A THEORY OF CORN SHELLING BASED ON A QUASI-STATIC ANALYSIS

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This is to certify that the

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ABSTRACT

A THEORY OF CORN SHELLING BASED ON
A QUASI-STATIC ANALYSIS

by Russell M. Halyk

An ear of corn represents an interesting geometrical structure. This structure, with its unique components, must be dealt with each time an ear of corn is shelled.

The objective of this study was to examine the geometry of an intact ear of corn in order to establish its relationship to the problem of shelling. The general case of shelling through the application of radial compressive loading on the ear was examined.

A theory of shelling that describes the process at quasi-static loading rates was arrived at by reducing the problem to the generalized plane stress case. This theory was developed on the basis of the following assumptions:

(1) that the shape of a corn kernel can be approximated as that of an ordinary truncated wedge,

(2) that the material constituting the kernel and cob can be considered rigid, and

(3) that the kernels are attached to the cobs by viscoelastic connectors having properties in

tension that are different from their properties in compression.

Laboratory experiments at quasi-static loading rates indicated that the theory does predict the form of the force displacement curve of the loaded kernel. In addition, it is convenient for predicting the point in an ear where shelling is likely to occur due to the application of radial compressive loading.

An attempt was made to examine the possibility of extending the theory into the dynamic range. Low velocity impact tests indicated that the energy required to induce shelling dynamically was in agreement with quasi-static test results. Significant advances in the knowledge of the material properties of a corn ear are required for a comprehensive extension of this theory into the dynamic range. These properties will have to be applicable to the high loading rates normally encountered in field shelling operations.

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A THEORY OF CORN SHELLING BASED ON
A QUASI-STATIC ANALYSIS

By

Russell M. Halyk

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1. INTRODUCTION

Corn ranks with wheat and rice as one of the world's leading grain crops. In a summary of agricultural production, Guidry (1964) reported that approximately 7 billion bushels of grain corn are produced in the world each year. Just over one-half of that total was produced in the United States. More recent figures by the Crop Reporting Board of the United States Department of Agriculture (1967), summarized the 1967 U.S.A. production as 4.7 billion bushels of grain corn.

Many sources of loss are associated with the production of corn. The losses due to mechanical harvesting have been estimated by the U.S.D.A. (1965) to reduce total production in the U.S.A. by 8 per cent.

Shelling of corn appears as a comparatively efficient process, with losses estimated between 1 and 2 per cent under ideal harvest conditions (Johnson and Lamp, 1966). During unfavorable harvest conditions these losses increase well beyond 5 per cent. If average annual losses due to shelling were only 1 per cent, this means that the benefits to be derived from over 70 million bushels of grain corn could never be realized each year because of inefficiencies in the shelling process.

In addition to a reduction in loss of product, improvements in harvest machine design are characterized by other factors. These include improved quality of the product, reduced equipment costs, lower power requirements and improved durability and safety.

Ordinarily, improvements in the design of harvesting machines are accompanied by advances in the economics of production. Economic advancement of the producer can be a worthy goal for any study such as this.

The impending world food problem, as noted by Borgstrom (1967), demands remedial action. A reduction of harvest losses through improvements in agricultural machine design can contribute significantly to a solution of this problem.

Improvements in harvest machine design depend upon a clear understanding of the process and the behavior of the product under the influence of the machine system. The task that remains is clear.

2. A STUDY OF THE CORN EAR

The intricate structure of a corn ear has captured the interest of many observers including artists, botanists, and anthropologists. Despite this wide interest, the form of a corn ear has been inaccurately described in many written accounts, sketches and carvings.

2.1 Physical Description of the Corn Ear and Kernel Arrangements

Finan (1950) has reviewed the descriptions of corn plants which have appeared in herbals published since the third voyage of Columbus. Many other descriptions of the corn ear appear in the modern literature. The descriptions by Weatherwax (1923, 1935) seemed most appropriate to this study and are as follows:

> Ears range in length from 1 inch in some of the South American pop varieties, to 20 inches in some of the more vigorous flints and dents. The absence of any consistent correlation between length and diameter makes possible a multitude of shapes. There is a natural tendency for the ear to taper gradually from the base to the tip, due to a progressive decrease in the size of the cob and the grains, to closer crowding or to the loss of two or more rows. (Weatherwax, 1923)

> In cylindrical sections the pairs of spikelets are arranged not only in linear rows but also in certain lateral relationships which never seem to have been considered. For instance, the members of one row are not opposite the members of adjacent rows but, alternate with them. Thus if we count upward from

> the base of the ear and mark the tenth pair of spikelets in each row, the marked members form an undulating row around the axis, no member being out of line more than half the distance between two consecutive members of the linear row, and this is as true of the thirtieth or fiftieth pairs in the rows as it is of the tenth. In ears in which the pairs of spikelets are in an odd number of rows, that is, in ears with 10, 14, 18, etc. rows of grains, exact evenly spaced alternation is of course, mathematically impossible, but the undulating row around the cob is maintained. (Weatherwax, 1935)

The apparent accuracy of the descriptions by Weatherwax can be readily verified by examining either an actual ear of corn or photographs (Figure 2.1) of corn ears.

2.2 Structural Composition of the Corn Cob

The cob consists of the composite structures that remain after the kernels have been removed from an ear. According to Sehgal and Brown (1965), the structure of the cob can be divided into the four arbitrary parts (Figure 2.2):

1) fine chaff--lemmas, paleas, and upper portions of first and second glumes.
2) coarse chaff--basal portions of first and second glumes, rachillae base and glume cushions.
3) woody ring or midcob--the rachis, nodes and internodes, inner and outer vascular system.
4) pith--the soft spongy parenchymous tissue in the center.

Figure 2.1.--Corn ears used in this study were of the single-cross hybrid variety 402-2X. The top ear contained 14 rows of kernels, the lower one 16 rows. (Photo 67-56)

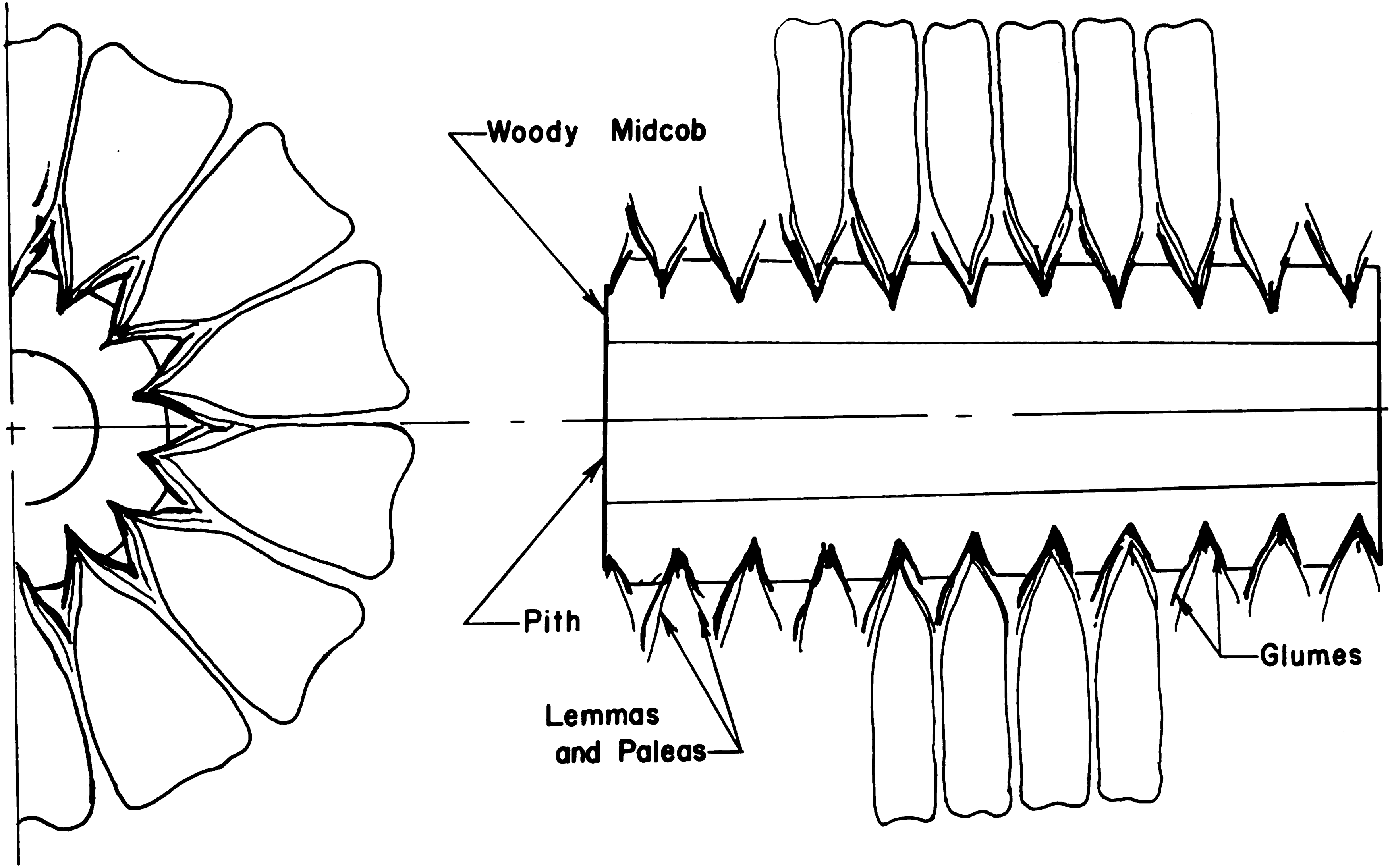

Figure 2.2.--Partial sections of a corn ear identifying the major structural components of the cob. Note that glumes to right of kernels (in longisection) were smaller than those on left. Tip of ear is at right.

2.3 Structure of the Mature Corn Kernel

Microscopic studies of mature corn kernels have been made by several researchers. The detailed studies by Kiesselbach (1949) and by Wolf *et al*. (1952) were most appropriate to this study because of their reference to the pedicel* (Figure 2.3).

The shelling process implies a consideration of the pedicel; that part which connects a kernel to its cob. Kiesselbach (1949) stated that "upon shelling the flower stalk or pedicel commonly remains attached to the base of the kernel." Wolf *et al*. (1952) noted that:

> . . . usually the kernel separates from the cob at the base of the tip cap. Sometimes, however, the tip cap remains attached to the cob and is removed by subsequent handling of the kernel. When present on the kernel, the tip cap is easily removed by a slight pull, exposing the dark hilar layer which lies above it and covers the base of the kernel.

