CHARACTERISTICS AND ANALYSIS OF CORN EAR FAILURE

A Thesis

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by

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INTRODUCTION

CORN IN INDIA

Maize is one of the important cereal crops grown in India. It can make a highly significant contribution toward increasing India’s cereal grain production. Its potential has been fully recognized by agriculturists and substantiated by an annual increase in acreage. Maize improvement schemes have recently entered a new phase marked by the introduction of more sophisticated breeding techniques, cultivation practices, use of higher yielding varieties, and improvement and better utilization of the available seeding and harvesting equipment. It is felt that improved implements and machines with increased capacity would permit the farmer to perform the operations timely, thereby minimizing the loss of grain and maintaining the quality of produce.

In India, the maize crop is usually left in the field to dry to about 15 to 18 percent kernel moisture (wet basis) before it is harvested, using hand tools. Grain is then separated by primitive methods which have prevailed from remote antiquity. A few years back, farmers started to use a hand-operated stationary shelling device which consists of a cylindrical beater that strikes the ears against a concave grate of wooden slats, and beats out the grain. Another device has spikes on both the cylinder and the concave grate.

When larger quantities are handled, these methods become laborious.

---

and time consuming. Agriculturists recognize the need for more expeditious and efficient methods such as using improved, small, stationary, power-operated shelling mechanisms, preferably with integrated separating and cleaning units.

DEVELOPMENT OF AGRICULTURAL MACHINES

Agricultural machines have been developed and improved largely by trial and error along with extensive field testing because this is likely to be the quickest method. A multitude of variables is encountered in the development of an agricultural machine, many of which are not clearly understood or cannot be controlled. Until an understanding of the fundamental principles and the significant physico-mechanical properties of the crop are acquired, the development of the machine will depend on the keenness of the designer and the ability of the operator to develop a similar art in its use.

Mechanical corn harvesting and shelling are examples of such a developmental procedure. American farmers have used three types of shellers; the spring sheller, the cylinder sheller, and the grain combine. The spring sheller holds the corn ears by a plate under spring pressure against a rotating toothed disc which loosens and separates the kernels from the cobs. The cylinder sheller consists of a cylinder with spiral plates or paddles which turn inside a cage with longitudinal bars and shells the ear by crushing them against the retaining cage and one another. These machines do not necessarily combine the processes of shelling and cleaning. The cylinder sheller has largely replaced the spring sheller because of its greater capacity, its ability to shell snapped corn, and its simplicity.
Since early in the century, the combine has been used to harvest wheat and some other small grains. But in 1928, a modified combine was developed for corn harvesting which used a rasp-bar-cylinder mechanism. Very few alternatives to this mechanism have been developed. The operation of this shelling mechanism is based on a shattering principle. Most of the shelling is done by the impact of the cylinder bars on the crop which also causes most of the damage to the grain. It is interesting to observe that the same principles of threshing developed between 1820 and 1826 are still used in the present combines. Introducing the grain to be shelled between a moving cylinder and a stationary concave is, in principle, similar to a flail (a large paddle attached to a long handle) acting on unshelled grain lying on a threshing surface.

There is an indication that proper mechanical actions are the crux of corn shelling. Grain cracking during shelling is a potential hazard. It affects the subsequent separating and cleaning processes and is a major factor accounting for the overall quality of the harvest. Shelling must be accomplished at a maximum harvesting efficiency with the least damage to the grain.

This study was initiated to contribute toward understanding the fundamental principles of corn shelling in order to provide a basis for more scientific design procedures.
OBJECTIVES OF INVESTIGATION

GENERAL OBJECTIVE

The general objective of the investigation is to develop a fundamental understanding of the failure of corn ears under the influence of external forces.

SPECIFIC OBJECTIVES

1. Analyze the behaviour of a corn ear under the application of force.
2. Characterize the process of kernel removal.
3. Study the effects of impact loading on the corn ear.
4. Characterize the damage to the kernel and the mode of cob failure.
REVIEW OF LITERATURE

During the past three decades, enormous strides have been made to improve the mechanical harvesting and shelling of corn. The improvements have been brought about largely by making optimum adjustments in the machines. Several studies have recently been initiated to develop efficient harvesting mechanisms on the basis of scientific design procedures which are affected by the physicomechanical properties and the growth characteristics of the ear.

MACHINE PERFORMANCE

Studies have been made to determine the harvesting and processing efficiencies of mechanical devices. Burrough (1953) and Beldin (1959) reported that the efficiency of the corn picker-sheller was affected adversely by high cob moisture content and by immature corn. The percentage of kernels left on the cobs by the shelling unit was almost directly proportional to the moisture content of the cobs. Johnson (1960) found that 0.8 percent of the kernels was left on the cob unsheilded at the 27.5 percent kernel moisture (wet basis) and that the percentage would normally decrease as the corn in the field became drier. The percentage of kernels damaged by the shelling unit was almost directly proportional to the moisture content of the kernels. Johnson (1963) showed that in the 20 to 35 percent moisture range, crackage increased from 0.5 to 3.5 percent when determined by the percentage passing a 12/64-inch round hole screen.

Recently, the mechanical corn picker-sheller gave way to the use
of the combine. Hopkins (1953) indicated that the combine appears to have greater gathering efficiency when it takes the whole plant inside and processes it. It has commonly been claimed that the picker loses more of the crop than does the combine. Pickard (1953) and many others carried out tests for corn shelling with a combine cylinder and demonstrated the effects of cylinder design, concave screen opening, number of concave bars, angle of approach, concave clearance and cylinder speed on shelling efficiency and kernel damage.

The existing shellers have no provision for variation among ears in grain maturity. Their operation is based on the removal of all grain from the ear. Pickard (1955) reported that less corn was lost if the cobs were not split, since split pieces were small enough to pass through with the kernels still attached. Apart from the loss of grain, the cob loses its value as a product also. Information is not available regarding the mode of cob failure and the characteristics of the end product.

