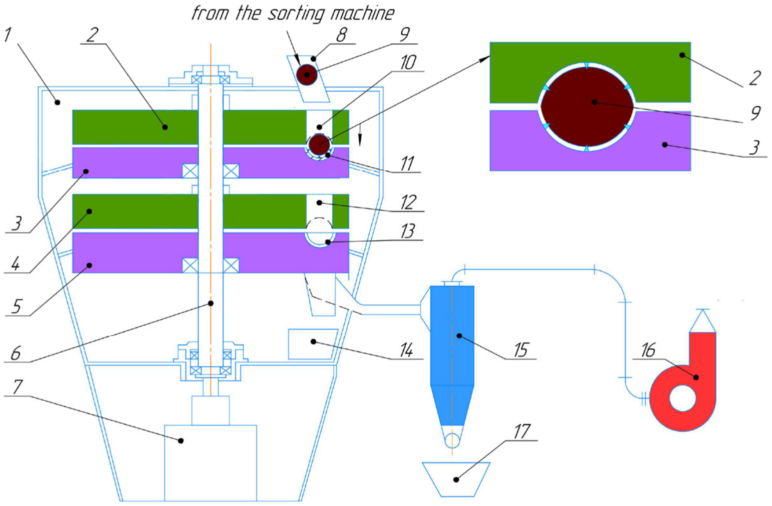

Fig. 1. Machine for breaking up and cleaning walnuts from shells: 1 — body; 2 — upper movable millstone of the first section; 3 — lower stationary millstone of the first section; 4 — upper movable millstone of the second section; 5 — lower stationary millstone of the second section; 6 — central shaft for driving the rotary and reciprocating motion of the movable millstones; 7 — servo drive providing rotary and reciprocating motion of the movable millstones; 8 — receiving pipe for sorted walnuts; 9 — sorted (calibrated) nut; 10 — through hole in upper movable millstone; 11 — groove with a curved trajectory; 12 — through hole in the movable millstone of the second section; 13 — groove with a curved trajectory; 14 — hopper for collecting the cleaned kernel; 15 — cyclone for separating the shell from the air flow; 16 — suction fan; 17 — walnut shell collection bin

The proposed installation of the original [11] design operates as follows (Fig. 1, 2). Sorted nuts from the sorting machine are fed by means of receiving pipe 8 to the through hole of upper movable millstone 10 and enter the working zone formed between upper movable 2 and lower fixed 3 millstones of the first section (Fig. 3, pos. 2, 3). The working zone of the installation forms a tubular space with a nominal diameter of 34 mm. Grooves 17 mm deep are made on the mating surfaces of the millstones. Additionally, roughness elements 1 mm high are placed on the working surfaces, creating local stress concentrators.

The upper movable millstone can rotate to a maximum of 120 degrees and then return to its original position. When a nut enters the working zone, the upper movable millstone of the first section rotates and translates at a predetermined angle. During this movement, the nut is simultaneously subjected to compression between the rough surfaces, torsion, and shear.

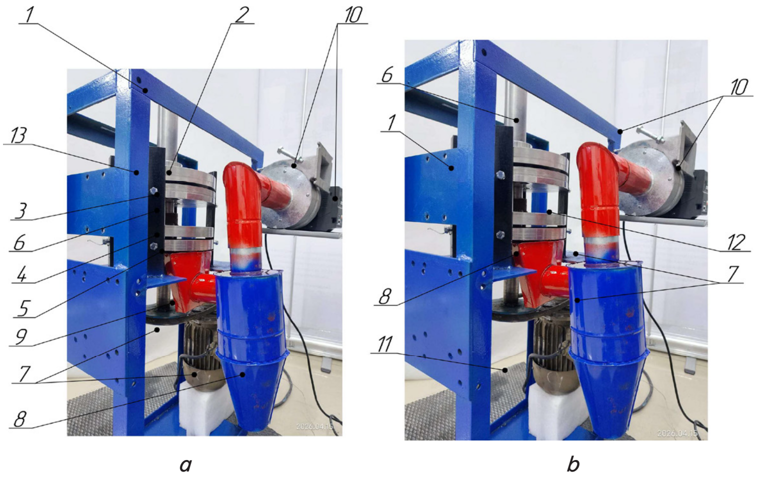

Fig. 2. Photograph of the unit for crushing and cleaning walnuts from shells: *a* — side view; *b* — front view: 1 — body; 2 — upper movable millstone of the first section; 3 — fixed millstone of the first section; 4 — movable millstone of the second section; 5 — fixed millstone of the second section; 6 — rotary shaft; 7 — unit drive; 8 — cyclone for separating shells from the air flow; 9 — confuser for sucking hot shells from the hole of the lower millstone of the second section; 10 — suction fan and frequency converter for regulating the speed of the fan electric motor shaft; 11 — hopper for hot shells; 12 — hopper for collecting cleaned walnut kernels; 13 — bar for attaching fixed millstones of the first and second sections