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*See Glossary, Appendix VI

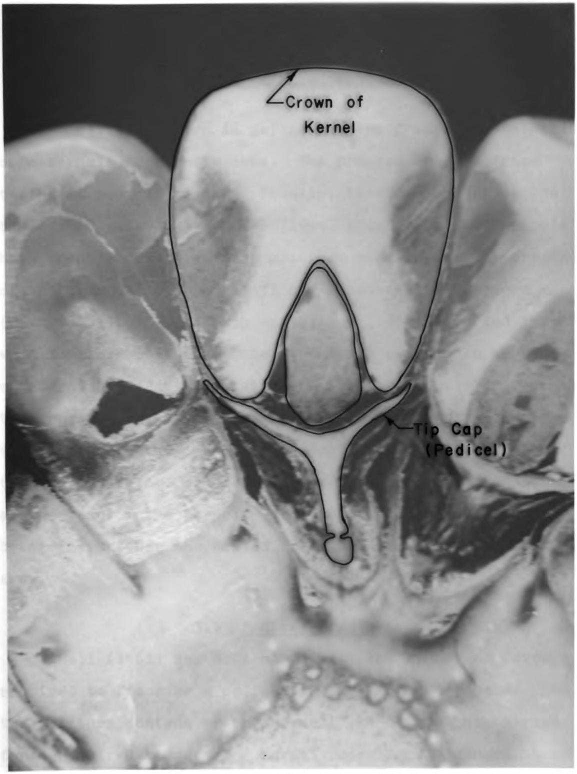
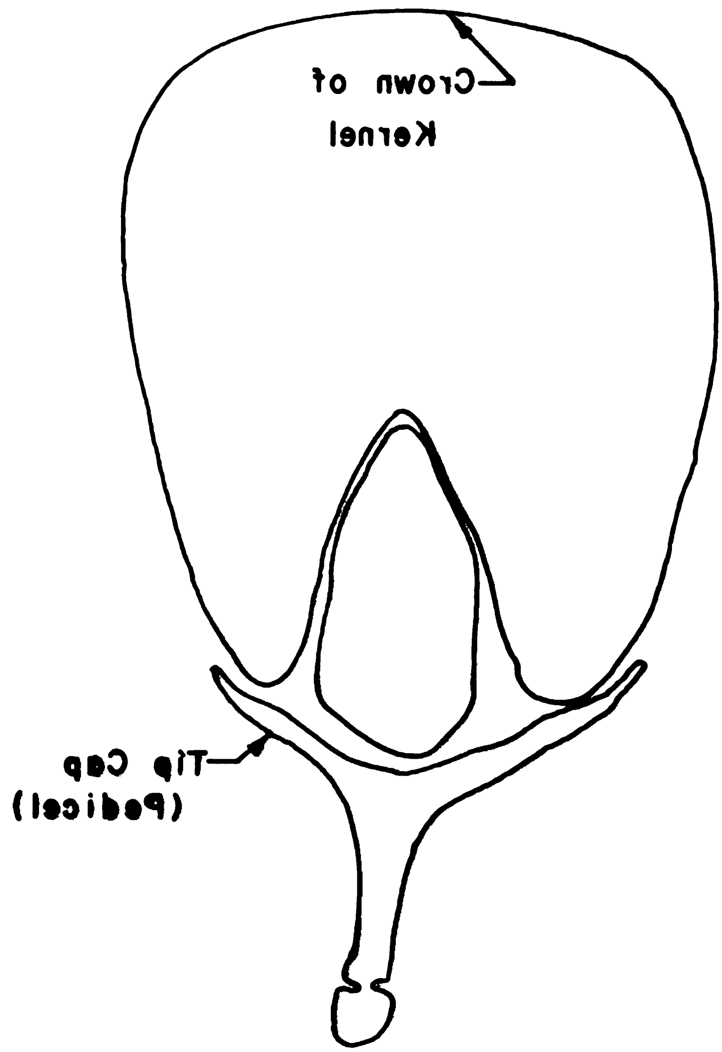


Figure 2.3.--Cross-section of [illegible] still attached to the cob. Actual width of [illegible] was 0.32 inch. Approximate magnification = 9[illegible] [illegible]70-2)


Crown of
Kernel
Tip Cap
(Pedicel)

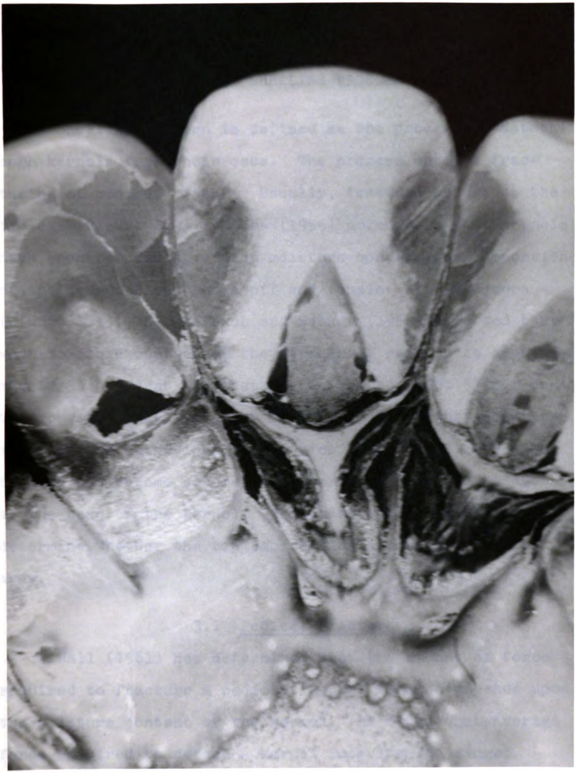


Figure 2.3.--Cross-section of a corn kernel still attached to the cob. Actual width of kernel at center was 0.32 inch. Approximate magnification = 9.2. (Photo No. 68370-2)

3. THE SHELLING PROCESS

Shelling of corn is defined as the process of detaching corn kernels from their cobs. The process entails fracturing of pedicel tissue. Usually, fracture occurs at the tip cap (Figure 2.3). Miles (1956) noted that when kernels have been removed at a high moisture content then a portion of the kernel tips breaks off and remains with the cobs (Figure 3.1). Kiesselbach and Walker (1952) reported that when moisture content of the kernels is reduced to approximately 34 per cent and that of the cob to about 53 per cent, then physiological maturity is attained. At that point the moisture and nutritional connection between the kernel and the cob has become severed by suberization of the tissue at the base of the kernel. The suberization process may determine whether the tip cap remains attached or breaks away.

3.1 Pedicel Fracture

Hall (1961) has determined that the amount of force required to fracture a pedicel in pure tension depends upon the moisture content of the kernel. He found that average force required to detach a kernel from its cob ranged between 1682 grams (3.71 pounds) and 2555 grams (5.63 pounds). Rate of load application was not reported.

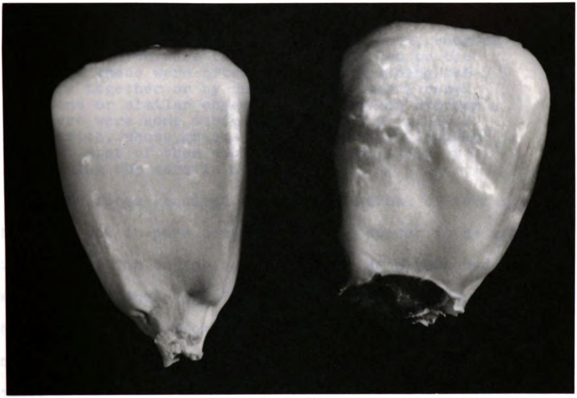


Figure 3.1.--Detached corn kernels. Kernel at right had tip cap missing due to shelling at a high moisture content. (Photo 68370-6)

Waelti and Buchele (1967) reported that the kernels of some varieties required greater tensile forces for detaching them from their cobs than did the kernels of other varieties. Rate of load application was variable. The effect of variety on ease of shelling was recognized as early as 1624 A.D., though not in a quantitative way. Weatherwax (1954) stated:

> Many of the flinty varieties had smooth, rounded grains which were very firmly attached to the cob. These were often shelled by rubbing the ears together or by rubbing them over a rough stone or similar object. At the other extreme there were some varieties especially in South America, whose grains were attached so loosely that most of them could be removed simply by shaking the ears in a basket.

The force required to detach a kernel of corn grain from its cob in pure tension does not appear to be affected by its position on the cob. From the data gathered by Waelti and Buchele (1967), differences in the force required to remove kernels from either the tip, middle, or basal regions of an ear within a given variety were not significant.

The rate at which load is applied to a kernel of corn in order to cause fracture of the pedicel is an important variable. Zoerb (1958) found that corn kernels exhibited a viscoelastic behavior. Mohsenin (1966) indicated that there is experimental evidence that most agricultural products are viscoelastic. The viscoelastic property implies a sensitivity to rate of loading.

3.2 Contemporary Shelling Mechanisms

One of the ultimate objectives in the design of an effective shelling device is the capability to remove all of the kernels from an ear of corn without incurring damage to either the kernels or the cob. Two types of field shelling mechanisms have been developed out of the many attempts at this objective.

The two shelling mechanisms found on American farms today are the cage-type sheller and the cylinder-type sheller. Johnson and Lamp (1966) have reported that both are capable of high shelling efficiencies when moisture content of the corn is low. However, when the moisture content of the corn exceeds 20 per cent, or when moisture of the cob exceeds 25 per cent, Goss *et al*. (1955) and Burrough and Harbage (1953) found that the performance of these mechanisms degenerates. The immediate result is that losses are sustained both in the quantity of grain obtained and in the quality of the resulting product.

The losses that are sustained through the operation of these shelling mechanisms appear to be unavoidable. Extensive studies by Byg *et al*. (1966) in Ohio reported that average seasonal losses from combined picking and shelling machines ranged from 1.6 to 4.0 bushels per acre more than the losses incurred by picking ear corn. Similar results were obtained by Goss *et al*. (1955) in California.

The consistency with which shelling losses are reported indicates that they may be inherent in the action of these mechanisms. In order that the real effectiveness of these mechanisms may be determined, it is necessary to know the kinds of forces that they impose on an ear of corn during the shelling process.

3.3 Shelling Forces

The kinds and magnitudes of forces that are imposed on an ear of corn when it is being shelled in either a cage-type or cylinder-type sheller have not yet been clearly defined. Johnson and Lamp (1966) have reviewed the recent literature pertinent to the shelling actions of these two mechanisms. They reported:

> The cage-type sheller consists of a cylinder with lugs, spiral flutes, or paddles which turn inside a cage. The cage has a perforated surface with holes large enough to let the kernels fall through but retains the cobs. The ears are fed, normally from two rows, into an opening at one end of the cage. The spiral flutes feed them through the cage and at the same time shell the ears by a rolling and crushing action against the cage surface and against each other.
>
> The cylinder type of sheller is used in combines. The corn is shelled by the impact of bars placed axially on the periphery of the cylinder as the corn is crushed against the concave. ... The intensity and number of blows received by an ear of corn as it passes between the cylinder and concave depends upon cylinder speed and resistance on the concave as determined by the number of concave bars and cylinder-concave clearance.

