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Methods for Identifying the Mechanical Properties of Wheat Grain in the Context of Normal Impact

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Abstract. This article has a review-empirical character. The first part synthesizes methods for identifying the mechanical properties of seeds used in bench tests, with particular emphasis on measuring the force–time course, contact time, and the coefficient of restitution under impact conditions. The limitations of non-standardized procedures and apparatus requirements-stemming from very short contact times and the diverse morphology of grain are discussed. The second part presents original experiments on a gravitational test bench for free fall of grain onto a piezoelectric force sensor, together with simultaneous velocity recording using a high-speed camera. Normal impacts of winter wheat (cv. Memory) with a flat metal surface were analyzed for 400 grains at four moisture levels (7–16%) and varied impact velocities. We observed an increase in peak force with impact speed, a non-linear decrease in the coefficient of restitution with increasing speed and moisture, and a lengthening of contact time with moisture. The compiled data serve as a reference for calibrating contact models, including discrete element method models, and as a basis for selecting loading ranges in the design of machine working elements; the methodology, , which combines review and experimental verification, helps reduce the number of costly full scale trials.

Key words: coefficient of restitution (CoR); force–time relationship; dynamic impact forces; agricultural machinery; winter wheat grains

Introduction

Modernizing existing machines [1] and designing new solutions in agricultural mechanization require reliable data on mechanical interactions in the system comprising the machine and the processed material. In the classical approach, a complete picture is obtained only at the stage of costly full scale prototype tests, which slows design iterations and increases the risk of incorrect design decisions [2, 3]. This problem is particularly evident in machines intended for the transport and dosing of plant derived granular materials, from sowing through harvesting and threshing to storage, packaging, and processing, where cereal grains are among the key working media.

The motion of a single kernel in seeder mechanisms and in conveying ducts involves numerous short duration impacts with elements of complex geometry. Accurately capturing these interactions in field studies or even in traditional laboratory experiments is difficult because contact times are very short, the response is sensitive to grain orientation, and the material is variable in shape, size, and moisture content.

For seed material, correct identification of static and dynamic loads is crucial, because excessive values can lead to internal and external damage that reduces germination and growth. The aim of this paper is to review research methods that enable the identification of the mechanical properties of grain under impact conditions, serving as a prelude to the development of a test stand and the planning of detailed, accurate experiments. The resulting synthesis is intended to support both the design and optimization of engineering solutions and the calibration of numerical models, such as the discrete element method, which in turn reduces the number of costly full scale tests and shortens the machine development cycle.

1. Wheat grain

From a nutritional standpoint, wheat holds a leading position among cereals, so understanding the properties of its kernels is of particular importance. Cereal grains, as plant material, have a complex morphological and anatomical structure that directly determines their physico mechanical properties. These are influenced by size, shape, chemical composition, moisture content, gluten and protein content, vitreousness, and density, which affect the condition of the endosperm [4 - 7]. Geometrically, the grain is highly variable: length about 5 to 10 mm, mass 30 to 50 mg, an elongated shape that is laterally flattened; the cross section ranges from evenly rounded to triangular, with variability both between cultivars and within a single ear [4]. Common features include a ventral groove reaching halfway into the cross section, an embryo surrounded by a scar at the boundary of the ventral and dorsal sides, and a brush at the apex [7]. Externally, the grain is protected by a fruit seed coat composed of several layers, including an aleurone layer; waxy compounds present in the coat limit water permeability and facilitate long term storage [8, 9]. The endosperm, which constitutes about 80 percent of the mass, is made up of protein starch cells, and its cohesiveness translates into grain strength [8].

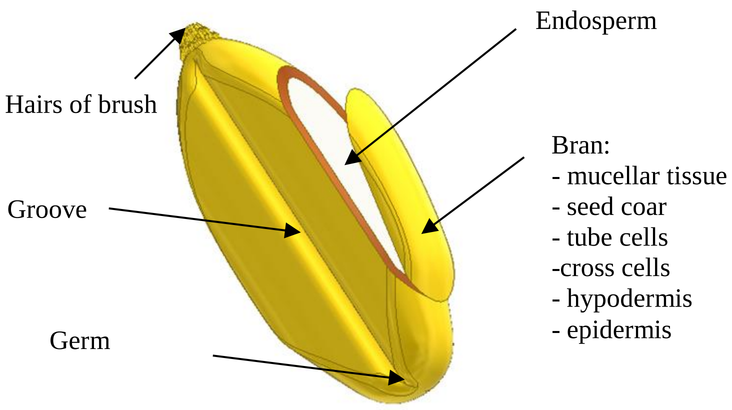
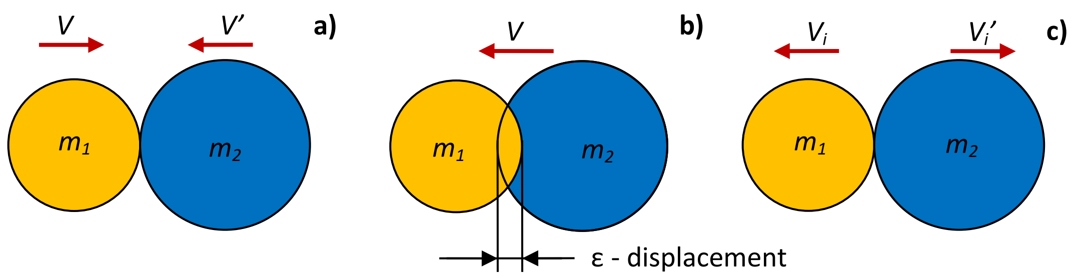


Fig. 1. - Diagram of a whole wheat [10]

Such morphology, and its variability in dimensions, shape, the layered seed coat, and endosperm traits, directly affect the course of collisions with working elements and the contact parameters. Therefore, as a direct consequence of the foregoing, bench studies with controlled geometry and measurement of short duration phenomena are necessary to reliably determine contact model parameters and to account for the material's morphological diversity.