DAMAGE TO GRAIN

The extent of damage to the grain during shelling was reported by Arnold (1964), Johnson (1963), Dehaan (1954), Burrough (1953) and Hopkins (1953) in relation to the overall efficiency of the mechanisms. Hopkins (1953) pointed out that most of the damage occurs while removing the grain from the cob rather than while passing it through screen openings after shelling. Kolgenov (1956) reported that the grain attaining full ripeness is not as firmly attached to the ear as the less ripe, insufficiently developed grain, and that less mechanical action is needed to shell it. The severe shelling action required at high
kernel moisture contents results in cracking of kernels and reduction of test weight. Johnson (1960) reported that as much as 18.4 percent of shelled kernels may be visibly cracked at 30 percent moisture.

Kolganov (1958) examined the possibility of reducing the mechanical damage to small grain by shelling it in two stages. He passed the ears through a low-speed drum shelling out the grains which are most easily separated, leaving the rest to be shelled out in a second drum having a higher peripheral speed and closer concave setting. Hazas (1963) and Ptitsyn (1963) conducted some experiments on maize and wheat to assess the effects of different types of damage and drum settings on emergence, vitality and rate of growth, immediately after threshing and after a period of storage. They indicated that the damage caused by the severe action would retard the germination and vigor of plant growth. Feiffer (1963) and Dehaan (1956) studied the effect of the volume of material flowing through the machine, the effect of the ear density and the number of grains per ear, the size, conformation and tightness of awn on drum design, which would influence the damage to grain. It was found that the varietal characteristics affect the performance of combine harvesters to such an extent that design modifications rather than different settings only were required.

Dehaan (1954) suggested that the mechanical damage caused to grain in a combine can be kept to a minimum by adjusting the concave setting and the drum speed according to the time of the day and the prevailing weather conditions, particularly the relative humidity. These factors would have little influence on the crop in the case of stationary threshing of stored material, when damage is mainly the
result of bent beaters, non-uniform or too narrow setting of the con-
cave, excessive drum speed, etc. Little or no information is available
regarding the underlying causes of damage occurring during corn shell-
ing.

PHYSICOMECHANICAL PROPERTIES

Grain forming on a corn ear is not uniform in its physicomechan-
al and biological properties. This lack of uniformity may be
explained by differences in nutrition, formation and ripening. Grain
on the middle two-third-portion of an ear is more uniform in size and
moisture because it has better conditions for formation and ripening
than grain on the other portions. Zoerb and Hall (1960) determined
some mechanical and rheological properties of grain including the
modulus of resilience and modulus of toughness. Studies have also
been made to determine physical and physicomechanical properties of
the corn plant, the ear and the grain. Physical properties refer to
the size dimensions or the configuration, whereas the physicomechanical
properties refer to the characteristics which have direct bearing on
the mechanical behaviour. Johnson and Lamp (1966) have summarized
some physical characteristics of the corn ear and plant. The fre-
quency of occurrence of some characteristics in designated ranges have
been reported. The information on the ear is given in Table 1.

From amongst the many physicomechanical properties of corn plant,
ear and grain, Hall (1961) attempted to characterize the force required
to detach the kernel from the cob. Using a strain-gage transducer,
he determined the force required to remove a kernel for a range of
kernel moisture contents. The force was applied to individual kernels
Table 1. Physical Characteristics of the Corn Ear*

<table>
<thead>
<tr>
<th>Factor</th>
<th>Unit</th>
<th>Frequency, % in Each Designated Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ear length</td>
<td>in.</td>
<td>10.3 6.0 10.6 18.7 26.8 19.7 6.9 1.0 0.1</td>
</tr>
<tr>
<td>Ear butt-</td>
<td>in.</td>
<td>&lt; 1.5 1.5-1.75 1.75-2.0 2.0-2.25 2.25</td>
</tr>
<tr>
<td>diameter</td>
<td></td>
<td>0.6 5.6 51.2 38.6 4.9</td>
</tr>
<tr>
<td>Ear taper</td>
<td>in./in.</td>
<td>0.03 0.03-0.05 0.05-0.07 0.07-0.09 0.09-0.011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11.9 36.4 38.8 11.1 1.8</td>
</tr>
</tbody>
</table>

*From Johnson and Lamp (1966).

along their axes of symmetry so that the kernel-cob attachment was essentially in tension, tangentially at the crown (perpendicular to the axis of symmetry) to the longer crown dimension and tangentially at the crown and perpendicular to the longer crown dimension. These force applications would be called tensile, bending 1, and bending 2, respectively. Results are presented in Table 2.

Table 2. Force Required to Detach Kernels*

<table>
<thead>
<tr>
<th>Moisture Content (％)</th>
<th>Force, grams</th>
<th>Number of Kernels</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Tensile</td>
<td>Bending 1</td>
</tr>
<tr>
<td>10.0</td>
<td>2555</td>
<td>238</td>
</tr>
<tr>
<td>21.7</td>
<td>1917</td>
<td>328</td>
</tr>
<tr>
<td>21.5</td>
<td>1682</td>
<td>302</td>
</tr>
<tr>
<td>27.1</td>
<td>2374</td>
<td>380</td>
</tr>
<tr>
<td>27.2</td>
<td>2279</td>
<td>326</td>
</tr>
<tr>
<td>30.7</td>
<td>2292</td>
<td>332</td>
</tr>
</tbody>
</table>

*From Hall (1961).
GROWTH CHARACTERISTICS

The origin and nature of the corn ear have been subjects for speculation since corn was first studied and many hypotheses have been presented to account for it. Description of all the hypotheses is beyond the scope of the present study; however, their salient features are discussed.

Poehlman (1959), Kiesselbach (1949) and Leuz (1948) described a typical corn ear to consist of a more or less elongated cylinder of hardened tissue (the cob) to which are attached pairs of fertile spikelets, usually borne in longitudinal or somewhat spiral rows.