High speed photography can be an effective tool in qualitatively determining the kinds of forces that are imposed on an ear of corn while it is being shelled. A high speed moving picture camera was used by Hopkins and Pickard (1953) in order to analyze the action within a combine cylinder during shelling. Their studies were designed to determine the magnitudes of the forces that exist between the concave and the cylinder during the shelling process and were not primarily concerned with the analysis of forces on the individual ears of corn.

A lack of information on shelling of corn by impact still exists despite the fact that the process has a pre-Columbian history. Weatherwax (1954) noted that the primitive Indians of Western Mexico shelled corn by placing the ears in coarse bags, suspending the bags like hammocks and beating the bags with contents by means of suitable clubs. The shelled grain could fall out through the openings in the coarse mesh.

Rubbing forces have also been used by these primitive Indians in order to shell corn. The ears were usually rubbed against a rough surface formed of corncobs. This action may be similar to that of the "rolling and crushing" which takes place in a cage-type sheller.

The foregoing descriptions of the shelling process indicate that some combination of radial-compressive and tangential forces is engaged to produce the desired results.

A theory of shelling can therefore justifiably assume that these are the forces which cause shelling to occur. On the basis of this assumption, the entire range of possibilities which can exist must be satisfied by one of the following:

1) shelling by combined tangential and radial-compressive loading.
2) shelling due to pure radial compressive loading.
3) shelling due to pure tangential loading.

3.4 Alternate Solutions to the Shelling Problem

Shelling of corn can be achieved in various other ways besides the application of impact and crushing forces. Jain (1966) has shown that when the cob is subjected to axial loads, shelling occurs. Lamp (1959) performed experiments demonstrating that centrifugal forces can also be used effectively to achieve shelling.

3.5 The Need for a Shelling Theory

The lack of a clear understanding of the shelling process becomes apparent from the vague descriptions required to characterize shelling forces. Terms such as "crushing" and "impact" are insufficient for accurate description of a problem. Consequently, present insights into the shelling process have advanced very little beyond those of the Columbian Mexican Indians observing their colleagues at the manual task of shelling corn.

The recent interest of agricultural engineering researchers in such fundamental properties as the attachment strength of kernels to cobs can be considered as substantial evidence of a search for a better understanding of the shelling phenomenon. Successes in other fields, such as engineering mechanics, indicate that the formulation of reliable theories from such studies can do much towards the advancement of knowledge in a subject area. Analogously, the development of a theory of shelling can serve to advance understanding of the shelling process.

4. OBJECTIVES OF THIS STUDY

The general objective of this study was to attempt an integration of present knowledge about the shelling process with the information available on the properties of corn ears into a unified theory of shelling. Such a theory could prove useful in analyzing those harvest machines that induce shelling by subjecting corn ears to radial compressive and tangential loading.

Formulation of an exact theory of shelling that would describe the actual phenomenon implies a dynamic analysis of the problem. Furthermore, such a formulation requires consideration of the dynamic mechanical properties of the material. An extensive literature survey (Appendix I) failed to disclose information of this nature which would correspond to loading rates ordinarily associated with the shelling process.

The heterogeneous nature of the material, complicated structure of the ear and vague descriptions of the shelling process suggested the desirability of developing such a theory through a stepwise procedure. The formulation of a rigorous quasi-static theory could serve as the very important first step in this development.

Ordinarily, the application of static test results to a dynamic phenomenon is considered no better than an extrapolation of the facts. Eirich, in the introduction to the proceedings of the first symposium on high speed testing (Dietz and Eirich, 1960) stated:

> This is an age of high speed in everything except testing of materials. This is particularly true in fundamental as opposed to engineering testing and leads to the paradoxical situation that much of material behavior during actual performance has to be extrapolated from laboratory tests at much lower speeds.
>
> There are, of course, good reasons for this situation, the principal one being that the exact conditions during actual performance are often unknown or very difficult to duplicate. There is also another, more basic cause. All studies of mechanical behavior require the correlation of stresses with strains and/or strain rates obtained from deformation experiments of rather simple geometry and with clearly defined variables. The measurement at high speeds of stresses and strains demands electronic or optical equipment of high complexity. Furthermore, very few materials develop large strains at high speeds before they fail. Failure, in general, is always due to the growth of existing cracks and flaws in the test piece and is therefore statistical in nature and depends on the specimen size.

Eirich, of course, was referring to materials much more amenable to materials testing procedures than most agricultural products usually are. In view of the anticipated difficulties associated with a dynamic analysis of shelling, the objectives of this study were directed towards approaching the problem from a quasi-static viewpoint.

The specific objective of this study was to formulate a suitable quasi-static theory of shelling for a general case. The theory would be developed around laboratory studies designed to observe the behavior of corn ears under loads similar to those normally encountered in field shelling mechanisms. The suitability of the theory would be assessed by the accuracy with which it predicts the behavior of actual corn ears.

The possibility of extending the theory into the dynamic range was considered also. Such considerations were restricted to qualitative observations of the dynamic process. The observations could also serve as the preliminary investigations for a detailed study of the dynamic behavior of corn ears during shelling. Such a study has been planned as part of a continuing program at Michigan State University with the ultimate objective of developing a comprehensive dynamic theory of shelling.

5. DEVELOPMENT OF A THEORY OF SHELLING

The nature of the shelling problem suggests that simplifying assumptions be adopted in the development of a theory. Such assumptions are necessary because of the many interrelated factors entering the problem.

Various approaches can be taken in the development of a suitable theory. An effective approach can be one which begins by assuming the simplest conceivable model of the problem. Development proceeds from that point by phasing out the crude assumptions either by modification or replacement. In this way it is possible to arrive at a theory that is applicable to typical ears of corn within acceptable error limits. This procedure is consistent with Toulmin's (1961) outline on evaluating the merits of a theory and its potential as a contribution to the evaluation of scientific ideas.

5.1 Simplifying Assumptions Regarding the Geometry of a Corn Ear

The descriptions of a corn ear by Weatherwax (1923, 1935) point to the existence of a repetitive pattern in the arrangement of kernels in an ear. Although these patterns may be repetitive, there exist important variations of parameters within them. For instance, kernel dimensions become smaller near the tip of the ear.

Ancillary experiments were conducted to assess the applicability of this concept of description. Kernel thickness, that dimension of a kernel which is parallel to the longitudinal axis of a corn ear, was measured for all of the kernels from several rows of different corn ears. A statistical analysis of the results was made, using the simple model:

$$t_i = \frac{A}{i+I} \tag{5.1}$$

where,

t_i = thickness of any kernel i.

i = period under consideration in the sequence 1, 2, 3, . . . The sequence was started at the basal end of the ear.

A = a constant

I = an integer constant.

The equation (5.1) could be further simplified to:

$$t_i = \frac{A}{i}$$

if it is understood that any particular sequence does not necessarily begin with the period numbered one.

A high correlation between the theoretically predicted and actual dimensions for some ears indicated that such mathematical modeling can provide an adequate solution to the problem of simple mathematical description (Appendix V). The Weierstrass Approximation Theorem (Tolstov, 1965), of course, proves that a polynomial exists which will describe such a parameter as accurately as desired. However, that polynomial may be of such a complicated form that it no longer serves as a practical form of description. A similar approach was reported by Frey-Wyssling (1957) and by Esau (1966) for describing the helical arrangement of leaves and buds along a shoot. The Fibonacci sequence

$$\frac{1}{2} \quad \frac{1}{3} \quad \frac{2}{5} \quad \frac{3}{8} \quad \frac{5}{13} \quad \frac{8}{21} \quad \frac{13}{34} \ldots$$

was used.

Development of the surface of a corn ear can also serve as an effective tool in elucidating ear geometry. If the concept of a repetitive pattern is superimposed on the development technique, the resulting figures can lead to further insights into the arrangements of kernels in an ear of corn.

Consider an ear of corn having negligible taper. Development of the surface becomes equivalent to the development of a cylinder. If the length of the cylinder is divided into shorter sections which can be called periods, (Figure 5.1) then the concept of a sequence emerges. And if more than one parameter is considered, say kernel length, thickness, weight and cob diameter, then a sequence of functions is generated. These in turn can yield one or more series of functions, thus providing additional information about the ear. For example, the summation of kernel thickness results in ear length data, as in the equations:

$$\text{Length} = \sum_{i=1}^{n} t_i = \sum_{i=1}^{n} \frac{A}{i+I}$$

where,

t_i = thickness of any kernel i

i = period under consideration in the sequence 1, 2, 3, . . .

A = a constant

I = an integer constant

n = total number of periods in the ear.

A single period within a sequence can be defined in several ways. All definitions are acceptable provided that they retain the recurrence of geometrically similar forms. In the present case, cylindrical sections of two kernel thicknesses were considered as one period. This was done in order to minimize variation of any particular parameter within a period, and was based on the assumption that kernel dimensions vary only according to their position along the longitudinal axis of the corn ear.

Variation of any parameter within a particular period cannot be entirely eliminated so long as that parameter is affected by its position along the length of the ear. This holds even if periods of one kernel thickness are considered, because of their alternating arrangement. The consideration of periods consisting of more than two kernel thicknesses should therefore be avoided.