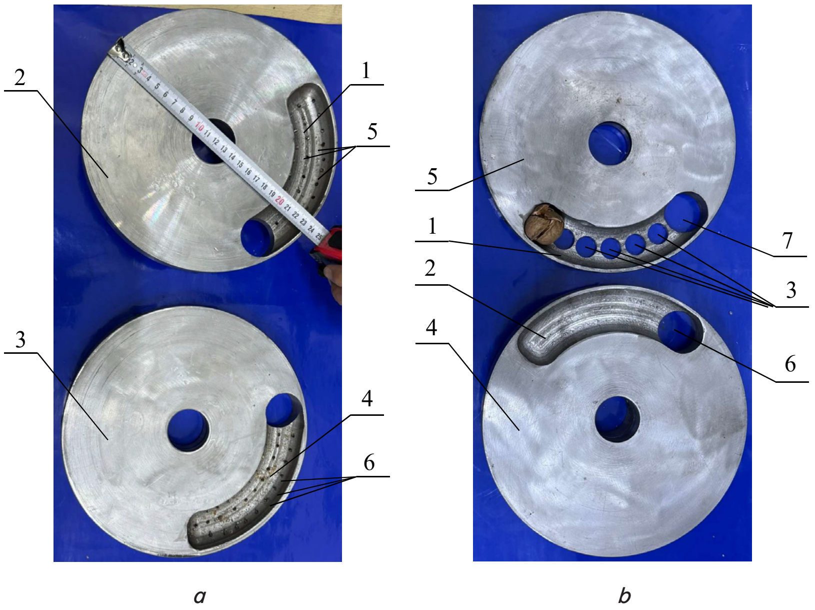

Fig. 3. Movable and fixed millstones of the first and second sections: *a* — millstones of the first section: 1 — groove of the movable upper millstone of the first section; 2 — upper movable millstone; 3 — lower fixed millstone of the first section; 4 — groove of the fixed lower millstone of the first section; 5 — roughness in the grooves of the upper millstone; 6 — roughness in the grooves of the lower millstone; *b* — millstones of the second section: 1 — groove of the lower millstone of the second section; 2 — groove of the upper millstone of the second section; 3 — hole for suction of walnut shells; 4 — upper movable millstone of the second section; 5 — lower fixed millstone of the second section; 6 — through hole of the upper millstone of the second section; 7 — through hole for the walnut kernel to come out

This breaks the nutshell into small particles. The nut, with its hot shell, passes through a through hole in the lower millstone of the first section into the second section. In the second section, the walnuts with their hot shells are also subjected to rotation, while the hot shell particles are simultaneously sucked out of the hole in the lower millstone of the second section by a suction fan through a diffuser and cyclone.

To extract the hot walnut shell particles, holes are made along a groove in the lower millstone of the second section (Fig. 3, *b*, item 3). The openings are connected through a diffuser, a cyclone, and a suction fan. To prevent damage to the kernels during rotation, the surfaces of the grooves of the upper and lower millstones in the second section are lined with a smooth, elastic material (not shown in the figures). The separated kernels fall into kernel collection bin 14, and the hot shells are sucked into a cyclone to separate them from the airflow and fall into shell particle collection bin 17. The proposed design ensures high-quality deshelling of walnuts.

The principal hypothesis assumes that walnut shell failure in the system under consideration is brittle and probabilistic in nature and can be described by a two-parameter Weibull distribution. Rational design parameters for the installation should be determined based on a statistically justified minimum contact load.

It is assumed that:

– walnut shells exhibit strength anisotropy depending on the loading stress;

– failure initiates in areas of maximum principal stress concentration;

– the probability of failure under a given load is determined by the strength distribution of the material;

– a rational installation operating mode should ensure a contact load above the characteristic value for the majority of nuts in the batch.

The following assumptions were adopted in the mechanical interpretation of the walnut shell fracture process:

– the shell is considered a thin-walled biological membrane with quasi-spherical geometry;

– fracture is brittle without significant plastic deformation;

– loading in the working channel is represented as a combination of compression, shear, and torsion;

– contact between the nut and the working surfaces is realized through local stress concentrators.

The following simplifications were accepted in constructing the mechanical model of the shell fracture process:

– variations in shell thickness within a single nut are not taken into account;

– the influence of structural microdefects is considered statistically using Weibull distributions;

– dynamic effects of high-speed loading are not considered (quasi-static testing mode);

– the interaction of the kernel and shell is modeled using the ultimate shell fracture force.

4. 2. Determining the shell strength and the probabilistic nature of failure under local loading

To determine the strength characteristics of walnut shells, tests were conducted under local indenter loading in two orientations: from the natural cleft side and from the intact shell side. Walnuts of a locally cultivated variety (Almaty variant) were used for all tests. The tests had a moisture content of 12 %, a shell thickness of approximately 2 mm, a loading rate of 1 mm/s, and an indenter contact area diameter of 10 mm.

Tests were conducted with a nut moisture content of 12 % and a loading rate of 1 mm/s. For each roughness pitch, 15 tests were performed under loading from the natural cleft side and 15 tests under loading from the intact shell side. A two-parameter Weibull distribution was used to statistically process the results and assess the variability of the strength properties of walnut shells grown in the Republic of Kazakhstan (Almaty Region). This method is preferred for analyzing the brittle fracture of biomaterials as it takes into account the stochastic nature of defects in the shell structure. The fracture probability (*P*) under an applied force (*F*) was determined using formula (1)

$$P_f = 1 - \exp\left[-\left(\frac{F}{F_0}\right)^m\right], \quad (1)$$

where m is the Weibull modulus (shape parameter) characterizing the homogeneity of the specimens' strength properties. The higher the m value, the smaller the data scatter and the higher the predictability of failure;

F_0 is the characteristic force (scale parameter) corresponding to the force at which the probability of failure is 63.2%.

To linearize the data and find the parameters m and F_0, a double logarithmic equation was used, after which a plot was constructed in $ln(F)$ and $\ln(-\ln(1 - P))$ coordinates). The parameters m and F_0 were determined using the least-squares method. The linearized form is written as follows (2)

$$\ln\left[-\ln\left(1-P_f\right)\right] = m\ln F - m\ln F_0. \quad (2)$$

The obtained parameters were used to determine the load that ensures a fracture probability of at least 0.95. Fig. 4, 5 show a device for determining the maximum fracture force of a walnut with and without a cleft.

Fig. 4. Determining the maximum breaking force of a walnut with a cleft on a special device

Fig. 5. Determining the maximum breaking force in Newtons of a walnut without a cleft using a special device

The special devices shown in Fig. 4, 5 provide a loading rate of 1 mm/s and an indenter contact area diameter of 10 mm.