2. Contact problem for cereal grain

Modeling contact forces in collisions poses a substantial cognitive challenge, because the system response is governed by complex processes of energy transfer and dissipation, which makes rigorous mathematical analysis difficult. Constructing dynamic contact models therefore requires extensive theoretical considerations, and the resulting hypotheses must each time be verified experimentally using appropriately chosen measurement setups. The collision of a cereal grain is a short lived and violent phenomenon: on a very small time scale there is an exchange of momentum, intense energy dissipation, and large changes in velocity and contact forces [11]



a) the initiation of contact, b) the movement of objects relative to each other until it ceases, c) the termination of contact [12]

Fig. 2. - Phases of contact

It should be described as a continuous process with a finite duration, in which local deformations occur in the contact zone with elastic, plastic, or elasto plastic character, energy is dissipated including in friction and micro slip, and vibrations and stress waves propagate throughout the system [13 - 17]The contact can be divided into two phases. In the loading compression phase, which begins at the moment of first contact, equal and opposite compressive forces act on both sides of the contact point and oppose the relative motion of the bodies [18]. This phase continues until the relative velocity at the contact point reaches zero; for two bodies of masses m and m′ and velocities just before impact V and V′, the common velocity of the system at the end of compression is:

$$V_w = \frac{mV + m'V'}{m + m'}$$

If the material is fully elastic, the unloading restitution phase follows compression immediately and ends at the moment the bodies separate [19]. This description applies both to the collision of two comparable masses in motion and to an impact against a surface treated as rigid [20]. In the second phase the deformed bodies tend to recover their original shape and the contact forces decrease; however, the separation of the bodies does not have to mean a full return to the initial state, because depending on the material properties permanent deformations and delayed restitution are possible, occurring partly after contact has ceased. For an ideally elastic system without energy losses, the kinematic and dynamic relations follow directly from the conservation of momentum:

$$mV_0 + m'V_o' = mV_i + m'V_i'$$

where V_0, V_0' are the velocities before the collision;
V_i, V_i' are the velocities after the collision.

An illustration of material differences is the comparison of force as a function of time for a normal impact: an elastic impact yields an approximately symmetric trace (compression and rebound times are similar, with a shorter contact time), whereas elasto plastic and plastic impacts show pronounced asymmetry, a longer compression phase, and a greater overall contact time; the share of energy dissipation increases and the ability to “bounce” decreases [21]. This qualitative picture underpins the choice of a contact model and the estimation of its parameters (for example, stiffness, damping, and plasticity thresholds), whose values require bench tests with synchronized force time records and kinematic characteristics to enable their determination and verification.

3. Methods for identifying the mechanical properties of seeds

The mechanical properties of plant based materials are understood as their response to applied external loads, resulting from elastic, plastic, and viscous behavior. Reliable identification of these properties requires precise laboratory tests that determine material constants and the curves describing the relationship between load and deformation [22, 23]. At present there are no general international guidelines that would unambiguously standardize measurements of the basic physical properties of seeds. In practice, many procedures derive from classical strength of materials, which, given the complex structure of biological samples, is not always fully adequate in terminology or methodology [8].

The complexity of cereal grain structure, evident in irregular shapes and sizes, variable water content, and a multilayered anatomical structure, makes an unambiguous assessment of strength characteristics difficult. For this reason, many studies have been conducted on seeds with geometry closer to a sphere, for example pea [24], lentil, soybean, rapeseed [25], and bean [26]. In research on granular materials two principal approaches are adopted, depending on how the medium is treated. The first is based on tests performed on a bulk granular mass [27], and the second on tests of single seeds [28]. These approaches should be regarded as distinct and complementary, because they provide independent mechanical characteristics that are not directly convertible into one another.

The choice of approach depends on the aim of the work. It may be the organization of knowledge and identification of features for a systematic treatment, the preparation of data for engineering calculations, or, increasingly, the calibration and validation of simulation models [8]. The outcome of such studies is sets of material constants and curves that describe the relationship between excitation and deformation. These data form the basis for identifying and parameterizing effective mechanical characteristics in constitutive models of an empirical or theoretical nature, which is crucial for further analyses of contact and impacts of seeds with working elements [8].

3.1. Studies on single grains

Previous work on identifying the parameters that describe the strength and mechanical characteristics of granular masses captures material behavior well during storage and transport, but attempts to transfer those generalized characteristics to the behavior of a single kernel have shown no simple correspondence [8]. Hence the need for detailed identification of mechanical properties at the level of an individual seed. The literature recognizes two main paths: indirect methods and direct methods [29].

In the indirect approach, strength is inferred from the grain’s response to an excitation applied in a technological process or under laboratory conditions. The excitation may take the form of a precisely defined parameter or be the effect of a process such as threshing, transport, drying, cleaning, or sorting [30]. The influence of loading is evaluated after the sample is unloaded and often relies on inspection of the surface for macroscopic structural damage, for example dents, cracks, or breaches of the coat. Although quick, this diagnosis is subjective, has limited repeatability, and does not provide information on the internal state [8]. For this reason laboratories readily use complementary techniques. A colorimetric method can reveal coat damage and deeper fissures: the sample is immersed in a dye that penetrates defects, then the dye is washed out and the extinction of the resulting solution is measured, which correlates with the level of damage [29]. When assessment of internal structure is required, X ray methods are used. The test is non destructive, so the same sample can then undergo biological tests. An integrative indicator of the effect of loading on the vital functions of seeds is biological resistance, understood as the ability to maintain viability and vigor for germination and growth [31 - 35].