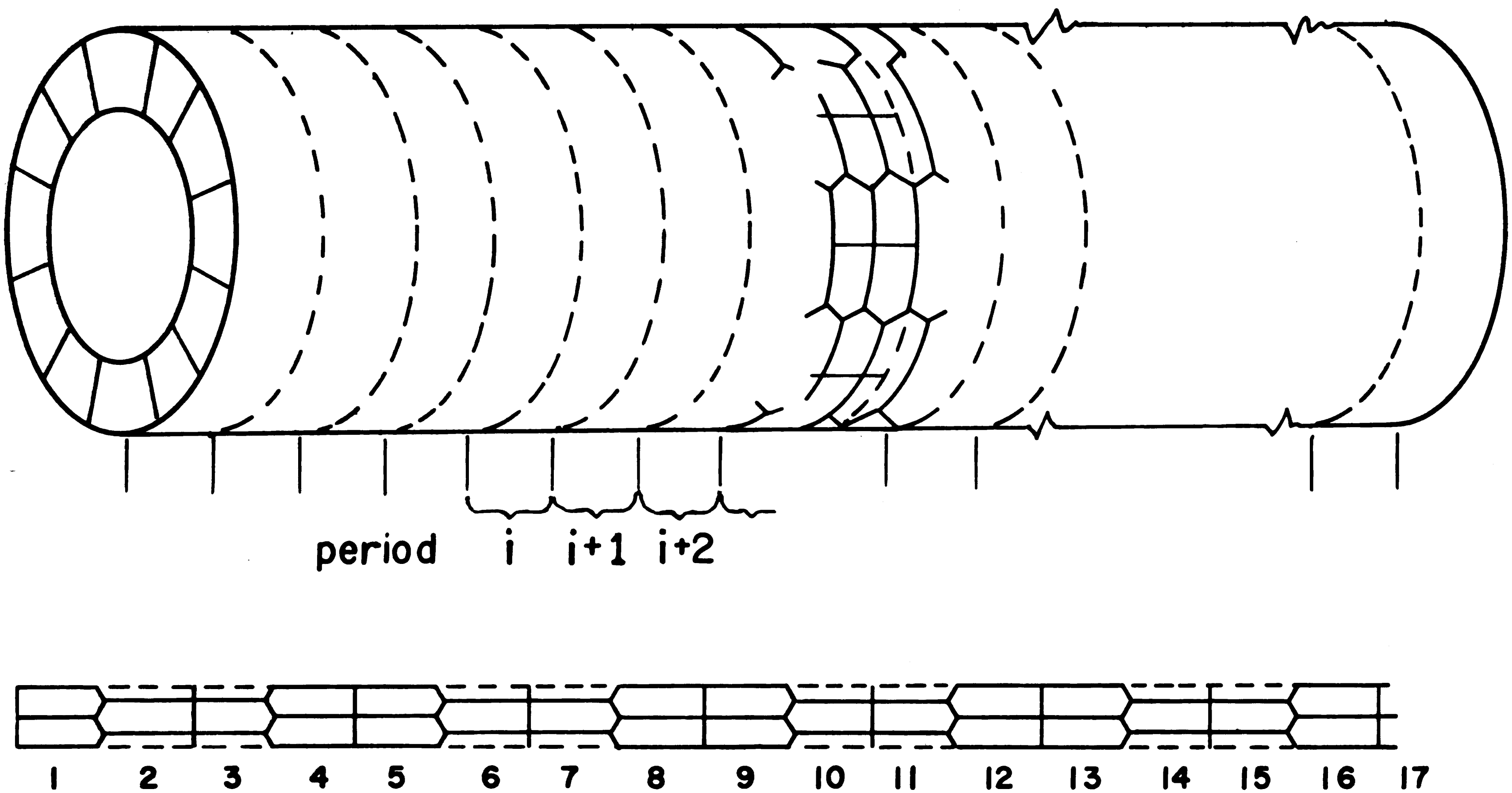


Figure 5.1.--Idealized concept of a corn ear divided into periods, top. Development of the surface contained by one period, bottom. In this example periods two kernel thicknesses wide were selected.

The development of a period consisting of two kernel thicknesses is shown in Figure 5.1. It can be seen, by attempting to reconstruct the cylindrical surface from this development, that row number 1 will only match properly with the kernels in even-row (8, 12, 16, . . . that is, exactly divisible by 4) ears. Misalignment occurs when odd-rows (10, 14, 18, 22, . . .) are considered. This misalignment sometimes results in the twisting of actual corn ears, as shown in Figure 2.1.

5.2a Kernel Geometry and Reduction of the Problem to the Plane Case

The preceding descriptions and development indicate that the shape of an individual kernel approaches that of a truncated pentagonal wedge. If the shape is assumed to be that of an ordinary truncated wedge instead, then visualization of traction forces on an ear of corn can be more easily realized. Indeed, plane case generalizations can then be introduced as desired in order to analyze the action of forces on this geometrical structure. These simplifications are outlined in the drawings of Figure 5.2.

5.2b Role of the Cob Structure in Shelling

The shape of a corn cob closely resembles a truncated cone. Jain (1966) considered the corn cob as a hollow elastic cylinder. The hollowness assumption appears valid for that

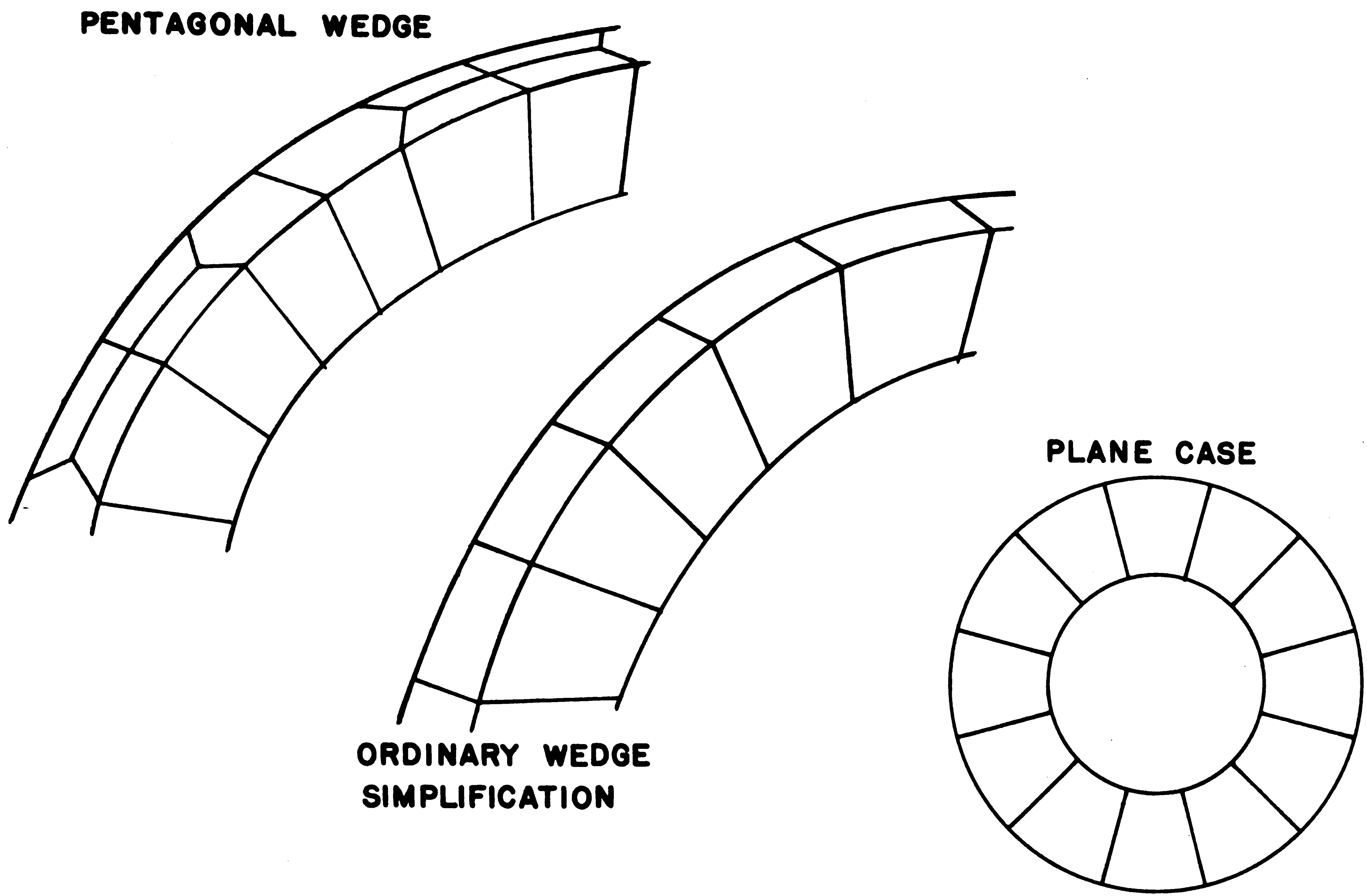


Figure 5.2.--Steps in reduction of the problem to the plane case.

part of a cob generally of interest in shelling studies. Hollowness can be readily acknowledged by noting the ease with which the pith can be removed from the center of the cob.

A corn kernel is attached to a cob by means of a pedicel. The entire attachment and the lower part of the kernel is contained within a cupule. The cupule is a depression on the surface of the cob that is formed by the two glumes.

The cupule supports the base of a kernel in such a way that the kernel is capable of resisting bending moments about its tip. A theory of shelling in which the process is induced by forces applied tangent to the ear must consider the support arrangement, as sketched in Figure 5.3. This drawing was made from a study of actual corn ears in which the fine chaff was removed physically.

A difference was noted in the size of the glume on the germ side of the kernel compared to the glume on the opposite side. The possibility of such a difference was suggested by the illustration of Nickerson (1954). This difference in glume size implies that bending resistance of a kernel towards the tip end of an ear may be different from that towards its base end.

Studies dealing with radially inward movements of kernels must also consider the support rendered by a cupule. The behavior of the cupule may affect kernel movements considerably.

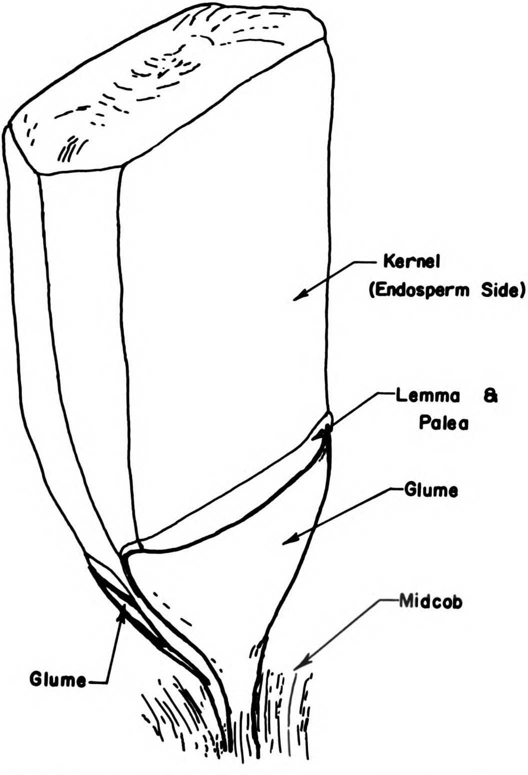


Figure 5.3.--Support structure of a corn kernel. The paper-like lemmas and paleas are surrounded by the tough outer glumes which are embedded in the woody ring of the cob.

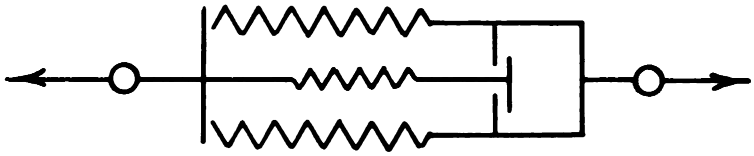
5.2c Modeling of the Kernel Attachment Structure

The structure constituting the attachment of a kernel to its cob can be thought of as a damped spring-mass system. Description of the behavior of such a system under applied load can be arrived at through the technique of structural and material modeling.