4. 3. Determining the influence of roughness pitch of working surfaces on the shell breaking force

To assess the effect of working surface geometry on shell breakage, additional experiments were conducted between surface roughness with protruding element pitches of 10, 13, and 16 mm. Thirty experiments were conducted for each roughness level, with and without a cleft. A total of 90 experiments were conducted. The force determination device is shown in Fig. 6.

Fig. 6. A device for determining the breaking force between rough surfaces with a pitch of protruding elements of 10, 13, 16 mm from the side of a natural crack

Fig. 7. Device for determining the breaking force between rough surfaces with a pitch of protruding elements of 10, 13, 16 mm from the side of a solid shell

Special devices were manufactured to replicate the working surface (grooves) of the upper movable and lower fixed millstones of the first section. Each pair of surfaces was roughened with protruding elements spaced at 10, 13, and 16 mm, respectively.

4. 4. Determining the strength characteristics of walnut kernels

The strength properties of walnut kernels were determined using an ST-2 structure meter (Fig. 8) (manufactured in Russian Federation). Tests were conducted at a nut moisture content of approximately 12%.

Fig. 8. Structure meter ST2 for determining the crushing force of walnut kernels

To describe the experimental data, a second-order quadratic regression model (3) was used

$$F = b_0 + b_1x + b_2y + b_{11}x^2 + b_{12}xy + b_{22}y^2. \quad (3)$$

A second-order quadratic regression model relates kernel fracture force to deformation and moisture content.

5. Results and discussion of the experimental study to determine the breaking force of walnut shells

5. 1. Determining the breaking force of the shell and the probabilistic nature of failure under local loading

Table 1 gives the results of determining the maximum shell fracture force under loading from a natural cleft.

Table 2 gives the results of determining the maximum force of shell destruction under loading from the side of the whole shell.

Analysis of the data given in Tables 1, 2 revealed a significant difference in shell strength depending on the loading orientation. When loading from the natural cleft, the average failure force was approximately 255 N, while when loading from the intact shell, it was approximately 354 N. This indicates pronounced anisotropy in the mechanical properties of the shell and the presence of a zone of reduced strength along the natural seam line.

Table 1

Results of tests on walnut under loading from a natural cleft

No.	d_{ek}, mm	Force F, N
1	31.5	244
2	33	233
3	31	237
4	31.5	286
5	32	245
6	31	269
7	30.5	258
8	29.5	288
9	30	289
10	33	262
11	31	254
12	31	279
13	31.5	243
14	31.5	240
15	32.5	204
16	31.5	272
17	30.5	240
18	32.5	249
19	30.5	254
20	31.5	256

Table 2

Results of tests on walnuts under loading from the whole shell

No.	d_{ek}, mm	Force F, N
1	31.5	370
2	32	365
3	30.5	361
4	31	342
5	30	320
6	33	386
7	32.5	359
8	31	365
9	31.5	344
10	31	382
11	32.5	338
12	32	317
13	32	352
14	34	354
15	31.5	386
16	31.5	305
17	32	368
18	31.5	368
19	31.5	345
20	30.5	344

A two-parameter Weibull distribution was used to statistically interpret the scatter of results. Fig. 9 shows the shell strength distribution density, and Fig. 10 depicts the shell failure probability curves.

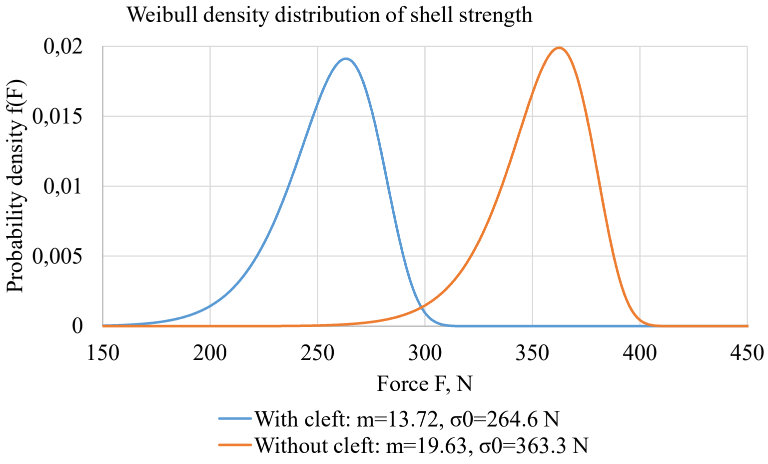

Fig. 9. Density distribution of walnut shell strength (Weibull distribution)

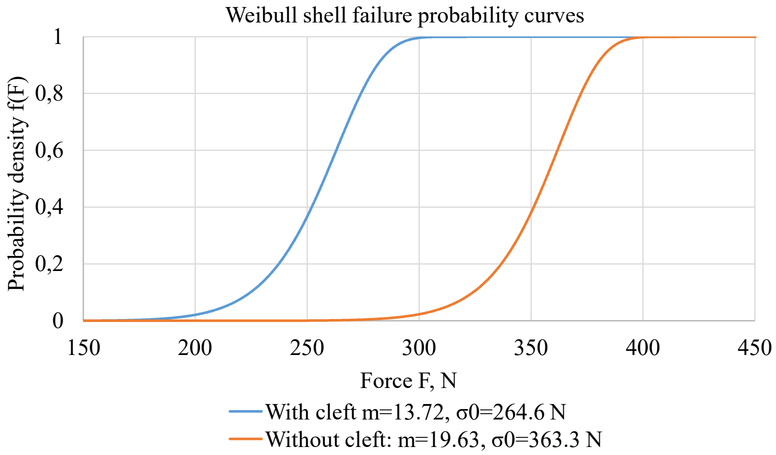

Fig. 10. Probability curves of walnut shell failure

Processing the results using the two-parameter Weibull distribution method allowed us to determine the following parameters:

– Weibull modulus $m = 13.72$ for loading from the cleft side;

– Weibull modulus $m = 19.63$ for loading from the solid shell side;

– Characteristic loads: $F_0 = 264.6$ N, $F_0 = 363.3$ N, respectively.