As the plant grows, shoots arise as branches from nodes about midway up the stalk. Each shoot is composed of a shank from which husks arise. The shank that bears the pistillate inflorescence (ear) is slender and terminates in the ear on which the pistillate flowers are borne. The ear is a spike with a thickened axis. At first, the ear is smooth but protuberances soon form in several longitudinal rows. The basal protuberances are formed first and development advances toward the tip of the ear. Each one becomes two-lobed, each lobe developing into a spikelet with two flowers, only one of which commonly persists.

The spikelets are borne in pairs and each spikelet normally produces one fertile ovule, giving one kernel of corn. A second ovule is present in the spikelet, but does not normally develop except in certain varieties. Accordingly, the kernels also will be in double rows and, thus, there will be an even number of rows of kernels on the ear. The sterile ovule of the spikelet, which does not develop into a kernel, remains as a "gap" or empty space between the bases of successive
kernels. At its lower surface, the kernel is attached to the rachis by the pedicel and held between the glumes and palea. All of these provide the strength of the attachment of the kernel to the rachis (cob).

Weatherwax (1935) showed that pairs of spikelets on the ear not only maintain a linear relationship but also a lateral one, and that the spikelets of one row are not opposite those of the adjacent row but alternate with them (Fig. 1). Cutler (1946) described the corn ear structure in which the cupules\(^1\) are arranged like bricks, each one covered with half a cupule from the right and half a cupule from the left, thus an ear is formed with cross-spiralling of the rows. In other words, rows can be traced in a spiral around the ear in two directions. A single grain will be part of a row that spirals to the left and also part of a row that spirals to the right.

According to Lenz (1948) it is difficult to interpret the morphology of an ordinary corn cob because its main features are obscured by the papery edges of the floral parts. The cob appears to be a mass of crowded, wrinkled chaff which has no apparent significance. In the mature cob, it is difficult to remove enough of this thin paper veil without destroying the underlying structures. Weatherwax (1935) prepared cobs for study by turning them in a lathe and removing all material down to the hard rachis, but could describe it only as "being made up of a cylindrical 'cob' around which the grains are arranged in many parallel rows".

\(^1\) Cupules are the depressions on the surface of cob which hold the lower portion of kernels.
Figure 1. Corn Ear Showing the Alternate Arrangement of Kernels.

Figure 2. Longitudinal Cross Section of an Ear
Laubengayer (1946) and others have carried out the internal anatomy of the cob. Most Corn Belt varieties have a hard tough cob. Cross sections of such types show a well defined scherenchyma zone forming a nearly solid tube between the epidermis and the pith. All corn cobs possess a central cylinder of pith. In general, the pith is rather uniform in different varieties of corn. Four distinct zones have been differentiated in the cross section (Fig. 2) of an average Corn Belt cob as follows:

(1) Immediately inside of the epidermis there is a more or less solid ring of thick-walled lignified cells.

(2) Inside the solid ring there is a cylinder of pith composed of large thin-walled parenchyma cells.

(3) Lying embedded in the above mentioned two zones are the vascular bundles, one inside the other.

(4) The fourth zone consists of branched parenchyma cells surrounding the vascular bundles as they leave the inner vascular tubes and extend out into the spikelets.

On the whole, the investigators who have written most about the ear, have been primarily concerned with its morphology only to describe the biological, histological and varietal differences.
CONCEPTS OF CORN EAR FAILURE THEORY

BASIC CONSIDERATIONS

Biological material is a complex body of structural components. The plant is an example. It is a composite structure of heterogeneous materials, where each component reacts in a specific manner to external forces. All components play important roles in the resistance of the plant to external forces.

The behaviour of homogeneous bodies and some heterogeneous bodies under load can be evaluated using certain formulae that yield tension, compression, shear and flexure. These calculations, however, are based on certain assumptions and constants which define the structure of the body, its modulus of elasticity, elastic limits, strength, etc. Assumptions are founded on physical properties, visual perception and preliminary tests; but constants are averages of a great number of individual observations, which may vary considerably. A few basic assumptions apply to a wide range of homogeneous bodies, but this is not true for heterogeneous bodies, especially for biological materials. Each material must be considered as a separate entity and the assumptions and constants should be based on the growth and structural characteristics.

Corn ears, like any biological material, have a complex structure. The formulation of a basic mathematical analysis of the process of kernel removal as well as the causes and effects of kernel damage and cob breakage requires information on the ear structure. Information contained in a previous section deals with the growth of cob and
kernels. Some important structural characteristics may be summarized as follows:

**Kernels.**

1. Kernels are arranged in longitudinal rows along the axis of the cob.
2. Generally, there is an even number of rows - between 10 to 18.
3. Kernels of one row are not opposite to those of the adjacent row, but alternate with them.
4. Kernels appear to have a trapezoidal shape in a transverse cross section of the ear.
5. Lower portions of the grains are held on the cob surface by the pedicel between glumes and pales.

**The Cob.**

1. The cob is a long and slightly tapered cylinder.
2. Transverse cross section of the cob shows
   - a cylinder of pith which is quite soft,
   - a scherenchyma zone,
   - the highly branched vascular system,
   - branched parenchyma cells which surround the vascular strands.

**PRELIMINARY TESTS**

The review of literature did not reveal sufficient information on the pattern of load distribution on the cob and kernels as one unit, under the influence of external forces. It seemed important to observe the behaviour of the different components of the ear, namely, the cob
and the kernels, and form the assumptions upon which the mathematical model may be based. In such a situation, it is desirable to perform some laboratory tests which may give the necessary information. An experimental attempt was made to explain force transfer between the cob and the kernels. Tests conducted are as follows:

A few fully matured corn ears of a yellow dent variety were selected. Each one of them was carefully examined to ensure that all kernels were intact and not loose as a result of rough handling or the husking process.

Test 1.