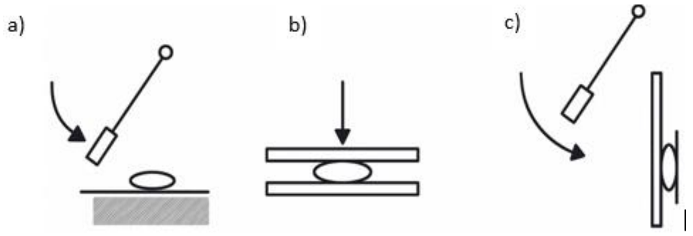
Indirect methods, however, do not provide the unambiguous and complete characteristics needed to build constitutive models that reproduce contact in numerical analyses, for example in the DEM environment. Much higher precision of identification is obtained with direct methods, in which a single grain is subjected to strictly defined excitations and its response is recorded. Two loading regimes are distinguished: quasi static and dynamic. In quasi static tests, compression, tension, and creep are most common. The dominant solution is to measure the relationship between displacement and load, from which a stress strain curve is determined. This type of test corresponds well to the frequent technological situations involved in processing and storage of the material [8].

Studies under dynamic loading conditions are described much less often, even though they are closest to real impacts in seeder mechanisms and conveying systems. The limited number of reports results from the very short durations involved and the small sizes and irregular shapes of the objects, which impose high requirements on apparatus and measurement procedures. In practice, nonstandard test stands are used. In one approach a moving grain strikes a fixed obstacle, and in the other a hammer strikes a fixed grain. Both variants make it possible to determine key contact quantities, provided that impact speed, contact time, and the force history are controlled precisely so that the results can be used to identify the parameters of models describing collisions of single seeds.

3.2. Dynamic loads

Issues concerning the behavior and mechanical properties of cereal grains under dynamic loading are addressed relatively rarely. This is primarily due to the small size of the grains and to measurement difficulties, because the processes change rapidly and require specialized, costly recording equipment. As in quasi static tests, no uniform method for assessing mechanical properties has yet been developed for dynamic loads. Consequently, the available publications present results obtained under diverse experimental conditions, differing in sample preparation, grain orientation, interaction velocities, and the design of the test stands.

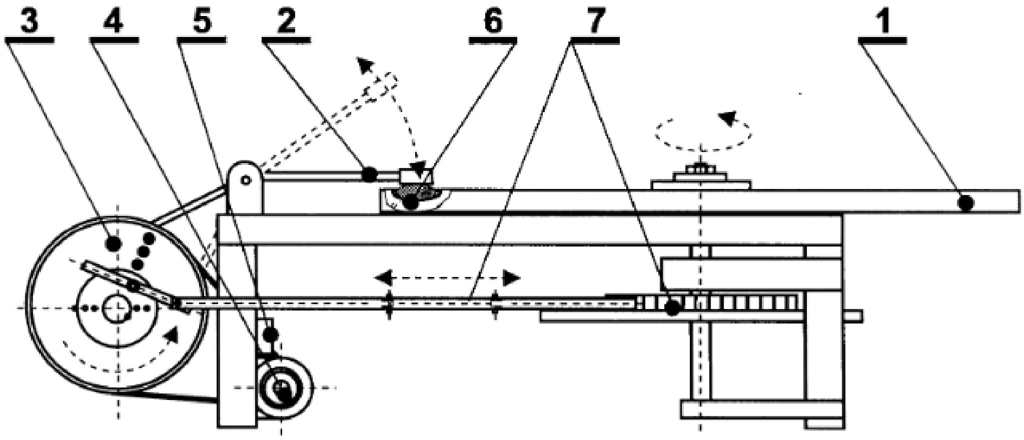
The earliest studies focused on indirect methods, in which the influence of excitation was evaluated through the subsequent biological usefulness of the seeds [36 - 40]. The scope of research was sometimes extended to include cyclic loading, carrying out fatigue like tests. In practice, simple impact rigs were used, which, following Mohsenin's proposal, are divided into two basic types: freely seated grain and supported grain (Fig. 3) [41]. This division organizes descriptions of the test stands and facilitates comparisons of results obtained in different dynamic configurations.



a) unsupported; b, c) supported [41]

Fig. 3. - Placement of the grain during dynamic tests

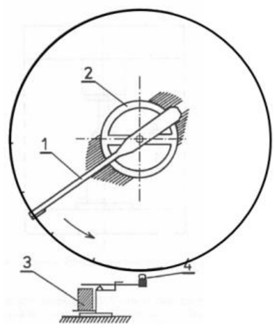
In the supported configuration, hammer type test stands are used to apply excitations at velocities on the order of 1 to 3 m s⁻¹ [41]. Structurally, the sample is stably seated on an anvil plate, and the excitation is generated by a pendulum or, in more advanced solutions, a push rod crank mechanism with an electric drive, as in Frączek's stand [42]. For multiple impacts, which better reflect processing conditions, the sample must be immobilized between a backing plate and a pressure plate to ensure repeatable orientation in successive cycles [41]. In such setups the hammer acts on the grain via the pressure plate, and both force and kinematics can be recorded with sensors integrated into the head (the operating scheme is shown in Fig. 4).



1 - rotating disc, 2 - hammer arm, 3 - crank lever mechanism, 4 - motor, 5 - drive belt, 6 - grain, 7 - rotary ratchet mechanism [42]