The obtained values confirm the brittle nature of shell fracture and its pronounced anisotropy. The higher fracture force values for loading from the solid shell side are explained by a more uniform stress distribution and the absence of an initial zone of weakness characteristic of a natural cleft line.

The calculation showed that to ensure a probability of at least 0.95 for any nut orientation, a contact load of approximately 350 N is required. This value can be considered the lower limit of the load required to fracture the shell in the working zone of the installation.

5. 2. Influence of the roughness pitch of working surfaces on the shell breaking force

To assess the influence of working surface geometry on shell breakage, additional experiments were conducted between roughness surfaces with protruding element pitches of 10, 13, and 16 mm. Unlike indenter tests, this stage of the study more closely simulates nut contact with working surfaces typical of a real nut cracking machine.

Summary results for shell breaking force determination are given in Table 3.

As can be seen from Table 3, the roughness pitch has a significant impact on the shell fracture force. The lowest fracture force values are observed at a pitch of 10 mm, whereas as the distance between protruding elements increases to 13 and 16 mm, the fracture force increases. When loading from the crack side, the average fracture force was 234.1 N at a pitch of 10 mm, 323.1 N at a pitch of 13 mm, and 331.6 N at a pitch of 16 mm. When loading from the solid shell side, the corresponding values were 283.1 N, 369.7 N, and 380.4 N.

To statistically interpret the scatter of results from the second stage of the experiment, an analysis of the shell strength distribution was performed using a two-parameter Weibull distribution. The distribution parameters are given in Table 4.

Fig. 11 shows the shell strength distribution density curves, and Fig. 12 depicts the probability fracture curves for different roughness steps of the working surfaces and two loading orientations.

An analysis of the curves in Fig. 11, 12 reveals that decreasing the roughness pitch shifts the distributions toward lower fracture forces. This means that at a pitch of 10 mm, shell fracture occurs at lower applied forces compared to pitches of 13 and 16 mm. As the distance between protruding elements increases, the probability curves shift toward higher forces, indicating an increase in the force required to fracture the shell.

Table 3

The influence of roughness pitch on the breaking force of walnut shells

Roughness pitch, mm	Load orientation	Number of experiments	Average destructive force, N	Standard deviation, N	Minimum N	Maximum N
10	with cleft	15	234.1	13.6	206	249
10	without cleft	15	283.1	12.2	263	302
13	with cleft	15	323.1	11.8	309	342
13	without cleft	15	396.7	9.8	356	392
16	with cleft	15	331.6	8.3	313	345
16	without cleft	15	380.4	12.5	360	398

Table 4

Weibull distribution parameters for the second stage of the experiment

Roughness pitch, mm	Load orientation	Weibull module (m)	Characteristic power (F_0), N
10	with cleft	23.63	240.1
10	without cleft	26.60	288.9
13	with cleft	29.56	328.9
13	without cleft	35.43	374.7
16	with cleft	44.89	335.6
16	without cleft	37.02	386.3

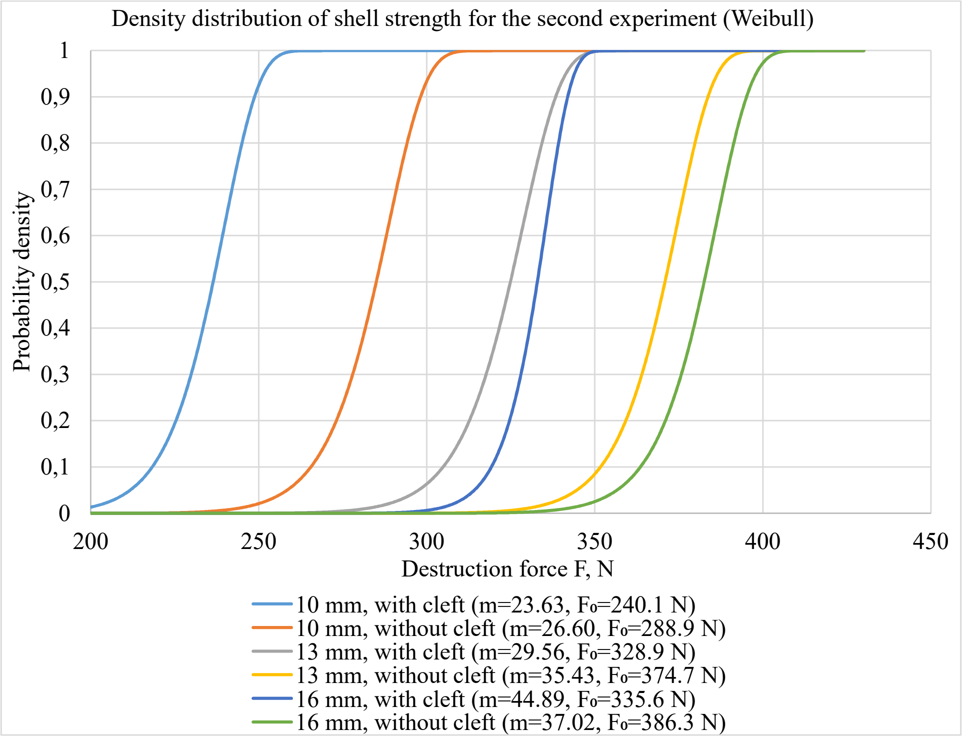

Fig. 11. Density distribution of the strength of walnut shells for different roughness steps of working surfaces and two loading orientations (Weibull distribution)