Two symmetrically opposite sets of two adjacent rows each of corn ear were shelled by hand. During the process, as far as possible, care was taken not to disturb the adjoining rows. Since there is always an even number of rows on the periphery of a cob, an equal number of rows was left on each side.

Transverse loading was effected by compressing the exposed parts of the cob between the jaws of a vise using a properly shaped wedge such that no contact was made with any kernel (Fig. 3).

Force was applied until the cob visibly failed. The following observations were made:

(i) No kernel was detached from the ear.

(ii) The cob failure resulted in four quadrants for nearly half the ear length, starting from the thicker end.
Test 2.

Two opposite sets of four adjacent rows each, were hand shelled and compressed as described in Test 1. In this test also, no kernel was detached and the cob failed into quadrants. Figure 4 shows a specimen after failure.

Test 3.

The ear was compressed as in the above tests but the removed sets were of five rows each. Identical results were observed. Figure 5 shows a specimen after failure.

Test 4.

Ears were shelled as in Test 1, but the force was applied as shown in Figure 6.
Figure 4. Cob Failure When Compressed as in Test 2.

Figure 5. Cob Failure When Compressed as in Test 3.
The following observations were made:

(i) As the force was applied, kernels in rows $K_1$, $K_2$, $K_3$ and $K_4$ turned about their attachment toward the exposed portion of the cob.

(ii) In a few samples, the kernels in rows $K_1$, $K_2$, $K_3$ and $K_4$ were sufficiently displaced so that they were detached.

(iii) Once all or part of the rows of $K_1$, $K_2$, $K_3$ and $K_4$ were detached, kernels of the adjacent rows started turning toward the exposed portion of the cob, and some were detached.

(iv) In all cases cobs failed almost along their planes of symmetry into four quadrants. Failure started from the thicker end.

Figure 7. shows a specimen after failure.
Figure 7. Turning of Kernels Toward Exposed Portion of Cob When Compressed as in Figure 6.
Test 5.

Several ears were flush cut at both ends leaving the middle four- to five-inch uniform portion. A few layers of kernels were removed at both ends exposing about 1/4-inch of the cob. This trimmed specimen was axially compressed between the jaws of a vise (Fig. 8).

![Diagram](image)

**Figure 8. Axial Loading on a Specimen of an Ear**

The following observations were made.

(i) The longitudinal deformation of the cob between A and B was observed to be more than between C and D.

(ii) Firstly, the kernels on face B started to turn toward the exposed portion of the cob and, when the specimen was compressed more, the kernels were detached progressively in the longitudinal direction (Fig. 9). In some cases, the kernels on the face C turned but were not detached.

(iii) No kernels were detached from the middle of the specimen.

(iv) The specimen failed into two pieces due to buckling as shown in Figure 10.
Figure 9. Turning of Kernels at Thinner End Toward Exposed Portion of Cob When Compressed as in Figure 8.

Figure 10. Removal of Kernels and Failure of Cob under Axial Compression.
EAR FAILURE AND DEFORMATION ANALYSIS

Failure of a corn ear under external forces cannot be precisely analyzed; however, if certain reasonable assumptions are made, a preliminary analysis can be developed. Based on the growth and structural characteristics of the ear and the observations from the tests discussed in the previous section, the following assumptions are made:

1. The kernels will be treated as equal elastic wedges attached as cantilevers to the surface of the elastic cob.
2. The cob is considered a hollow elastic cylinder.
3. The pith inside the cob does not contribute to the strength of the cob.

The transverse cross section of this idealized model for an ear with sixteen rows of kernels under transverse loading is shown in Figure 11.

Figure 11. Cross Section of an Ear under Transverse Loading and a Free Body Diagram of the ith Kernel
The symbols used in the analysis are explained as follows:

\( P \) = external force.

\( i \) = kernel number.

\( F_i \) = normal force exerted by the \((i + 1)\) kernel on the \(i\)th kernel; also, the inverse of the force exerted by the latter on the former.

\( f_i \) = friction force exerted by the \((i + 1)\) kernel on the \(i\)th kernel; also, the inverse of the friction force exerted by the latter on the former.

\( T_i \) = radial force along the attachment.

\( t_i \) = tangential force at the attachment.

\( M_i \) = retaining moment at the attachment.

\( a \) = the distance between the normal force \( F_i \) and the attachment.

\( b \) = the distance between the friction force \( f_i \) and the attachment.

\( \alpha \) = half of the angle subtended by a kernel at the center of the cob.

Due to the symmetry of the system, the kernels of the first quadrant of the model will only be considered.

The equations of equilibrium are derived for a kernel not acted upon by the force \( P \).
In the radial direction:

\[(F_{i+1} + F_i) \sin \alpha + (f_{i+1} - f_i) \cos \alpha = T_i\]

In the tangential direction:

\[(F_{i+1} - F_i) \cos \alpha - (f_{i+1} + f_i) \sin \alpha = -t_i\]

for \(i = 1, 2 \text{ and } 3\)

Moment equation:

\[(F_{i+1} - F_i) a + (f_{i+1} + f_i) b = M_i\]

for \(i = 4\),

\[(F_5 + F_4) \sin \alpha + (f_5 - \frac{p}{2} - f_4) \cos \alpha = T_4\]

\[(F_5 - F_4) \cos \alpha - (f_5 - \frac{p}{2} + f_4) \sin \alpha = -t_4\]

and \((F_5 - F_4) a + (f_5 - \frac{p}{2} + f_4) b = M_4\) \(\square\)

In addition to these 12 equations, symmetry yields the following two equations:

\[f_1 = 0; \quad f_5 = 0\] \(\square\)

The number of unknowns appearing in these 14 equations is 22, which are as follows: 5 \(F\)'s, 5 \(f\)'s, 4 \(T\)'s, 4 \(t\)'s, and 4 \(M\)'s. Eight more equations are needed in order to be able to solve this system. These equations are obtained from the deflections of the kernels and the cob, which depend on the geometric compatibility of the system. The derivation of these equations is beyond the scope of this investigation.