Fig. 4. - Test stand with one sided support

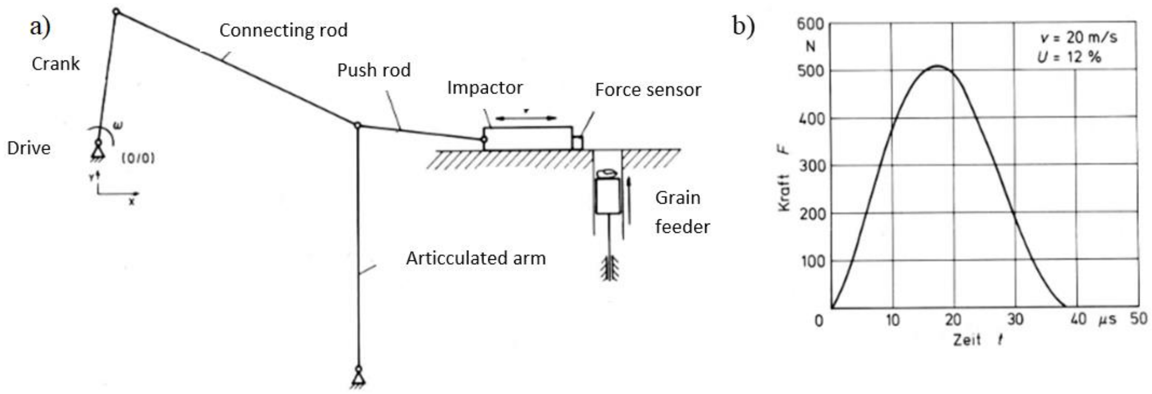
To reproduce higher energy phenomena characteristic of threshing or cleaning units, rotating hammer rigs are used. In Bilanski's design [33], employed among others by Niewczas [43], the exciter is a short rotating arm ending with a hammer, and the test grain is introduced into the path by a launcher synchronized with the rotation. In simpler variants, a lifting table serves this function. Such stands make it possible to achieve impact velocities from 3 to 40 m s⁻¹ [41] and to assess the threshold energy of damage; for wheat, complete structural breakup has been shown above about 25 m s⁻¹ [43]. Bilanski [33] observed increased resistance to impact damage with increasing moisture and a dependence on grain orientation relative to the loading direction.



1 - hammer, 2 - drive, 3 - grain launcher, 4 - grain [43]

Fig. 5. - Rotor test stand

An important area of research is the direct identification of the force history during impact. Kustermann [44] developed a test rig with a hammer driven electrically by a push rod crank assembly (Fig. 6), in which the striking head was equipped with a piezoelectric force sensor. The setup enabled impact velocities in the range of 0.1 to 20 m s^{-1} and simultaneous measurement of the motion of both the hammer and the grain, which made it possible to obtain full F(t) records for maize kernels.



(a) schematic of the test rig, (b) example force measurement at an impact velocity of 20 ms^{-1}

Fig. 6. - Kustermann's studies [44]

In Poland, Kęska's spring arm launcher (Fig. 7) [45] enabled studies on maize, pea, lupine, vetch, and wheat with a maximum speed of about 10 m s^{-1}. Force was recorded with a PCB piezoelectric sensor with a natural frequency of 70 kHz, and pre and post impact velocities were measured with photoelectric sensors [46]. This made it possible to determine regression relations for F_max and for contact time as functions of speed and moisture, as well as to record typical force histories.

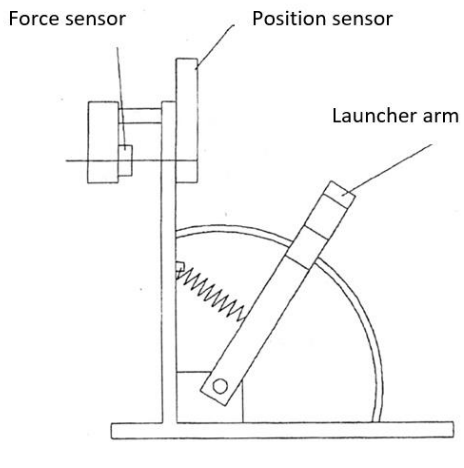


Fig. 7. - Schematic of the test stand [45]

Among the many research efforts, Kęska drew attention to issues related to the proper selection of measuring apparatus. In a 2021 article [46], he pointed out the risk of difficulties in interpreting signals recorded from a piezoelectric force sensor during dynamic measurements of hard, low moisture grains. Based on results showing the impact force impulse, the author noted the form of the trace, in which, in addition to the main reading indicating the maximum force reached, numerous subsequent decaying oscillations can be observed. A characteristic feature of the phenomenon is that the oscillations occur after the grain has rebounded and, despite the lack of contact between the grain and the sensor surface, they persist for a longer time. According to the author's findings, these oscillations resulted from the sensor's own vibrations excited by a sufficiently short force impulse, which he demonstrated by performing numerous simulations for various contact stiffness parameters for the grain sensor interface. As a result, there is a risk of a significant difference between the sensor's measurement signal and the true contact force history (Fig. 8). Thus, the author indicated that to obtain reliable measurements of the impact force history, one should use impact force sensors of special design with a high resonance frequency [46].

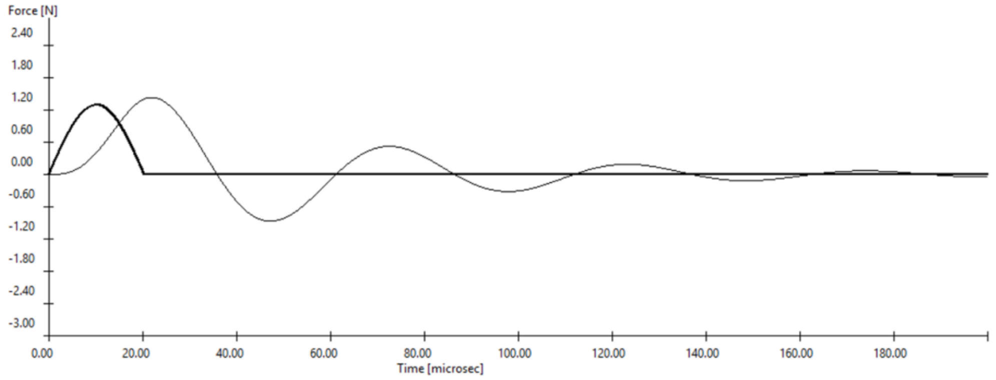
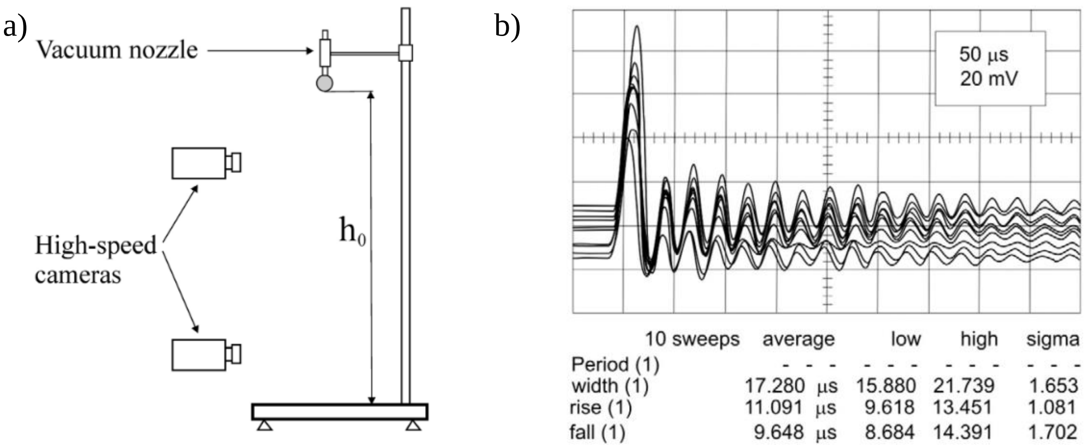