The structure of the cupule surrounding the pedicel suggests that a different reaction will be observed when forces are applied to the kernel so as to create tension in the pedicel as compared to the compressive reaction. Modeling of the attachment structure in tension, therefore, will have to differ from the compressive model. It is possible to integrate these models by a technique similar to the examples illustrated in Figure 5.4 for elastic elements. In each case two stress-strain equations are required to describe the behavior; one for the tensile case, the other for the compressive.

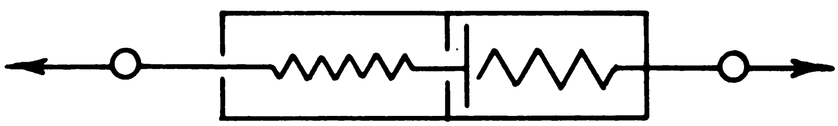
Viscoelastic modeling depends upon experimental results for appropriate formulation of the material behavior. Examination of the structure and location of the pedicel immediately discloses some of the difficulties that can be encountered in determining its mechanical properties. For example, force-displacement relationships that are measured by determining the position of the kernel relative to the cob include error due to kernel and cob deformation. Specialized techniques such as optical strain measurement can be utilized,

Elastic Tension or Compression Model



Integrated Model - Units Independent

Integrated Model — Units Interrelated



Integrated Model — Units Interrelated

Figure 5.4.--Combined tension-compression elastic models adapted to the case where tensile behavior differs from the compressive reaction. The technique can be extended to include viscous elements. Dependence refers to the compressive reaction.

but require removal of adjacent tissue which may entail disturbance of the results. An alternate approach is to assume that the material constituting the cob and kernels is hard, and therefore does not deform significantly.

A rigid material assumption for the kernel and cob requires justification. Ancillary experiments were conducted to determine the validity of such rigid material assumptions. From the available literature and experimental results (Appendix II) it was found that this assumption leads to errors less than 4 per cent in the 11 per cent wb to 19 per cent wb moisture content range.

5.2d Summary of the Structural and Material Assumptions

The foregoing discussion on simplifying assumptions has pointed to the desirability of assuming an ear of corn to consist of rigid kernels and a rigid cob. The connections between the kernels and the cob can be visualized as visco-elastic links whose properties can be determined experimentally.

Examination of an ear of corn indicates that spaces exist between kernels. These spaces seem to be larger in some ears than in others. Observation of this fact plus a recapitulation of elements from the previous discussion in this chapter leads to the plane case generalization of Figure 5.6. This model differs from the plane case of Figure 5.2 in that clearances between the kernels have been introduced.

Clearance between kernels has been assumed to be angular (Figure 5.9). A detailed analysis may prove that clearance is the same at both the inner and outer diameter of the ear. This detail is not fundamental to the study.

5.3a Assumptions Regarding Applied Shelling Forces

The geometry of a corn ear permits a wide class of surface forces to serve as potentially admissible shelling forces. Those surface forces which will be considered inadmissible as shelling forces in this study are of two kinds, namely:

1) Forces acting on the inside surface of the cob due to the hollow cob assumption of section 5.2b.
2) Forces acting on either one or both ends of the cob so as to produce axial shelling similar to that reported by Jain (1966).

Every surface force acting on an ear of corn can be completely specified by three force components, regardless of the coordinate system considered. The cylindrical coordinate system aids in visualizing all admissible shelling forces as a combination of only two components: one radial, the other a directed tangential component, as illustrated in Figure 5.5. A convention for measuring the angle Ψ should consider the positional relationship of the kernel acted upon and those it is forced to bear against. Bearing may be against either aligned or alternating kernels.

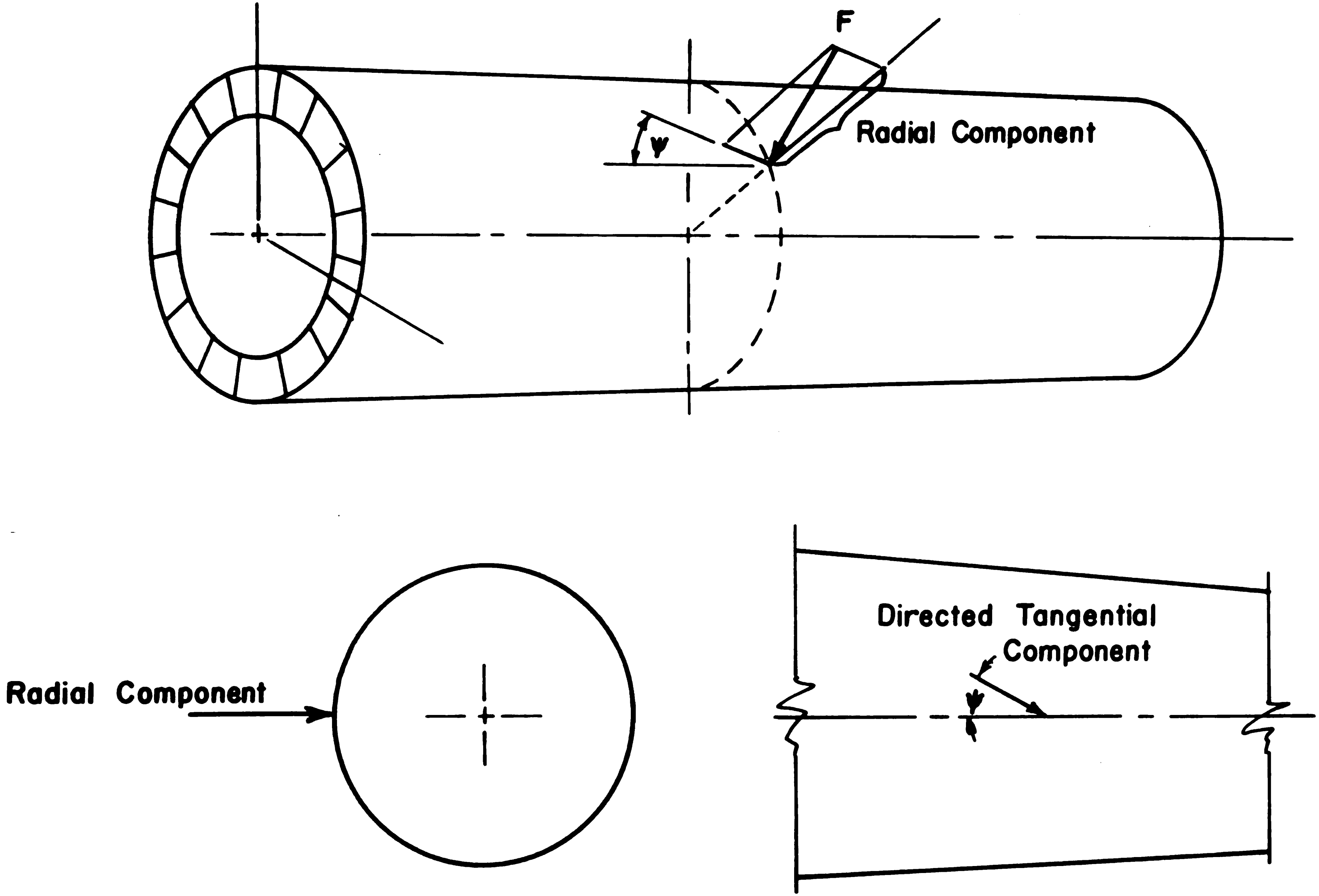


Figure 5.5.--Resolution of general shelling forces into two components. Measurement of the angle ψ must be defined according to a convention dictated by kernel arrangement.

Radial loadings of homogeneous and composite cylinders usually appear as problems in diametral compression. This kind of loading can also apply to a particular case in the shelling of corn.

A generalized case of shelling due to the application of radial compressive loading is illustrated in Figures 5.6 and 5.7. Here the load P is resisted by the two components yP and (1-y)P. The factor y simply describes the fraction of the total force that is transmitted to the kernel in the same plane and diametrically opposite the point of load application. For radial compression,

$$0 \leq y \leq 1$$

must hold. This conception of radial loading appears to hold for many of the conditions that can exist within contemporary shelling mechanisms. Some of these conditions are given in Figures 5.7a, b and c. It should be noted that in Figure 5.7b the loading function yP can be related to position along the length of the ear. In addition to external factors such as the shape of the concave surface in the shelling mechanism, the nature of these functions is also determined by such characteristics of the corn ear as kernel length variations, pedicel material properties, and cob shape and properties. Figure 5.8 illustrates the effects of kernel length variations on such a loading function, which may occur when an ear of corn is compressed against a plane surface.

A wide variety of these functions exist. Admissible functions must satisfy equilibrium conditions.

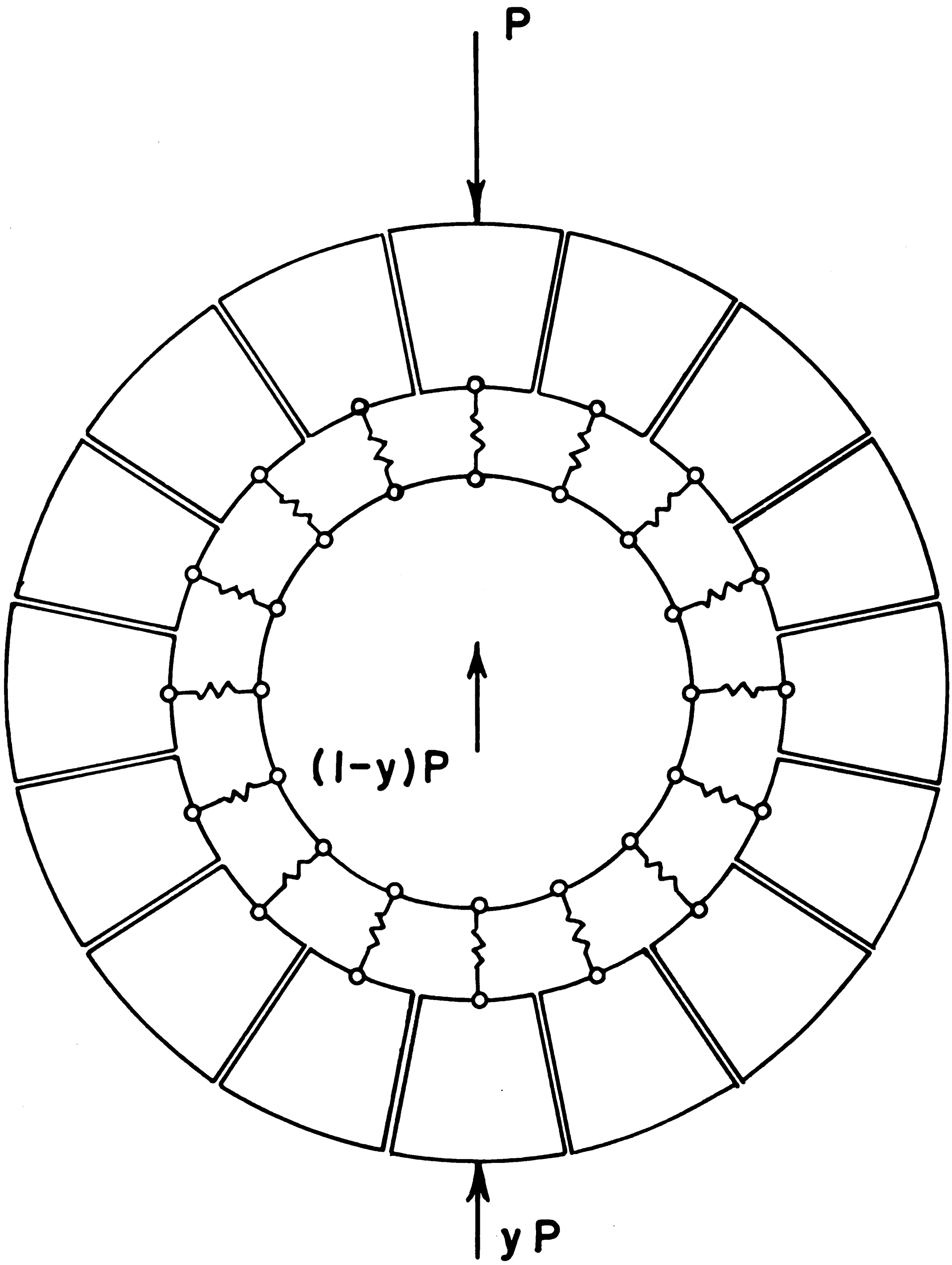


Figure 5.6.--Generalized radial loading of a corn ear in cross-section. The plane model has been modified to include clearances between the kernels in the unloaded condition.