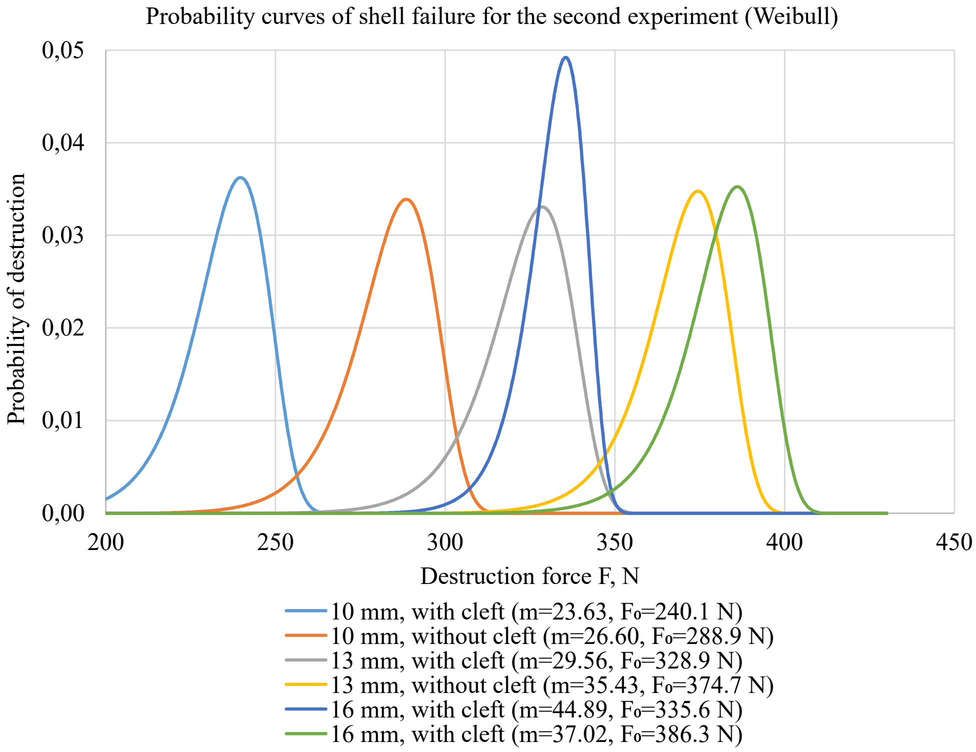

Fig. 12. Probability curves of walnut shell failure for different roughness steps of working surfaces and two loading orientations (Weibull distribution)

In all studied loading series, the fracture forces from the natural cleft side were lower than those from the intact shell side. This result is consistent with the results of the first stage of the study and confirms the presence of pronounced anisotropy in the mechanical properties of walnut shells.

This pattern can be explained by changes in the density of local stress concentrators in the contact zone. With a smaller roughness pitch, the number of active contact points between the nut and the working surfaces increases, leading to increased localized stress and facilitating crack initiation. With a larger roughness pitch, the contact localization decreases and the stress is distributed more evenly, thereby increasing the force required to break the shell.

An analysis of the curves in Fig. 11, 12 reveals that decreasing the roughness pitch shifts the distributions toward lower fracture forces. This means that at a pitch of 10 mm, shell fracture occurs at lower applied forces compared to pitches of 13 and 16 mm. As the distance between protruding elements increases, the probability curves shift toward higher forces, indicating an increase in the force required to fracture the shell.

In all studied series, when loading from the natural cleft, the fracture forces were lower than when loading from the intact shell. This result is consistent with the results of the first stage of the study and confirms the presence of pronounced anisotropy in the mechanical properties of walnuts.

This pattern can be explained by changes in local stress concentrators in the contact zone. With a smaller roughness pitch, the number of active contact points between the nut and the working surfaces increases, leading to increased local stress and facilitating crack initiation. With an increased roughness pitch, the contact localization decreases and the stress is distributed more evenly, thereby increasing the force required to break the shell. The results obtained in the first stage characterize the basic strength of walnut shells under localized loading and allow us to evaluate the influence of nut orientation on the magnitude of the breaking force. It was found that when loading from the natural cleft, shell failure occurs with lower forces compared to loading from the intact shell. This indicates pronounced anisotropy in the mechanical properties of the shell and the presence of a zone of reduced strength along the natural seam.

The second stage of our study focused on the influence of the geometry of the working surfaces, specifically roughness pitches of 10, 13, and 16 mm, on the shell breakage force. Unlike indenter testing, this stage more closely simulates the contact of the nut with rough surfaces, closely resembling the conditions found in the working zone of a nutcracker.

A comparison of the results from the two stages shows that they complement each other rather than duplicate each other. The first stage of the study addresses the question of the intrinsic strength of the shell and allows for a quantitative assessment of its probabilistic characteristics under localized loading. The second stage determines how the geometry of the working surfaces influences shell breakage under conditions similar to those of a real machine.

At the same time, the general pattern established in the first stage remains consistent across all series: shell breakage from a natural cleft requires less force than shell breakage from a solid shell. This means that the shell anisotropy is maintained both under local loading by indenters and in contact with rough working surfaces.

The results of the second stage showed that the roughness pitch influences the magnitude of the fracture force. The lowest forces were obtained with a pitch of 10 mm, indicating more efficient crack initiation due to the high density of localized stress concentrators. As the pitch increases to 13 and 16 mm, the fracture force increases, due to a decrease in stress localization in the contact zone.

It should be noted that the tests between rough surfaces, despite their closeness to the actual structure, still primarily implement a compression mode. In a real nut cracking machine, the nut is subjected not only to compression but also to the combined effects of shear and torsion due to the reciprocating motion of the upper millstone and the interaction of the shell with protruding roughness elements. Therefore, the second stage of our study should be considered an intermediate level of modeling, linking the basic shell strength test with the actual operating conditions of the machine.