Fig. 8. - Impact force history (thick line) and sensor measurement signal (thin line) for a small dry grain. Contact stiffness k2=1e5 N/m, frez=20 kHz [46]

The most commonly used solution today for identifying the force history during collisions of cereal grains is the free fall method. This approach to studying dynamic phenomena has been presented for years by numerous researchers, largely because the measurement method offers a major advantage in the simplicity of the test stand's construction. The method gained popularity in studies of traditional engineering materials [47 - 50], and was later adapted for testing plant derived materials [51 - 56].

One of the most recent grain studies in Poland using a gravitational test stand was carried out on rapeseed at the Institute of Agrophysics in Lublin. The stand shown in the figure consisted of a simple support column on which a pneumatic gripper was mounted to release the seed sample onto the surface of a piezoelectric sensor. The setup allowed adjustment of the nozzle height from 1 to 100 mm, yielding a maximum impact velocity of 2 m s⁻¹. For velocity measurement, the system was equipped with high speed cameras. The experiments made it possible to analyze in detail the impact force history and to characterize its dependence on the velocity at the moment of contact, determining the coefficient of restitution. Example results from these tests are illustrated in Fig. 9.



a) test stand, b) example impact force history for a rapeseed grain [51]

Fig. 9. - Measurements using the free fall method

Recording only the force history over time does not provide all the information needed to characterize the physico mechanical processes occurring in the tested object during its impact with an obstacle. For this reason, years of research aimed at a more comprehensive understanding of phenomena in plant derived materials under dynamic excitation led to the development of more complex measuring apparatus capable of recording, simultaneously, both the applied excitation and the sample's response in the form of deformation. Work in this area was initiated, among others, by Jindal and Mohsenin, who defined an experimental technique for testing the dynamic strength of food materials. They designed a new test stand, drawing on experience with hammer type impact rigs in the form of pendulum impact testers. They justified this choice by, among other things, the greater precision in controlling the imposed excitation parameters compared with a freely falling grain or a falling mass, as well as by the higher precision in determining the point of contact and the ability to use very low impact energy levels [12].

The core of the pendulum impactor developed by the researchers was an arm with a counterweight mounted on a bearing supported axis (Fig. 10). For measuring the position of the pendulum arm, the setup was equipped with angular displacement sensors. The forcing force was identified indirectly by measuring impact deceleration with a piezoelectric accelerometer mounted at the height of the striking head. The adopted design solutions provided a maximum excitation speed of 1 m s^{-1}. Using the newly developed device, the researchers carried out some of the first comprehensive dynamic measurements of the properties of maize kernels by identifying their dynamic hardness. The results showed a slight effect of strain rate on the determined dynamic hardness, but a significant effect of grain moisture content [51].

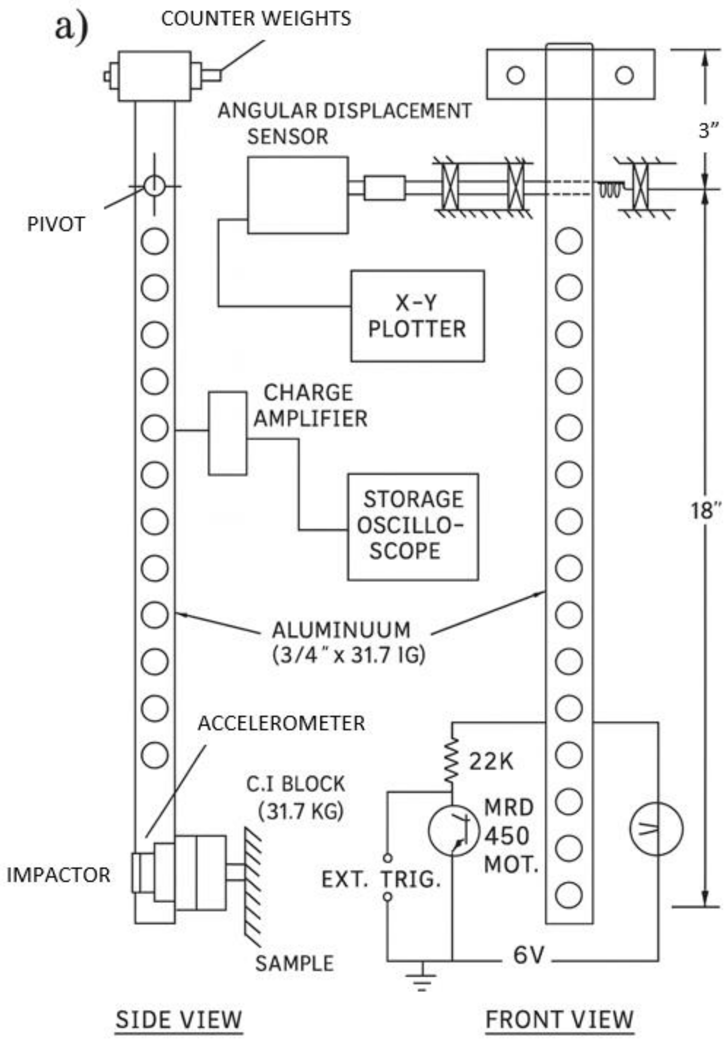
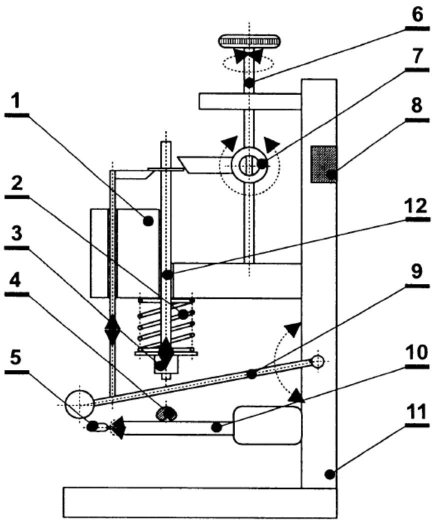