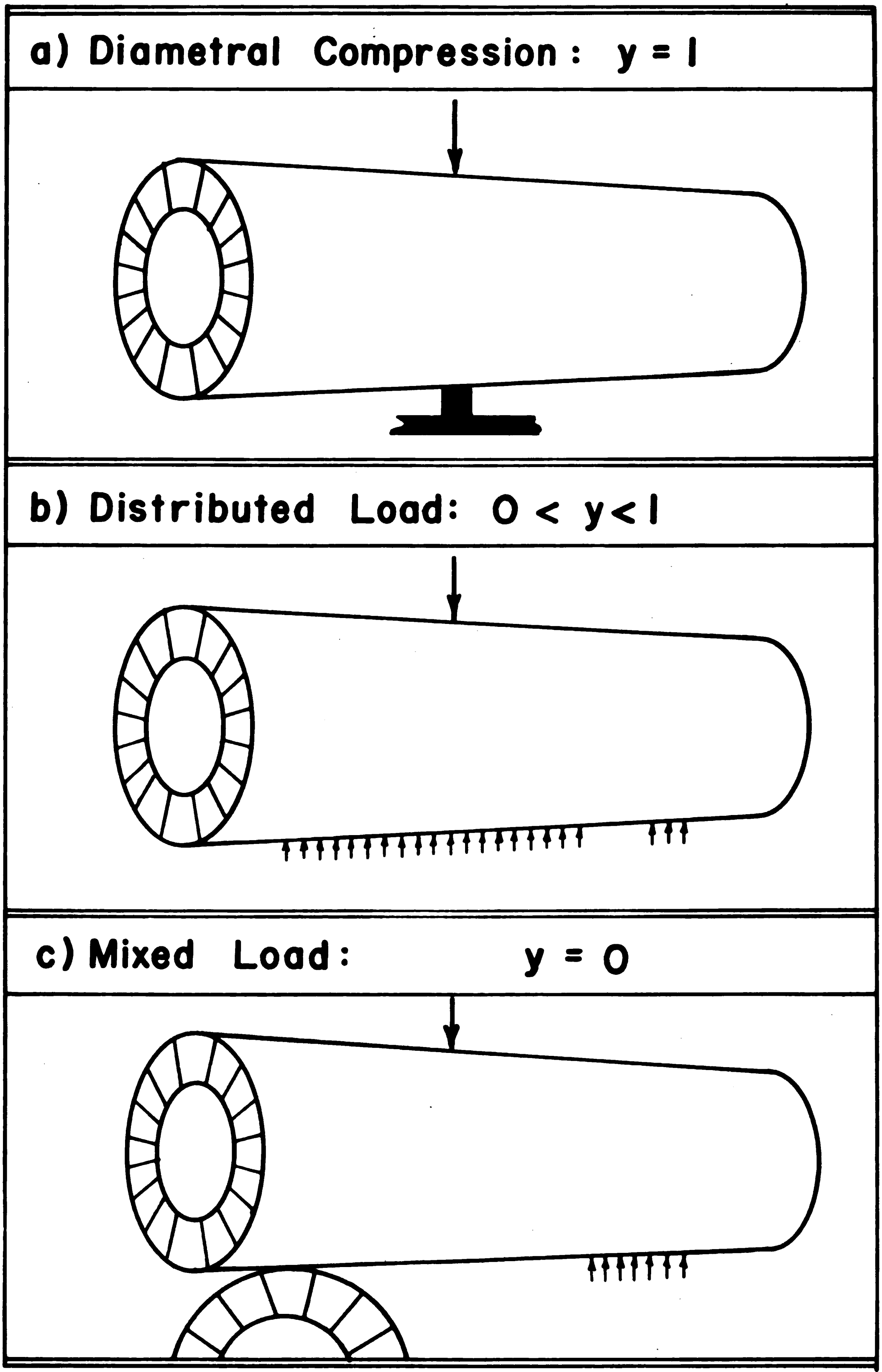


Figure 5.7.--The range of general radial compressive loading conditions considered in this study.

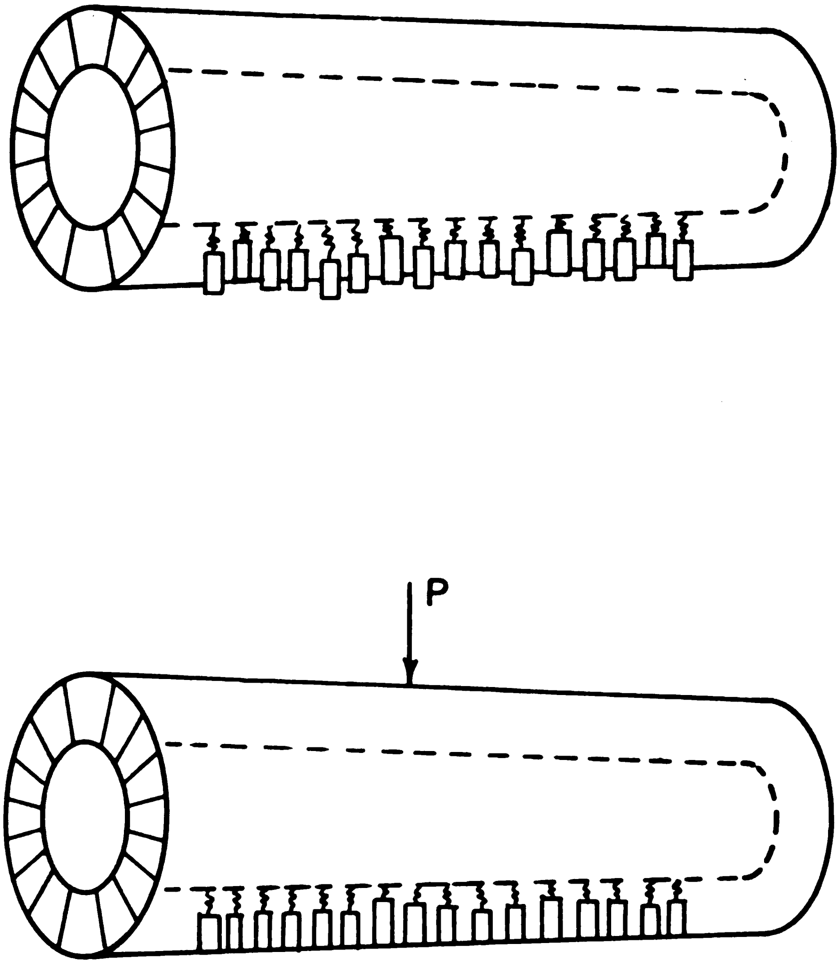


Figure 5.8.--Various factors affect the force distribution in radial compressive loading. Here, the effect of kernel length variations are illustrated for the case where a corn ear is compressed against a plane surface.

5.3b Radial Compressive Loading of Rigid Model: Mixed Loading Condition

Consider the mixed loading condition which occurs when $y = o$. Application of a load P on a given kernel causes a reaction in its pedicel structure that is, at first, dependent only upon the characteristics of that structure. Displacement of the kernel is illustrated in Figure 5.9. The response to load P remains independent of other factors up to the point where clearance between the kernel in question and the two adjacent kernels still exists or has just been taken up; that is when,

$$x \leq R_i \frac{\sin \gamma}{\sin \alpha}$$

where,

x = displacement of radially loaded kernel towards center of the ear.

R_i = inside radius of kernels.

γ = clearance angle between kernels prior to loading.

α = one half the angle included by a kernel.

Continued application of the load P causes a reaction by the adjacent kernels. This reaction depends upon the nature of the pedicel structures of the kernels. In any event, the adjacent kernels must move to accomodate the rigid kernel that is being forced down between them.