Thus, a combined analysis of the two stages of the study allows us to draw the following conclusions. The first stage determines the probabilistic and mechanical characteristics of the shell as a brittle, anisotropic shell. The second stage demonstrates how the geometry of the working surfaces influences the magnitude of the load required to fracture this shell. Combined, these results lay a mechanically sound basis for selecting parameters for the working surfaces of a nutcracker.

5. 3. Mechanical interpretation of the process of shell destruction

Analysis of the results from the two stages of the study reveals that walnut shell fracture is determined not only by the absolute magnitude of the applied force but also by the nature of the stress state formed in the contact zone. Under localized loading by indenters, normal compressive stresses predominate in the shell, whereas contact with rough surfaces additionally generates localized shear stresses associated with uneven contact and load redistribution across the nut surface.

In the designed nut-cracking machine, this effect should be even more pronounced since the nut in the working channel is subjected not only to compression but also to shear and torsion due to the reciprocating motion of the upper millstone. Thus, the actual shell fracture process occurs under complex combined loading conditions.

In the first approximation, the normal contact deformation δ is determined by the geometry of the working channel and can be estimated by expression (4)

$$\delta = d_{eq} - D_{eff}, \tag{4}$$

where d_{eq} is the equivalent nut diameter;

D_{eff} is the effective diameter of the working channel.

If there are protruding elements of height h_p on the upper and lower millstones, the effective channel diameter is determined as follows (5)

$$D_{eff} = D_0 - 2hp, \tag{5}$$

where D_0 is the nominal diameter of the tubular space.

As a first approximation, the normal compressive force is determined by the following relationship (6)

$$F_n = k_n \delta, \tag{6}$$

where k_n is the reduced stiffness of the “nut-contact-working surfaces” system.

The tangential force arising from the interaction of the shell with the protruding roughness can be estimated as follows (7)

$$F_s = \mu F_n, \tag{7}$$

where μ is the effective friction coefficient in the contact zone.

When the nut rotates, a torque (8) is generated in the working channel

$$M = F_s r_{eff}, \tag{8}$$

where r_{eff} is the effective radius of application of the shear force.

Thus, normal and shear stresses arise simultaneously in the shell. To qualitatively describe the failure conditions, the equivalent stress according to the von Mises criterion (9) can be used

$$\sigma_{eq} = \sqrt{\sigma^2 + 3\tau^2}, \tag{9}$$

where σ is the normal compressive stress,

r is the shear and torsional stress.

Shell failure occurs when the equivalent stress reaches a critical value (10)

$$\sigma_{eq} \geq \sigma_{cr}. \tag{10}$$

Given the fragile nature of the shell, the moment of failure is probabilistic. A two-parameter Weibull model (11) was used to describe it

$$P_f = 1 - \exp\left[-\left(\frac{F}{F_0}\right)^m\right], \tag{11}$$

where P_f is the fracture probability,

F_0 is the characteristic fracture force, and m is the Weibull modulus.

The previously obtained values of the parameters m and F_0 allow us to relate the mechanical loading model to the probability of shell fracture. In this case, increasing the normal force F_n, the shear force F_n, and the torque M leads to an increase in the equivalent stress and, consequently, to an increase in the probability of shell fracture.

The experimental results obtained are consistent with this concept. As the roughness pitch decreases to 10 mm, the density of local contact points and the concentration of shear stresses increase, leading to a decrease in the shell fracture force. As the surface pitch increases to 13 and 16 mm, the localization of contact decreases, which is accompanied by an increase in the fracture force.

Thus, the process of walnut cracking in the designed setup can be interpreted as the fracture of a brittle anisotropic shell under the combined action of compression, shear, and torsion. The experimentally obtained values of the crushing force and the parameters of the Weibull distribution form the basis for the working elements of the nut-cracking machine.

5. 4. Strength characteristics of walnut kernels

The results of testing walnut kernels on the ST-2 structure meter showed that their strength characteristics depend significantly on deformation and moisture content. A second-order quadratic regression model was used to describe the experimental data. For the studied variant, the following equation (12) was derived

$$F = 4{,}137{,}704{,}512 - 2{,}626.9045x - 7{,}955.0652y + \\ +34.9617x^2 + 450.4758xy + 7.7666y^2, \tag{12}$$

where F is the core breaking force, g;

x is the strain, mm;

y is the core moisture content, %.

Based on this equation, a response surface was constructed that reflects the combined effect of strain and moisture content on the kernel breaking force (Fig. 13).

The response surface analysis reveals that the dependence of the fracture force on the factors studied is significantly nonlinear. As moisture content increases, a decrease in kernel strength is observed, which is explained by a decrease in the resistance of its internal structure to external loading. The effect of deformation is also nonlinear: as deformation increases, the force increases until a limiting state is reached, at which point the kernel fractures.