Fig. 10. - Jindal and Mohsenin test stand

Over the years, the above approach has been modified. As a result of work by a few researchers, alternative solutions have appeared to increase measurement precision. Some of the most recent studies on the influence of dynamic excitation on selected cereal grains were carried out at the University of Krakow. The researchers Frączek and Ślepek [41] focused on seeking an objective indicator for assessing the resistance of wheat to damage under repeated dynamic loads. In their studies, they analyzed the deformation of individual kernels at different moisture levels.

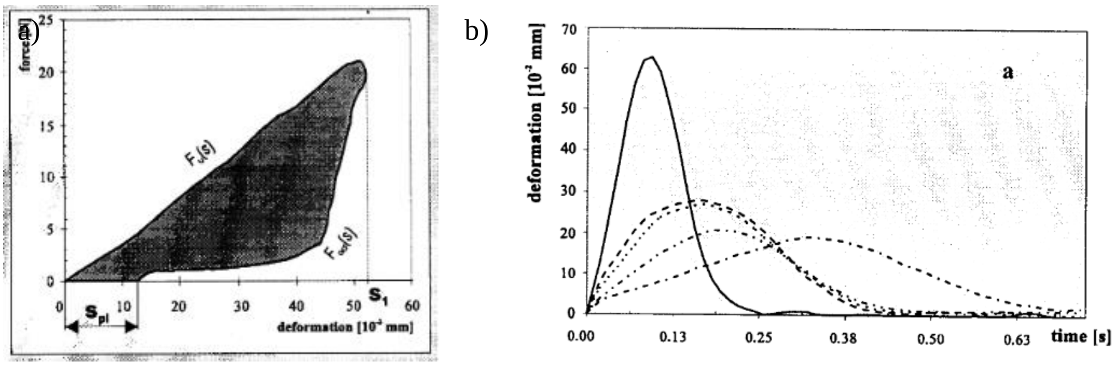
To this end, they developed a special impact apparatus (Fig. 11). In the device, the main working element was a movable hammer pin driven by a spring as the exciter. The spring was coupled to a ratchet mechanism that allowed it to be tensioned and then released abruptly, generating a dynamic motion of the hammer pin, which struck the tested grain sample via a measuring head. The measuring head, built as a strain gauge sensor assembly, enabled precise recording of the forcing forces. To measure deformations occurring in the tested sample, the stand incorporated an optical displacement sensor that tracked the motion of the hammer pin. The adopted design allowed excitations with a speed of 0.005 m s^{-1}.



1 - optical displacement sensor, 2 - tension spring, 3 - strain gauge force sensor, 4 - grain, 5 - adjustment screw, 6 - pawl screw, 7 - pawl, 8 - electronic amplifier, 9 - tensioning lever, 10 - measuring table, 11 - housing, 12 - hammer pin [41]

Fig. 11. - Schematic of the impact apparatus

The studies carried out on the above apparatus provided many important insights. Among other things, the effect of successive excitations on the sample was determined, showing that the largest changes in grain elasticity occur between the first and fifth impact. The occurrence of fatigue strengthening of the material and its dependence on moisture were identified [41]. Moreover, the researchers were able to determine force deformation relationships in the form of hysteresis loops with a highlighted area representing changes in kinetic energy (Fig. 12). However, the reported data concerned relatively small ranges of excitation velocities, and the plotted deformation excitation characteristics were presented only symbolically, as they were not the main focus of the study. As a result, the work did not provide the full information needed for rheological modeling of the grain's response to excitations accompanying its impact with a machine's working surface, leaving room for further research.



a) force deformation relationship, b) deformation of the tested sample

Fig. 12. - Example results of wheat grain studies by Frączek and Ślepek[41];

4. Empirical studies of contact force histories in the system comprising plant grain and the surface of a working unit

Following the literature review focused on identifying the mechanical properties of grain under impact conditions, a research stand based on a gravitational drop setup was adopted for further development. This solution combines structural simplicity with precise control of impact velocity by selecting the drop height and with simultaneous recording of the force history, the coefficient of restitution, and the contact time. The stand makes it possible to synchronize force measurement with video recording of grain velocity and orientation.

First, attention was focused on characterizing the test material itself, namely wheat grain, for which the principal physical parameters were measured. The resulting characteristics provided basic information needed to select measurement groups of grains that would ensure reliable and repeatable experimental results at later stages. Next, the effort focused on proper identification of the force history during the impact of a single grain with a flat surface, during which the impact impulses accompanying dynamic interactions were measured. The planned experiment provided information that serves as boundary conditions for the target research.