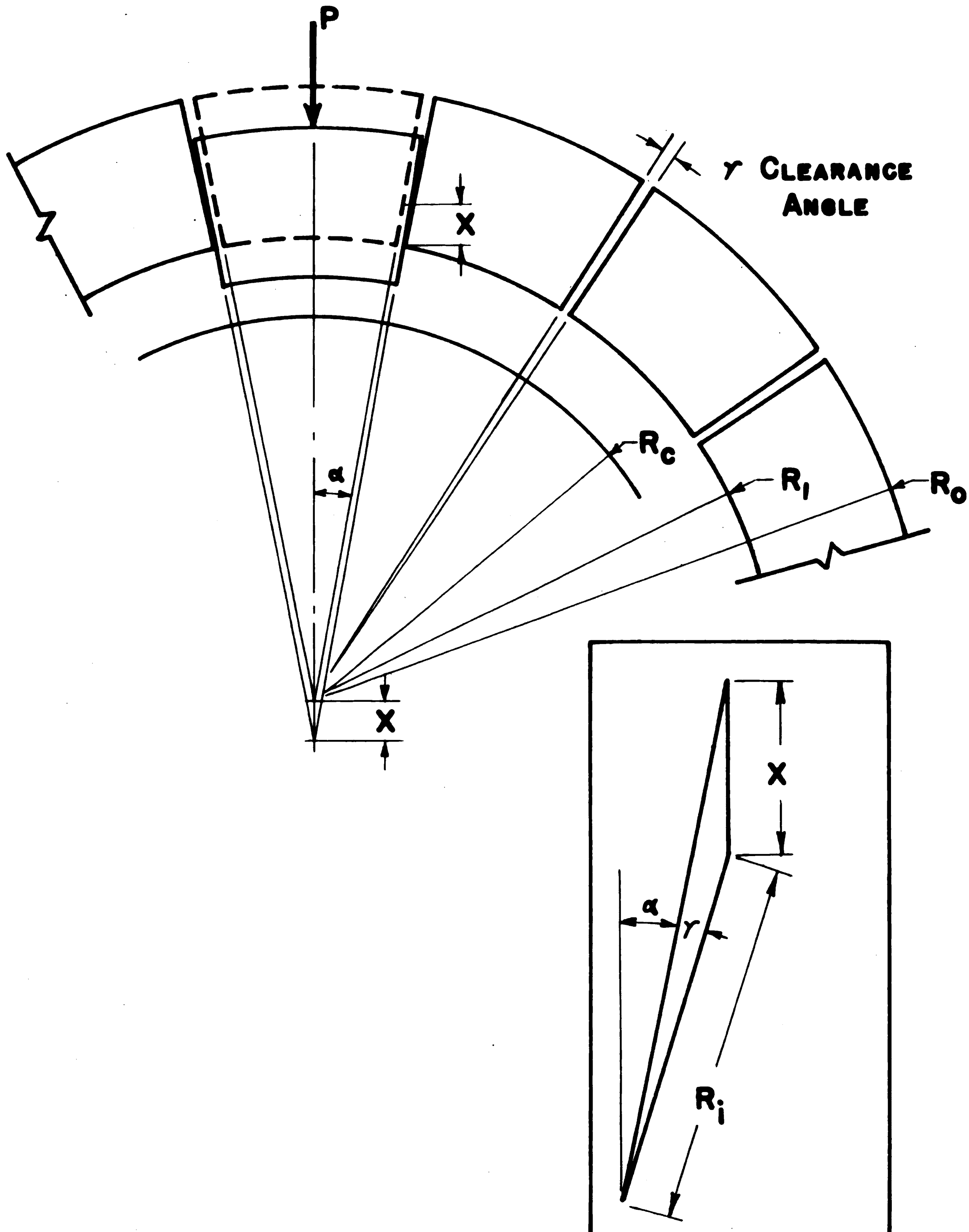


Figure 5.9.--Initial reaction of a corn ear to radial compressive loading. Note that initial contact between the loaded kernel and those adjacent to it occurs at the inner radius, R_i.

Movement of the adjacent kernels can be assumed normal to a radial line in the plane. In other words, movements are circumferential or can be described as rotary with the center of the ear acting as the axis of rotation. Such an assumption was derived from the observation that the individual cupules (Figure 5.10) extend deep into the structure of the cob. The assumption may not hold for all varieties and would be determined largely by the rachis-pith ratio, as discussed by Sehgal and Brown (1965).

Predominantly circumferential movement of the adjacent kernels is possible in the model of Figure 5.11 if the compressive elements offer much greater resistance to deformation per unit load than the tensile element does. More specifically,

$$k_{compressive} >> k_{tensile}$$

where k is the usual spring constant from the force-displacement equation:

$$F = kx.$$

Movement of the adjacent kernels in a circumferential direction will also occur if tangential force components are large compared to the radial forces. This is true when the coefficient of friction between kernels is small.

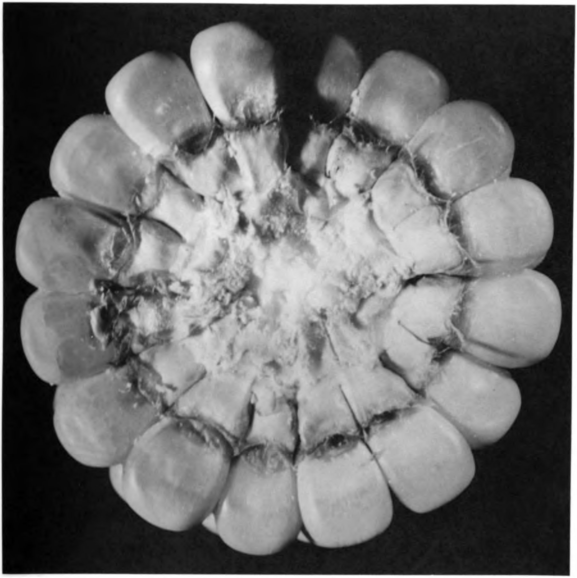


Figure 5.10.--Cross-section of a corn ear. Cupules, which support the bases of the kernels, extend deep into the structure of the cob. (Photo 68370-5)

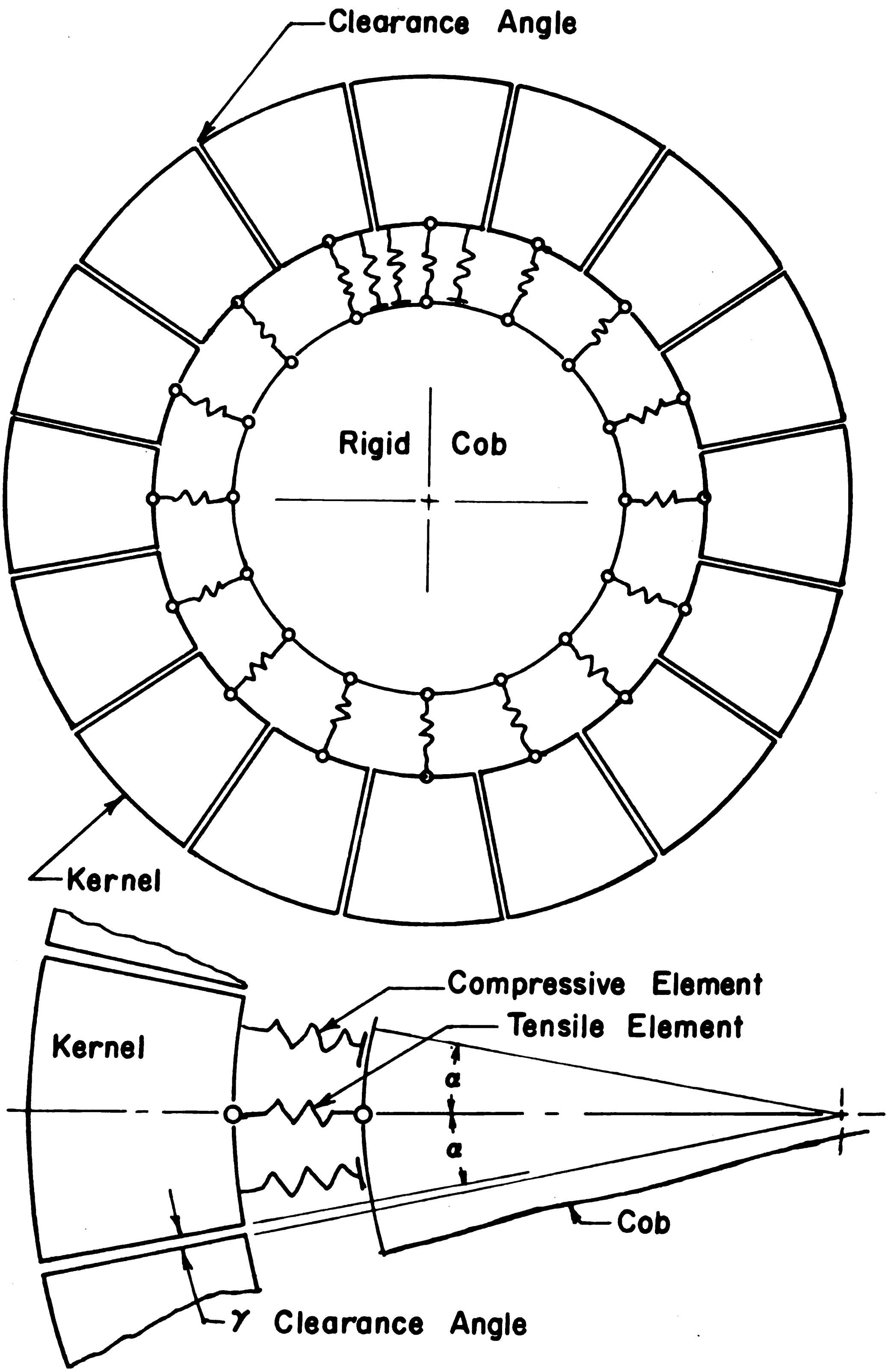


Figure 5.11.--Plane model of the ear modified to include compressive elements. All kernels have identical connecting structure shown at bottom.

The model in Figure 5.11 consists of elastic elements only. Appropriate viscoelastic elements can be substituted directly into the model to account for the time dependent properties of the pedicel and surrounding support structure. This procedure is in accord with the well known correspondence principle of viscoelasticity (Bland, 1960). It should be noted that the position of the compressive elements is important in describing resistance of the kernels to bending forces. The modeling approach taken by Moustafa (1966) may be useful in such a problem.

Increase in the load P causes succeeding clearances to be taken up. When j+f clearance angles are taken up, the radial displacement is given by:

$$x = R_i \frac{\sin (j+f) \gamma}{\sin \alpha} \tag{5.2}$$

where,

x = displacement of radially loaded kernel towards center of the ear.

R_i = inside radius of kernels.

γ = clearance angle between kernels prior to loading.

j = the number of clearance angles completely taken up between the loaded kernel and the point diametrally across.

n = total number of kernels in the model.

f = fraction of one clearance angle taken up.

α = one half the angle included by a kernel.

In the above equation,

$$0 \leq j+f \leq \frac{n}{2}$$

must hold.

5.3c Cases of Interest Related to Shelling in Loaded Rigid Model

Loading of the model has at least two cases of interest. One case occurs when the pedicel on an adjacent kernel is elongated to the point of fracture. The second case occurs when all of the clearance angles in the model have been taken up due to circumferential movements of the kernels.

Case 1: Fracture of pedicel in adjacent kernel.

Elongation of the pedicel in any kernel can be determined from the geometry of the problem. The geometry is based on a previous assumption: that movement of all kernels, except the loaded one, is in a circumferential direction.

Consider any displaced kernel g in the loaded model. In order that this kernel can be referred to specifically, a naming or numbering system is required.

The system adopted here uses numbers. The number, one, is assigned to either of the kernels adjacent to the kernel being loaded. The following numbers are assigned by counting in the direction away from the radially loaded kernel. Thus there will be two kernels with the number one, two with the number two, and so forth. End of the counting sequence occurs at or before a point diametrally opposite the radially loaded kernel.

Assume j+f clearance angles have been taken up due to the displacement of the radially loaded kernel. Then, from the previous discussion:

$$x = R_i \frac{\sin (j+f)\ \gamma}{\sin \alpha}$$

The initial length of any pedicel g (Figure 5.12) is given by:

$$L = R_i - R_c$$

where,

L = initial length of any pedicel

R_i = inside radius of kernels

R_c = radius of cob.