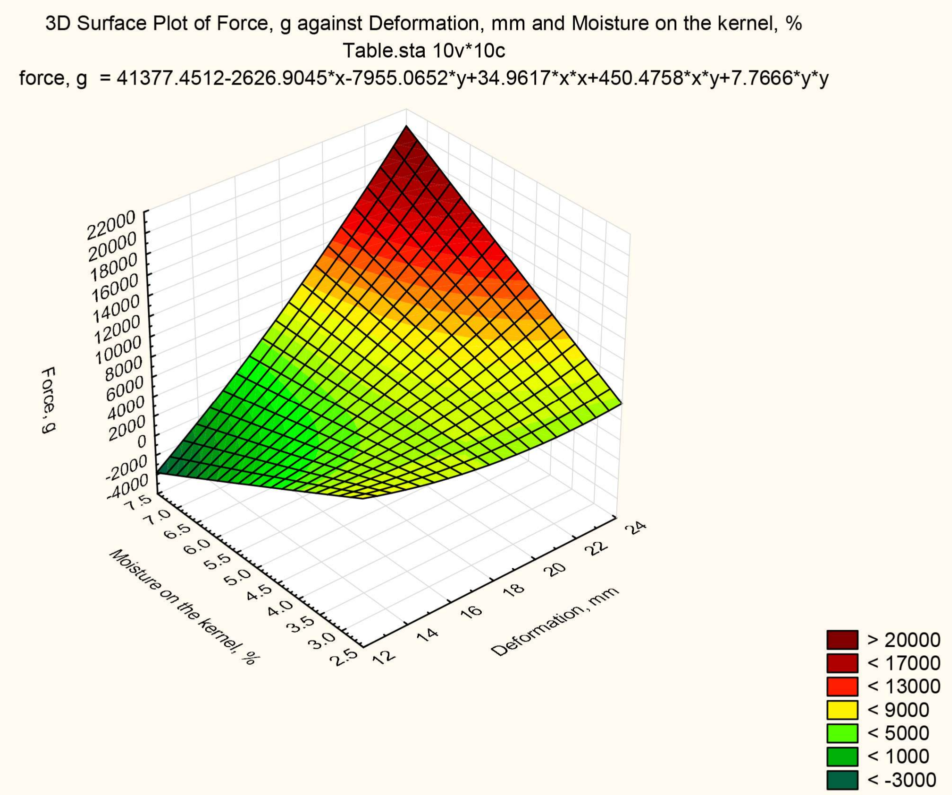

Fig. 13. The response surface reflecting the combined effect of deformation and moisture on the kernel failure force

Our results (Fig. 13) show that, for a certain combination of moisture content and deformation, there is a region of minimum fracture force. This confirms the need to consider the physical state of the kernel when selecting nut cracking modes. Thus, the constructed regression model and the corresponding response surface enable us to estimate the limiting conditions for kernel fracture and use them to develop a safe operating range for the nut cracking machine.

5. 5. Formation of a safe range of loads based on the conditions of shell destruction and kernel preservation

The safe working load range was determined based on the condition of ensuring shell fracture while maintaining kernel integrity. It was found that walnut shell fracture occurs under loads of approximately 255 N on the crack side and approximately 354 N on the intact shell side. Weibull analysis results indicate that fracture in any orientation requires a load of approximately 350 N.

Kernel tests on the ST-2 structure meter showed that fracture under direct loading occurs at an average force of approximately 120 N. Since the kernel in a real machine does not directly bear the full external load, a load transfer coefficient η was introduced, relating the external force F_n to the force acting on the kernel: $F_{kernel} = \eta F_n$, where $\eta < 1$. The safe working load range is then determined by relation (13)

$$F_{shell} \leq F_n < \frac{F_{kernel,ave}}{\eta}. \tag{13}$$

It follows that a rational operating mode of the installation should ensure the destruction of the shell due to the combined action of compression, shear, and torsion with minimal transfer of load to the kernel.

6. Discussion of results based on the study to determine the breaking force of walnut shells

Our results demonstrate that walnut shell fracture is determined by two key factors: the anisotropy of the shell's mechanical properties and the geometry of the contacting working surfaces. This is confirmed by the data from the first stage of our study (Tables 1, 2), according to which the average fracture force under loading from the natural cleft is approximately 255 N, while under loading from the intact shell, it is approximately 354 N. Consequently, the natural cleft line is a zone of reduced strength, and the shell itself exhibits pronounced structural anisotropy. The scatter of experimental values and the shape of the probability curves in Fig. 9, 10 further demonstrate that shell fracture is probabilistic in nature, typical of other brittle biological shells.

The explanation for this result is related to the characteristics of the stress state in the shell. Under localized indenter loading, normal contact stress predominantly develops in the material. Under loading from a natural cleft, fracture is initiated at a lower force, as the natural joint acts as a weakened zone and promotes earlier crack initiation. This is consistent with the Weibull distribution parameters obtained in the first stage (Fig. 9, 10): lower fracture resistance from the cleft side is accompanied by greater sensitivity to localized defects in the shell structure. Under loading from the solid shell, stress is redistributed more uniformly, requiring a higher load to reach the critical state.

The results of the second stage of our study show that the roughness pitch of the working surfaces is a significant design parameter affecting the shell failure force. According to the data in Table 3, the minimum failure force is observed at a pitch of 10 mm; while increasing the pitch to 13 and 16 mm increases the required load. This pattern is confirmed by the distributions and probability curves in Fig. 11, 12, where a decrease in the roughness pitch is accompanied by a shift in the distributions toward lower forces. Mechanically, this can be explained by the fact that with a smaller pitch, the density of local contact points increases and, accordingly, the number of stress concentrators initiating crack development. With a larger roughness pitch, contact becomes less localized, and the stresses are distributed more evenly, requiring a higher external force.

It is particularly important that the pattern established in the first stage is maintained in all series of the second stage: fracture from the natural cleft occurs at lower forces than from the solid shell. This indicates that the identified shell anisotropy is maintained not only under localized indenter loading but also during contact with rough working surfaces, that is, under conditions closer to those encountered in a real nutcracker. In other words, the first stage of our study characterizes the intrinsic strength of the shell, while the second demonstrates how this strength is realized in the nut-working surface system.

The proposed mechanical interpretation of the fracture process allows us to relate the experimental results to the operating conditions of the machine. While compression predominates under indenter loading, interaction with rough surfaces also generates shear stresses, and in a real machine, a torque caused by the reciprocating motion of the upper millstone. Consequently, actual shell fracture occurs under the combined action of compression, shear, and torsion. This is fundamentally important, as it explains why, in the machine's operating zone, fracture can be achieved not only through increased normal force but also through more efficient use of the shear components of the load.