Assuming that these equations were determined, the forces and moments at the kernel tips would be obtained. A kernel would be detached if the tensile stress across its attachment exceeds the strength of the attachment. The tensile stress \(S_i\) may be estimated using the formula
\[ S_1 = \frac{T_1}{A} + \frac{M_1}{Z} \]

where \( A \) = area of cross section of tip attachment.
\( Z \) = section modulus of tip attachment.

Equations (1), (2) and (3) are valid as long as no kernel is detached. If a kernel is detached, the adjacent kernels will no longer experience its normal or frictional forces. The equations characterizing this new model have to be correspondingly adjusted.

The kernels and the cob have been treated as elastic bodies maintaining their geometry under load, which is a limitation of this analysis. It seems likely that the deflection of the cob under the applied force may subject the kernels to large moments (by shifting the points of contact between adjacent kernels) which cannot be accounted for in this analysis.

DEFLECTION OF COB UNDER TRANSVERSE LOADING

The cob has been assumed to be a hollow elastic cylinder. Assuming further that this cylinder is subjected to two equal and opposite forces uniformly distributed along its length in the YY-plane, and that the cylinder consists of thin rings, the deflection can be found as follows:

![Figure 12. Thin Circular Ring under Compression.](image)
The symbols appearing in this analysis are explained in the following list:

\[ p = \text{external force per unit length.} \]
\[ Q = \text{arbitrary vertical load with zero magnitude.} \]
\[ R = \text{arbitrary horizontal load with zero magnitude.} \]
\[ m_A = \text{moment due to deflection, at A} \]
\[ m_B = \text{moment due to deflection, at B.} \]
\[ m = \text{moment at any section.} \]
\[ \delta = \text{linear deflection in the direction of the applied force.} \]
\[ r = \text{mean radius of the ring.} \]
\[ \beta = \text{angle describing the position of application of arbitrary load.} \]
\[ ds = \text{a small element of the ring.} \]
\[ \theta = \text{angle describing position of } ds. \]
\[ U = \text{strain energy.} \]
\[ E = \text{modulus of elasticity.} \]
\[ I = \text{second moment about } Z\text{-axis per unit length of the cylinder.} \]
\[ m-n = \text{plane of section.} \]

Due to symmetry, only one quadrant of the ring is considered. Compressive force on section \( m-n \) is equal to \( \frac{p}{2} + Q \). The magnitude of the bending moment \( m_A \) acting on this cross section is statically indeterminate but can be found by the Castigliano theorem as given in Timoshenko (1956).

\[ m \int_0^\beta m_A + \left( \frac{p}{2} + Q \right) r (1 - \cos \theta) \quad (4) \]
\[
\begin{align*}
\delta_Q &= \frac{dU}{dQ} = \frac{Pr^3}{2EI} \left[ \frac{\beta}{2} - \frac{2}{\pi} \sin \beta - \frac{\sin 2\beta}{4} + \frac{2 \beta \cos \beta}{\pi} \right] \\
\text{when } Q &= 0 \\
R &= 0 
\end{align*}
\]

and

\[
\begin{align*}
\delta_R &= \frac{dU}{dR} = \frac{Pr^3}{2EI} \left[ \frac{1}{2} - \frac{2}{\pi} \beta \sin \beta - \frac{2 \cos \beta}{\pi} + \frac{\sin^2 \beta}{2} \right] \\
\text{when } R &= 0 \\
Q &= 0 
\end{align*}
\]

For a given thin hollow cylinder under a constant load, the quantity \(pr^3/2EI\) is constant. Other terms on the right hand side of equations (7) and (8) are functions of \(\beta\) only. Therefore, the curve of deflection is defined. The curve so obtained is illustrated.

![Figure 13. Deflection Curve for Ring](image-url)
Figure 13 shows that the curvature of the segments CD and C'D' would decrease whereas that of the segments CC' and DD' would increase under the load p. Due to the reduction in the curvature of the segment CD, the kernels attached to it may experience additional moment. Also the increase in the curvature of the segment CC' may cause the kernels attached to it to lose contact between them. The kernel near D would possibly fail under the conditions of unilateral loading. This situation agrees with observations made in Test 4.

Referring to Figure 12 and applying conditions of the Castigliano theorem in equations (4), (5), and (6), the magnitude of moment \( m \) at any point can be evaluated as given in Timoshenko (1956).

\[
\begin{align*}
m &= \frac{pr}{2} \left( \frac{2}{\pi} - \cos \theta \right) \\
(9)
\end{align*}
\]

At \( A, \theta = 0 \), equation (9) gives the largest negative moment; while at \( B, \theta = \frac{\pi}{2} \), equation (9) gives the greatest positive moment. This indicates that the cob is likely to break in quadrants along the XX- and YY-planes. Such a mode of cob failure was consistently observed in all tests for transverse loading. Cob failure was seen first along the XX-plane.

**Physical Model for Longitudinal Loading**

A model is proposed to characterize cob failure when the external force is applied axially.

The growth pattern of kernels on a cob shows that there are empty spaces between the bases of successive kernels as shown in Figure 2. Kernels are arranged in a spiral-like manner on the surface of the cob. When a compressive force \( P \) is applied axially, axial contact
forces are developed between kernels. The rows of kernels provide a rigid column outside the cob where deflection is less than that of the cob; and consequently the tips of kernels tend to get closer. The upper and lower kernels will be subjected to vertical forces from one side only and, therefore, would start turning toward the exposed portion of the cob. Since the cob is slightly tapered, the smaller end AA' is subjected to a higher compressive stress and experiences higher deflection than the thicker end BB'. The kernels at AA', therefore, are subjected to higher bending and are detached first.
The cob fails due to buckling; failure starts from section AA'.

These characteristics are in agreement with the observations made in Test 5.
EXPERIMENTAL INVESTIGATION

A set of experiments was designed to examine the effect of the loading mode, kernel moisture content and level of impact on the shelling of corn ears.