For the experiments, the test material was winter wheat of the cultivar Memory, which is currently one of the more commonly grown wheats in Poland. This relatively new cultivar, characterized by excellent yield potential, is classified in the highest quality groups A/B. The grain used in the study was purchased from a seed center as certified seed, meaning that it was obtained from special laboratory fields intended for the cultivation of seed material.

Before the preliminary tests, the test material was characterized in terms of physical features that affect the measurements, that is, its mass, moisture content, and main dimensions.

As a result of the measurements, the following material characteristics were determined [12]:
- average grain mass: 0.045 ± 0.008 g,
- base moisture: 7 %,
- grain length: 6.41 ± 0.5 mm,
- grain width: 3.04 ± 0.38 mm.

4.1 Test stand

As part of the undertaken work, a specialized research stand was constructed in the form of a system for dropping a grain onto a force sensor (Fig. 13). The stand comprised the following components: an aluminum frame serving as a support column; a transparent grain guide; a piezoelectric force sensor; a high speed camera; lighting; a measurement amplifier; and a computer for data acquisition and processing [12]. A piezoelectric force sensor was used to measure the force history. The control and measurement system employed an HBM GEN2tB amplifier, which enabled recording of measurement data at a frequency of 1,000,000 Hz. In addition, a Chronos 1.4 high speed camera was used to measure the velocity of the grain during impact.

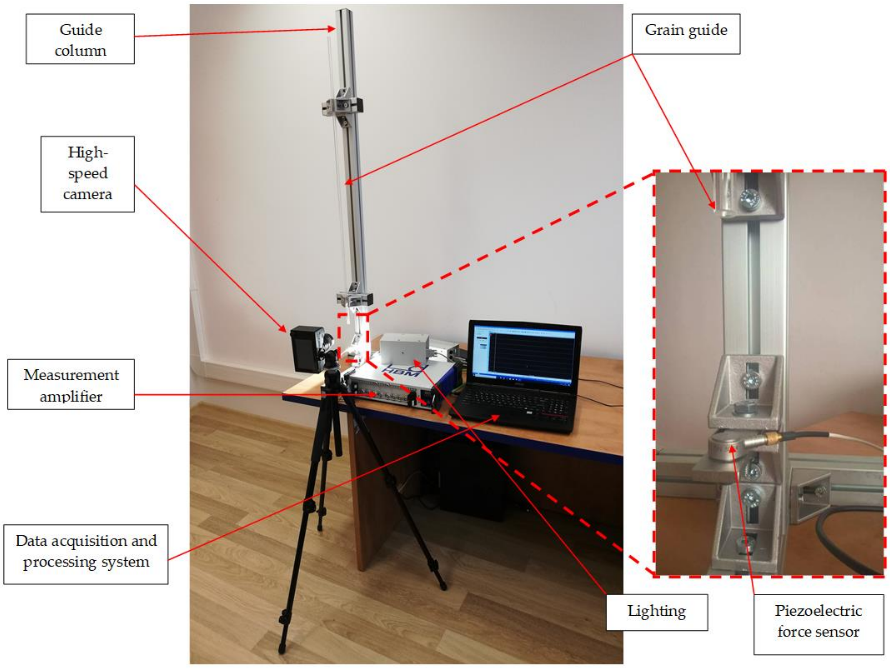


Fig. 13. - View of the impact test stand

The vision system enabled image recording at a resolution of 640×240 pixels with a frame rate of FPS = 8,816 frames per second. The recorded field of view covered the distance between the outlet of the transparent guide and the measuring surface of the force sensor. To determine velocity, a method was used that tracks reference points on the surface of the moving grain, assuming for the calculation that these points move in the same direction at the same speed relative to the observer, that is, the camera. Because during free fall the object may rotate due to, among other things, air resistance, the notional geometric center of the grain was adopted as the point satisfying these assumptions. With a stable camera setup, it was assumed that the velocity calculated relative to the camera equals the velocity relative to the force sensor. This approach made it possible to determine the flight time of the grain, Δt, by counting the number of frames, FR, in the recorded sequence, from which the instantaneous velocity was computed.

The stand made it possible to carry out a series of repeatable tests in which a single grain was dropped via the transparent guide onto the surface of the piezoelectric sensor. The experiment was performed for four moisture levels of the test material: 7, 10, 13, and 16 percent. For each moisture level, measurements were taken on 100 randomly selected wheat grains. The impact velocity was adjusted in the range from 1.5 to 4.5 m s^{-1}. Lower velocity ranges were achieved by free drop from an appropriately selected height between 200 and 1,000 mm [12].

The velocity range was established with reference to the results of Segler (1951), who determined a limiting permissible air velocity for pneumatic transport of wheat grain equal to 27.5 m s^{-1}. Above this value, structural damage is observed that reduces biological value and germination capacity. According to measurements carried out at the Department of Working Machines of Poznan University of Technology for wheat [57, 58], air velocities of about 27.5 m s^{-1} in the seed tube of a pneumatic seeder correspond to grain velocities of about 4.5 m s^{-1}, which justifies the adopted range of impact velocities [12].

4.2 Results

Using the developed stand, a series of measurements was carried out to identify contact forces during impacts of wheat grain with a flat metal surface. The recordings made it possible to reconstruct single impact characteristics at various impact velocities; example force-versus-time traces are shown in Fig. 14.