A practically significant result of our work is the development of a safe operating load range for shell fracture and kernel integrity. The results of the first stage indicate that, for any nut orientation, a load of approximately 350 N is required to achieve a high probability of fracture. However, kernel testing on the ST-2 structure meter showed that its strength is significantly lower (Fig. 13). At first glance, this creates a contradiction between the need to break the shell and the requirement to maintain the integrity of the kernel. However, this contradiction is resolved by the fact that in a real machine, the kernel does not directly bear the full external force: part of the load is expended on the deformation and destruction of the shell, redistribution in the contact zone, and compensation through shear interactions. Therefore, a safe operating mode must ensure shell destruction not by simply increasing the normal pressure but by a rational combination of compression, shear, and torsion with minimal load transfer to the kernel.

Compared to other studies on the strength of nutshells and similar biological shells, the proposed approach has several distinctive features.

First, the study combines local strength tests, tests between model rough surfaces, and a mechanical loading scheme similar to a real machine.

Second, along with average values of destructive forces, a probabilistic analysis based on a two-parameter Weibull distribution is used, allowing for the natural variation in the properties of biological material to be taken into account.

Third, shell strength is considered in conjunction with kernel strength, thereby framing the problem of shell failure not in isolation but within the context of the technological requirement for the preservation of the target product. This distinguishes our work from those studies in which the analysis is limited to determining the shell failure force without regard to the parameters of the working element and the risk of kernel damage [1–6].

However, the study results have certain limitations. They were obtained for nuts of a single local variety at a moisture content of approximately 12%, a shell thickness of approximately 2 mm, a specific range of equivalent diameters, and a loading rate of 1 mm/m. Consequently, the established fracture force values, Weibull parameters, and safe load range are primarily valid for the specified range of input conditions. Furthermore, the second-stage tests, although close to the actual contact pattern, still primarily implement quasi-static compression between rough surfaces and do not fully reproduce the kinematics of a reciprocating millstone. Therefore, the obtained relationships should be considered a mechanically valid, but not yet definitive, complete model of the actual cracking process.

The study's disadvantages, which are not consistent with its limitations, deserve special mention. These include the relatively limited sample size in individual series, the lack of direct visualization of crack initiation and development, and the lack of direct measurement of the proportion of external load transferred to the kernel in the machine's working channel. Furthermore, our study did not take into account variability in local shell thickness, possible asymmetry of the nut's internal cavity, and variations in kernel shape. These limitations can be addressed in the future by expanding the experimental base, using high-speed video recording, finite element modeling, and instrumental monitoring of contact forces directly in the machine's operating zone.

Further studies should be linked to a transition from model testing to experiments on a full-scale nut-cracking machine. A promising approach is to explore the influence of the amplitude and frequency of the reciprocating motion, the shape and height of roughness, the relative speed of the working elements, and the moisture content of the nut on the probability of shell fracture and the degree of kernel damage. Mathematical and experimental difficulties may arise in describing the transient contact interaction of a brittle anisotropic shell, the high sensitivity of the biomaterial to changes in humidity, and the natural variability of the geometric and strength properties of nuts.

Therefore, our study results demonstrate that walnut shell fracture should be considered as a probabilistic process of brittle fracture of an anisotropic shell under combined loading conditions. Minimizing the roughness pitch to 10 mm reduces the required fracture force by increasing local stress concentration, and taking into account the strength characteristics of the kernel allows for the substantiation of a safe operating load range. The combined data obtained provides a mechanically and technologically sound basis for selecting parameters of the working elements for a nut cracking machine.

7. Conclusions

1. We have found that walnut shell strength depends significantly on the loading orientation. Under localized loading from the natural cleft, the average failure force was approximately 225 N, while under loading from the intact shell, it was approximately 354 N. This confirms the pronounced anisotropy of the shell's mechanical properties and the presence of a zone of reduced strength along the natural seam (on the cleft side). It was shown that shell failure is probabilistic and is correctly described by a two-parameter Weibull distribution. For loading from the crack side, the obtained parameters were $m = 13.75$ and $F_0 = 264.6$ N, while for loading from the solid shell side, $m = 19.63$ and $F_0 = 363.3$ N. A probabilistic analysis revealed that a contact load of approximately 350 N is required to ensure a fracture probability of at least 0.95 for any nut orientation.

2. A significant influence of the roughness pitch of the working surfaces on the shell fracture force has been established and experimentally proven. The lowest fracture force values were obtained with a pitch of 10 mm, whereas with increasing pitch to 13 and 16 mm, the required force increased. This is explained by an increased density of local stress concentrators with a smaller distance between protruding elements and, consequently, easier crack initiation in the shell. It is shown that the results of the two stages of our study do not duplicate each other but rather complement each other. The first stage allowed us to determine the basic probabilistic and mechanical characteristics of the shell as a brittle anisotropic shell, while the second stage made it possible to establish the influence of the geometry of rough working surfaces on fracture behavior under conditions similar to those of a real machine.

3. A mechanical interpretation of the shell fracture process in the designed setup has been proposed as the fracture of a brittle shell under combined compression, shear, and torsion. It is shown that, unlike indenter tests or tests between rough surfaces under static compression, a more complex stress state is formed in the real working zone of a nut cracking machine, increasing the efficiency of crack initiation and propagation.

4. It has been established that the strength characteristics of walnut kernels are significantly dependent on moisture content and deformation and are described by a second-order quadratic regression model. Analysis of the response surfaces revealed a nonlinear change in the fracture force of the kernel and the presence of a region of minimum strength for a certain combination of deformation and moisture content.

5. A safe operating load range was compiled based on the conditions for shell destruction and kernel integrity. It was shown that a rational operating mode for the installation should ensure shell destruction under external loads of approximately 350 N.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Temov Baurzhan: Investigation, Data curation, Data processing; **Nurakhmetov Baurzhan Kumargaliyevich**: Supervision; **Askarov Ardak Dakharbekovich**: Conceptualization, Methodology, Writing – review & editing; **Nurakhmetov Ilyas**: Formal analysis, Data analysis, Statistics; **Nasrullin Galymzhan**: Formal analysis, Data analysis, Statistics.

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