A yellow dent variety of corn, Zea Mays L 51, was used throughout the investigation. One lot of corn ears was obtained in the second week of September, 1965 and a second lot was procured from the field during the second week of October, 1965. Ears were husked by corn picker.

VARIABLES

1. **Loading mode:** The effect of impact loading was studied for two loading modes: transverse and axial. Transverse loading was obtained by dropping a weight onto a wooden block placed over a horizontal ear (Fig. 15). The block was used to distribute the load over the ear. Axial loading was similarly obtained, but the ear was vertically supported (Fig. 16).

2. **Kernel moisture content:** Three ranges of moisture content (wet basis) were chosen for the study, which are as follows:
   - (1) High . . . . . . . 25 to 30% moisture content
   - (2) Medium . . . . . . 15 to 20% moisture content
   - (3) Low . . . . . . . about 10% moisture content

Field shelling is generally started in the moisture content range designated high. Tests were first conducted on the high moisture content group. Ears in the medium or low range of moisture contents were
Figure 15. Arrangement of Transverse Loading.

Figure 16. Arrangement of Axial Loading.
studied later, after they had been kept in an unheated open room for some time.

3. **Level of Impact**: The level of impact was characterized by the momentum of the falling weight. The weight was released from rest and the momentum was controlled by selecting different initial heights above the ear. The momentum is given by

\[ m \cdot v = m \sqrt{2gh} \]

where
- \( m \) = mass of the falling weight
- \( v \) = velocity just before impact
- \( g \) = acceleration due to gravity
- \( h \) = height of drop.

A constant weight (8.125 lbs.) was used throughout all tests. The following groups of drop heights were considered:

1. 18", 24", 27", 30", 33", 36"
2. 15", 18", 21", 24", 27", 30"
3. 9", 12", 15", 18", 21"

The classification of these three groups correspond to the kernel moisture content levels, described earlier. It was found that kernels having a moisture content in the high range were not effectively removed by drop heights less than 18 inches and that heights more than 36 inches would develop too much momentum and would break the ears before grain was shelled. On a similar basis, the drop height of group (2) and group (3) were chosen for moisture levels (2) and (3), respectively.

The amount of energy, \( E \), imparted to the ear at the instant of impact is associated with the drop height and is given by the
relationship

\[ E = mgh \]

where \( m \) = mass of the falling weight
\( g \) = acceleration due to gravity
\( h \) = height of the drop.

TEST APPARATUS

The test apparatus was designed to develop different magnitudes of momentum, as required in the experimental variable (3). As indicated, the mass was kept constant for all the tests, whereas the momentum was varied by changing the heights of the drop. A simple apparatus was constructed in which the test sample was placed on a platform and the weight was allowed to strike the sample, falling free from a measured height and guided between three fixed vertical rods. The rods were marked in inches to facilitate reading the heights.

Since it was necessary to collect the kernels removed from the ears after impact, the structure was enclosed at the bottom (Fig. 17).

TEST PROCEDURE

The apparatus was set on a firm table and the three rods guiding the weight were plumb. This condition ensured that the weight would drop without touching the rods.

On each day of testing, the required number of ears were selected from the whole lot. The ears were examined for uniformity and any ear with missing or loose kernels was discarded. All the selected ears were kept in a closed container so that they would retain their moisture uniformly for a longer length of time. This was particularly done
Figure 17. Test Apparatus

Figure 18. Shelling of an Ear by Impact under Transverse Loading Mode.
for the high-moisture group of ears, because they were likely to change moisture quickly.

An ear was removed from the container and placed on the rigid platform between the three vertical rods. Having chosen the high-moisture group of ears and the transverse type of loading as initial test conditions, the height of the drop was first 18 inches. This was the lowest limit for the high-moisture group. After placing the ear and the block over it, the height of drop was measured from the top of the block to the bottom edge of the weight and the block position was adjusted so that the falling weight would strike at the mid-point. The weight was released from rest. It would strike the ear and shell the kernels (Fig. 18). The shelled kernels, undamaged or damaged, were collected after the impact and placed in a numbered paper bag. The process was repeated on the same ear until no kernels shelled from the cob. The shelled kernels were collected after each impact in separate marked bags. Finally, the unshelled grains were removed by hand and collected in another bag. Also the cob and its pieces were collected and placed in marked bags. The bags were then weighed and the net weights of the contents of all bags were recorded.

In the axial loading mode, the ear was held by a fork in a vertical position but the tests were conducted identically with the transverse loading mode. If a portion of the ear was broken after any impact, the drop height was adjusted accordingly. This was done to ensure that at any stage the ear would receive the same momentum.

Contents of all the bags were oven-dried for 72 hours at about 100 - 105°C. Thereafter the net dry contents of the bags were immediately weighed. The moisture content of each sample was then calculated.
The complete procedure was repeated on six ears for each combination of loading mode and drop height in the respective ranges of kernel moisture contents.

CALCULATIONS

The total energy imparted to each ear was calculated on the basis of the number of impacts. Dry weights of all shelled kernels were also determined. Energy was expressed in foot-pounds per gram of shelled kernels and was designated $E_g$.

To calculate kernel damage, all the samples obtained from each ear were sieved over a 12/64-inch round hole screen and any other visibly cracked or damaged kernels were separated by hand. Damage was expressed in percentage of dry weight of damaged kernels to the total dry weight of kernels from the ear. The moisture contents were determined for kernels and cobs separately.

STATISTICAL ANALYSIS

A step-wise, multiple regression, statistical analysis conducted by Weaver$^1$ was used as a means of evaluating the effects of the test variables. Student's "t" distribution technique was used to test the significance of each variable. The linear and quadratic effects of the test variables on the factor being evaluated were checked. An empirical equation was then determined by multiple regression which permitted the calculation of the factor being evaluated.