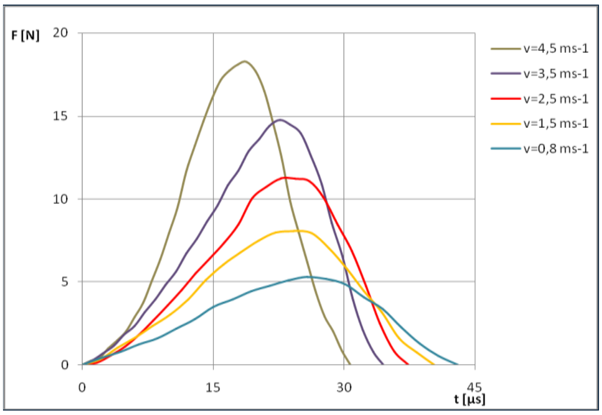


Fig. 14. - Comparison of example impact force histories for wheat grain at 10 percent moisture

The study was performed on a sample of 400 randomly selected grains, dropped at different velocities and for four moisture levels. To make a preliminary determination of interdependencies among the analyzed quantities, linear and nonlinear regression models were estimated. This approach yielded a complete dataset needed to compute the coefficient of restitution R, which characterizes the dissipation of energy during impact and is an important parameter describing the elasticity of the system; for plant materials it is equivalent in significance to viscoelastic damping parameters. To calculate R, the recorded force histories F(t) were approximated and written as finite polynomial functions, separately for the compression and restitution phases, and then used for integration to obtain the force impulse and the pre and post impact velocities, from which the coefficient of restitution R was computed.

Key measurement data were tabulated (Tables 1 to 4), including impact velocity v, restitution coefficient R, peak force Fmax, and contact time t_c. The results show that grain moisture is the leading factor governing the course of the impact. As moisture increases, the contact time with the flat surface increases systematically, while the peak interaction force decreases and the restitution coefficient declines. The response of the system therefore shifts from a shorter, more elastic impact toward one with a clearly larger share of plastic deformation and viscoelastic damping, which yields a longer compression phase and greater energy dissipation. As a consequence, higher moisture grains bounce less, and the impulse transmitted to the working element is lower but stretched in time.

This trend is consistent with the material structure: increasing water content reduces the effective stiffness of the endosperm and modifies the properties of the coat, which facilitates local plasticization and prolongs contact relaxation. Practically, strategies for limiting mechanical damage should consider moisture conditioning and the selection of surface material and roughness so as to reduce peak loads while maintaining control over contact time. The collected force time curves, contact times, and restitution values form a coherent dataset for calibrating contact models, for example DEM, and for selecting safe operating ranges in conveying and metering systems, especially where short duration impacts dominate over sliding friction.

Table 1. Summary of results for 7 percent moisture

Velocity	**Coefficient of restitution**	**Force**	**Contact time**
m*s^{-1}	**-**	**N**	**μs**
v	R	F	t
1,5	0,56±0,02	6,27±0,5	32,30±0,0002
2,5	0,51±0,02	10,34±0,5	29,37±0,0002
3,5	0,48±0,02	14,37±0,5	27,45±0,0002
4,5	0,47±0,02	18,38±0,5	26,03±0,0002

Table 2. Summary of results for 10 percent moisture

Velocity	Coefficient of restitution	Force	Contact time
m*s^{-1}	-	N	µs
v	R	F	t
1,5	0,53±0,02	5,65±0,5	42,05±0,0002
2,5	0,47±0,02	9,73±0,5	35,82±0,0002
3,5	0,43±0,02	13,91±0,5	31,50±0,0002
4,5	0,41±0,02	18,19±0,5	29,01±0,0002

Table 3. Summary of results for 13 percent moisture

Velocity	Coefficient of restitutioncji	Force	Contact time
m*s^{-1}	-	N	µs
v	R	F	t
1,5	0,48±0,02	5,13±0,5	49,96±0,0002
2,5	0,44±0,02	8,84±0,5	45,11±0,0002
3,5	0,41±0,02	12,55±0,5	42,06±0,0002
4,5	0,41±0,02	16,39±0,5	40,12±0,0002

Table 4. Summary of results for 6 percent moisture

Velocity	Coefficient of restitution	Force	Contact time
m*s^{-1}	-	N	µs
v	R	F	t
1,5	0,45±0,02	3,78±0,5	64,12±0,0002
2,5	0,40±0,02	6,76±0,5	56,33±0,0002
3,5	0,38±0,02	9,94±0,5	51,83±0,0002
4,5	0,37±0,02	13,20±0,5	48,64±0,0002

Conclusion

The aim of this work was to review research methods for identifying the mechanical properties of grain under impact conditions and to indicate methodological solutions that enable reliable data collection for design and modeling. Against the background of transport and dosing of granular materials, it was shown that variability in grain morphology and very short contact times hinder the use of classical measurement procedures. The state of the art in indirect and direct methods was synthesized, highlighting the limitations of visual and colorimetric assessments and the benefits of single grain tests in quasi static and dynamic configurations. A lack of uniform standards for seeds was noted, leading to limited comparability of some results.

In the methods section, the choice of a gravitational drop setup was justified as a solution that combines structural simplicity with control of impact velocity and the ability to record force and motion simultaneously. Attention was drawn to critical aspects of data acquisition, including the need to use impact force sensors with high natural frequency and to synchronize force recording with video capture to control grain orientation and eliminate measurement artifacts.

Empirical studies on wheat grain confirmed the usefulness of the adopted methodology. Force versus time histories were recorded; contact time and peak forces were determined; and the coefficient of restitution was calculated from pre and post impact velocities. A monotonic increase in peak force with impact velocity was demonstrated, as well as a decrease in the coefficient of restitution with increasing velocity and moisture. Contact time increased with moisture, which is consistent with a shift in the deformation mode toward a more viscoelastic response. The results were summarized in tables, yielding a coherent input dataset for the calibration and verification of contact models, including models used in DEM simulations.

The considerations and results presented have direct application. They enable the determination of load ranges for machine working elements, the reduction of biological damage to seeds, and the shortening of the design cycle through better grounded calibration of numerical models. At the same time, they point to areas requiring further work: expanding the range of impact velocities, analyzing oblique impacts and contact with surfaces of varied roughness and materials, systematically studying the effect of grain orientation, and standardizing measurement protocols and uncertainty reporting. Including these elements in subsequent stages will help build a clear bridge between experiment and modeling and consistently reduce the number of costly full scale tests while increasing the safety of seed transport and dosing processes.

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