$^1$Dr. C. R. Weaver, Statistician (Ohio Agricultural Research and Development Center, Wooster, Ohio).
RESULTS AND DISCUSSION

Energy requirements for shelling. The data were subjected to the statistical analysis. The results of this analysis are summarized in Table 3. It was found that the effect of the loading mode was not significant, but that the linear effect of both the kernel moisture content and the drop height were significant at the 1 percent level and their quadratic effect was significant at the 5 percent level. Tests for interactions found the variables non-significant. Based upon this analysis the equation relating energy per gram of kernel to loading mode, height of drop and moisture was derived:

\[ \text{Energy per gram of kernel} = -1.1102 + 0.4656 \, L + 0.0486 \, H + 0.1387 \, M \\
\quad -0.0012 \, H^2 - 0.0014 \, M^2 - 0.0244 \, (L \times H) \\
\quad -0.018 \, (L \times M) - 0.0006 \, (H \times M) \\
\quad +0.0011 \, (L \times H \times M) \]

where \( L \) = coded loading mode (transverse = 0; axial = 1)
\( H \) = height of drop, inches
\( M \) = kernel moisture content, percentage.

This equation was solved for the following values:

Loading mode = 0 and 1
Height of drop = 9", 18", 27" and 36"
Kernel moisture content = 10%, 20%, and 30%

A plot of this equation is shown in Figure 19.

The figure indicates that in general, an increase in height of drop decreases the energy requirements, \( E_g \), for shelling of kernels. A possible explanation for this may be that at low drop heights, the number of kernels receiving a critical stress level is relatively low.
Table 3. Statistical Analysis of the Effects of Test Variables on Energy per Gram of Kernel

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Error of Coefficient</th>
<th>'t'-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loading mode (L)</td>
<td>0.4656</td>
<td>0.3596</td>
<td>1.310 N.S.</td>
</tr>
<tr>
<td>Height of drop (H)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.0486</td>
<td>0.0181</td>
<td>2.681**</td>
</tr>
<tr>
<td>Quadratic</td>
<td>-0.0012</td>
<td>0.0006</td>
<td>2.000*</td>
</tr>
<tr>
<td>Moisture content (M)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.1387</td>
<td>0.0232</td>
<td>5.974**</td>
</tr>
<tr>
<td>Quadratic</td>
<td>-0.0014</td>
<td>0.00062</td>
<td>2.260*</td>
</tr>
<tr>
<td>L x H</td>
<td>-0.0244</td>
<td>0.0169</td>
<td>1.442 N.S.</td>
</tr>
<tr>
<td>L x M</td>
<td>-0.0180</td>
<td>0.0198</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>H x M</td>
<td>-0.0006</td>
<td>0.0009</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>L x H x M</td>
<td>0.0011</td>
<td>0.0008</td>
<td>1.375 N.S.</td>
</tr>
</tbody>
</table>

N.S. = Non-significant
* = Significant at the 5% level
** = Significant at the 1% level

Energy/gm. of kernel = \(-1.1102 + 0.4656(L) + 0.0486(H) + 0.1387(M)\)
\(-0.0012(H^2) - 0.0014(M^2) - 0.0244(LxH)\)
\(-0.018(LxM) - 0.0006(HxM) + 0.0011(LxHxM)\)

where

Energy = ft.-lbe.

L = coded loading mode (transverse = 0; axial = 1)
H = height of drop in inches
M = kernel moisture content in percentage
Figure 19. Effect of Drop Height, Moisture Content and Loading Rate on Energy Requirements
Under such a condition some energy would be dissipated in development of strain permanent set in the ear. As the drop height increases, a larger number of kernels are subjected to a failure stress level and are detached. The net result is a reduction in energy per gram of kernels removed. The curves of Figure 19 are idealized by the selection of the statistical model and the experimental limits on drop heights for each moisture content. As such, there is likely little physical significance to the resulting curve shapes. The logical shape of any one moisture content curve would be as shown in Figure 20.

![Figure 20. Expected Curve for $E_g$ vs. Drop Height](image)

The curve in Figure 20 shows that there is likely a range of drop heights which results in a minimum $E_g$ and would give the range of maximum efficiency. The dotted portion of the curve indicates that $E_g$ is expected to increase with an increase in drop height beyond the range of maximum efficiency.

Figure 19 also indicates an increase in energy with an increase in kernel moisture content. Ears with higher moisture content would absorb more energy before they fail, and would require higher forces to detach the kernels.

The statistical analysis has shown that there are no significant
differences in energy requirements, $E_g$, for the transverse and axial loading modes. It is difficult to understand such a behaviour on the basis of this study. Additional detailed studies are required.

**Damage to kernels.** The effects of the test variables on the percentage damage to kernels were evaluated. The results of the statistical analysis are presented in Table 4. The analysis indicated that quadratic effects of moisture and the interaction between loading mode and kernel moisture content were the only significant contributing factors examined in the percentage of cracked kernels. The following equation relating the percentage of cracked kernels to the contributing variables was obtained from the analysis:

$$\text{Percentage damage} = -1.6368 - 2.5463(L) + 0.0799(H) - 0.0034(H^2)$$
$$+ 0.1549(M) - 0.0059(M^2) + 0.0947(L \times H)$$
$$+ 0.2254(L \times M) + 0.0061(H \times M) - 0.0033(L \times H \times M)$$

A graph of the above equation is shown in Figure 21 for the following values of the variables:

- Type of loading = 0 and 1 (coded)
- Height of drop = 9", 18", 27", 36"
- Kernel moisture = 10%, 20%, 30%

The graph indicates that, in general, damage increased with the increase of kernel moisture content and impact level. The loading mode apparently influences crackage in that the interaction ($L \times M$) appears significant. The axial loading contributes to higher crackage. In axial loading, the process of kernel removal is progressive as described in the physical model. The cob fails piece by piece longitudinally and the surface of failure is irregular. At any stage, the
Table 4. Statistical Analysis of the Effects of Test Variables on the Percentage of Kernel Damage

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient</th>
<th>Error of Coefficient</th>
<th>'t' Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of loading (L)</td>
<td>-2.5463</td>
<td>1.7860</td>
<td>1.427 N.S.</td>
</tr>
<tr>
<td>Height of drop (H)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.0799</td>
<td>0.0909</td>
<td>&lt; 1 N.S.</td>
</tr>
<tr>
<td>Quadratic</td>
<td>-0.0034</td>
<td>0.0028</td>
<td>1.213 N.S.</td>
</tr>
<tr>
<td>Moisture content (M)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear</td>
<td>0.1549</td>
<td>0.1173</td>
<td>1.321 N.S.</td>
</tr>
<tr>
<td>Quadratic</td>
<td>-0.0059</td>
<td>0.0031</td>
<td>1.901*</td>
</tr>
<tr>
<td>L x H</td>
<td>0.0947</td>
<td>0.0848</td>
<td>1.114 N.S.</td>
</tr>
<tr>
<td>L x M</td>
<td>0.2254</td>
<td>0.0995</td>
<td>2.262*</td>
</tr>
<tr>
<td>H x M</td>
<td>0.0061</td>
<td>0.0048</td>
<td>1.271 N.S.</td>
</tr>
<tr>
<td>L x H x M</td>
<td>-0.0033</td>
<td>0.0040</td>
<td>&lt; 1 N.S.</td>
</tr>
</tbody>
</table>

N.S. = Non-significant
* = Significant at the 5% level
** = Significant at the 1% level

Percent kernel damage = -1.6368 - 2.5463(L) + 0.0799(H)

-0.0034(H^2) + 0.1549(M) - 0.0059(M^2)

+0.0947(LxH) + 0.2254(LxM)

+0.0061(HxM) - 0.0033(LxHxM)

where L = coded loading mode (transverse = 0; axial = 1)

H = height of drop in inches

M = kernel moisture content in percentage
impact would be received by the top kernels of a few rows only, which results in considerable damage in axial loading. When energy is imparted at higher rates (larger increments of drop heights), the crackage increases.
CONCLUSIONS

The observations from the preliminary tests, concepts in ear failure and results of the experimental investigation have been presented in the previous sections. Based on the study, the following conclusions are drawn:

1. The preliminary tests have given an indication that kernel removal comes about by different deflections in the kernel system and cob, caused by an external force.

2. It appears that the stresses which ultimately cause kernel removal come about because of the load transmission from kernel to kernel rather than being induced directly by cob deflection.

3. In transverse loading, the typical cob failure can be described by splitting in "quarters" of the cross section of the cob; whereas in axial loading, the cob generally breaks in small longitudinal pieces.

4. The ear failure and deformation analysis shows that the primary mode of failure for kernel removal is bending of the attachment (pedicel tissue) of the kernels to the cob. This is induced by a moment set up by the kernel side-contact forces.

5. The stresses resulting from a tensile loading as a consequence of the components of normal and frictional forces, at the kernel tip appear to be relatively low.
6. Ultimately, the stresses which cause failure and removal of kernels probably come about by impact loading in practical mechanisms, because under the dynamic loading higher deflections and stresses are induced in the system.

7. The results of the experiments show that the energy per gram of kernel removed reduces as the drop momentum increases. This comes about because for the range of input momenta studied, a higher proportion of kernels are subjected to critical failure stresses at the higher impact levels.

8. There is likely a minimum to the energy per gram-drop momentum relationship which comes about by maximizing kernel stresses before severe cob failure.

9. The energy per gram of kernel removed increases as moisture content increases, because the ears with higher moisture content absorb more energy before they fail.

10. The loading mode does not significantly influence the energy requirements for shelling of kernels.

11. The damage to the kernel increases as the kernel moisture content and loading mode changes. The kernel damage is higher using the axial loading mode and at higher moisture contents.

12. Since there is a direct relationship of stresses in the static and dynamic loadings, the further study of the static system should yield valuable results which could be correlated to the dynamic system.
13. The experimental evaluation of constants and physical properties of a corn ear will help in formulating more equations and make possible the solution of the stresses. The basic theoretical approach, then, can be extended.
SUMMARY

The objectives of this investigation were (1) to analyze the behavior of a corn ear under the application of force, (2) to characterize the process of kernel removal, (3) to study the effects of impact loading on the ear of corn, (4) to characterize the damage to the kernel and the mode of cob failure.

The growth characteristics of a corn ear were summarized so that some reasonable assumptions could be made. Several preliminary tests were conducted on the ears to observe the possible mode of kernel removal and typical failure patterns under the application of force. Based on the structural characteristics and observations from the tests, some assumptions were made. Equations allowing the calculation of stresses induced in a corn ear have been developed for the transverse loading. The solution of these equations depends upon the evaluation of certain physical properties and geometrical dimensions for both kernels and cob. Also the derived equations are limited to the concept of elastic bodies and to the point of kernel removal; but these equations do show the expected mode of failure and characteristics of kernel removal. It appears that the process of kernel removal is basically by bending induced by a moment about the kernel tip. Also it appears possible that shelling can be accomplished with less damage to the grain and the cob.

The effect of impact loading on corn ears was investigated experimentally. The effects were characterized by (1) energy requirements for kernel removal and (2) damage to kernels. The kernel moisture
content, impact level and loading mode were chosen as the test variables. It was found that the energy requirements for kernel removal are influenced by the kernel moisture content and the impact level but the loading mode does not have a significant effect on the energy requirements. The experimental results have also shown that the cracking of kernels is increased with an increase in kernel moisture content. Crackage resulting from the axial loading of ears is considerably higher than from the transverse loading. The damage to the grain can be kept to a minimum in the machine if corn ears could be loaded only in the transverse mode.

This study has provided some basic fundamental concepts needed in developing corn ear failure theory. Further work, both experimental and analytical, may establish a complete theory of failure and help formulate scientific design procedures for corn shelling mechanisms.
BIBLIOGRAPHY


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