For the kernel g to be displaced it is necessary that

$$g \leq j$$

After load P is applied so that j+f clearance angles are taken up, the cosine law yields the following equations:

$$L_g' = \sqrt{[R_i^2 + F_c^2 - 2R_iR_c \cos (j+f-g)\gamma]} \qquad (5.3)$$

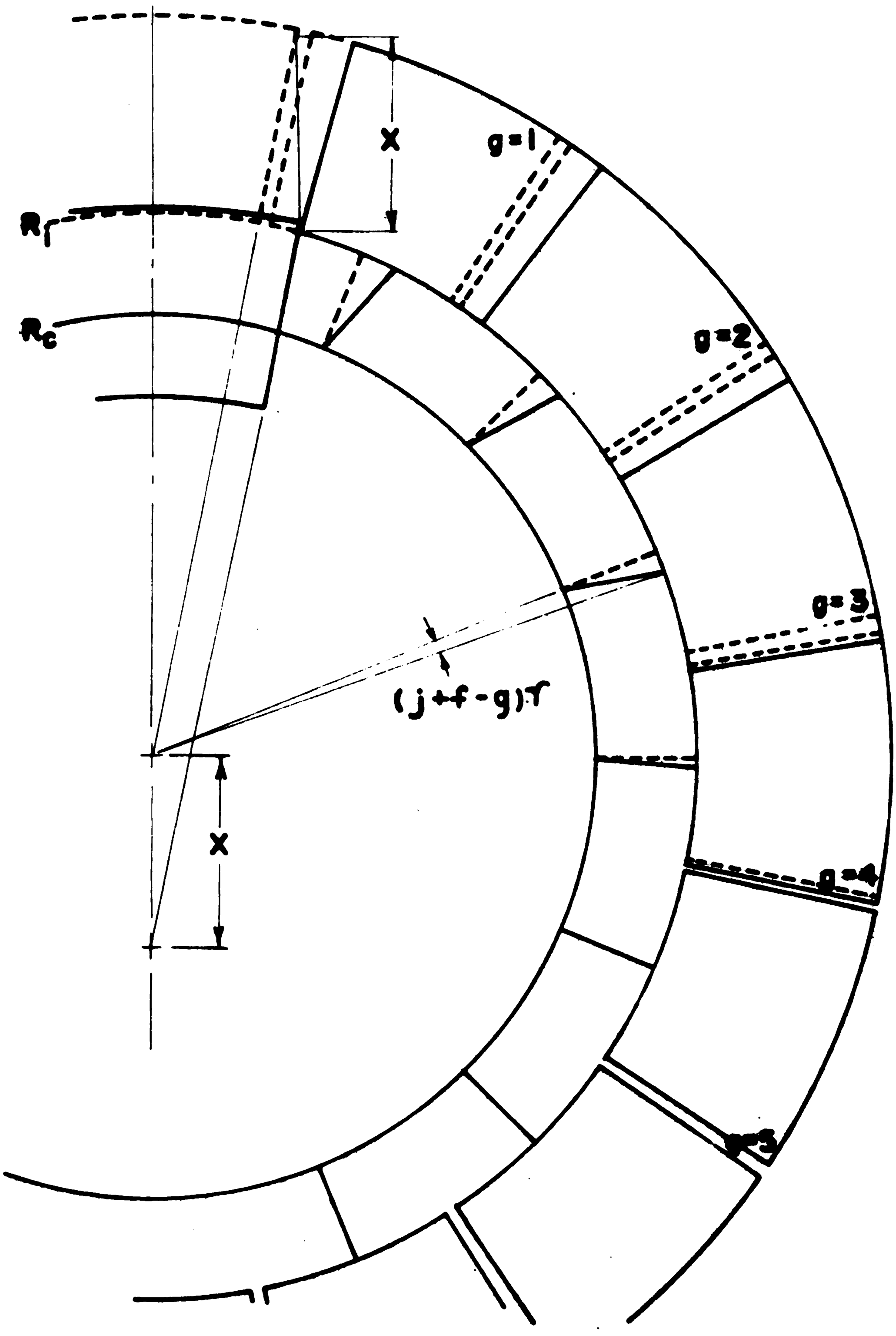


Figure 5.12.--Rigid model loaded with j+f = 4.5 clearance angles taken up.

where L_g' is defined as the new length of pedicel g due to the displacement of that kernel. Elongation of the pedicel for kernel g is

$$\varepsilon_g = L_g' - L$$

$$= \sqrt{[R_i^2 + R_c^2 - 2R_iR_c \cos (j+f-g)\gamma]} - L$$

$$\varepsilon_g = \sqrt{[R_i^2 + R_c^2 - 2R_iR_c \cos (j+f-g)\gamma]} - R_i+R_c \quad (5.4)$$

$$\text{for } g = 1, 2, \ldots, \frac{n}{2} - 1$$

It is evident from Figure 5.12 and from the above equation that maximum pedicel elongation occurs in the kernels adjacent to the radially loaded one, for which g = 1. Elongation of either pedicel to the point of fracture signifies the initiation of shelling.

<u>Case 2</u>: All Clearance Angles in the Rigid Model Completely Taken Up

When the displacement, x, of the radially loaded kernels becomes

$$x = \frac{R_i \sin \frac{n}{2}\gamma}{\sin \alpha} \quad (5.5)$$

and shelling has not commenced, then all of the clearance angles in the rigid model are taken up. The above statement was obtained by setting $j+f$ at its maximum value, $\frac{n}{2}$, in the equation (5.2). Since symmetry of the model has been assumed, then the bounds on x are given by

$$0 \leq x < R_i - R_c$$

for radial compressive loading. Near the upper bound $(R_i - R_c)$, the compressive elements approach zero length in the model.

The distribution of forces in the model is determined largely by the behavior of the attachment structures of the kernels. A force, or stress, analysis of the problem becomes necessary if strain in the first pedicel, $g = 1$ is not sufficient to have initiated shelling at this point.

The applied radial compressive force P is resisted by the compressive reaction of the loaded cupule plus the friction which results from wedging apart of the two adjacent kernels. The problem of analyzing the forces acting on the loading kernel is statically indeterminate unless either H, the wedging force (Figure 5.13) or C_o, the compressive resistance is known.

Let it be assumed that the force-deformation behavior of the cupule structure is known. Then C_o can be related to the displacement x of the loaded kernel. Knowing this, H can be determined if the coefficient of friction between kernels is known. Burmistrova _et al_. (1963) reported $\mu = 0.36$ for this, which corresponds to a friction angle of 19.8 degrees.

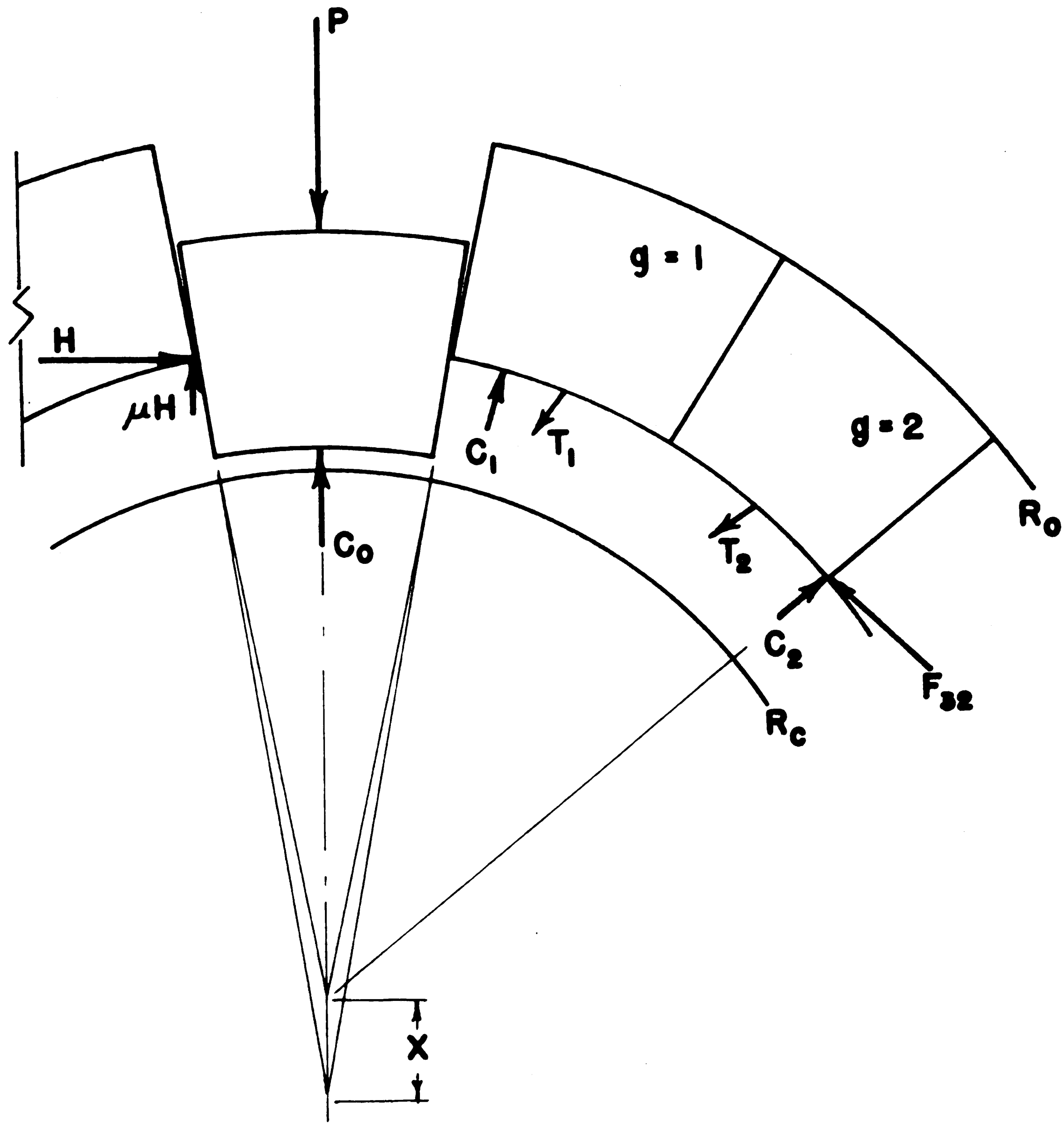


Figure 5.13.--Free body consideration of the rigid model with all clearance angles taken up. H is the wedging force in the model due to the radial-inward displacement of the loaded kernel. The subscripted force vectors denote cupule compression (C), pedicel tension (T), and frictional-compressive components (F).

With H obtained in the above manner, the three free-body diagrams of Figure 5.14 can be considered. These three force diagrams will yield 9 equilibrium equations, but only 6 of these equations will be independent. There are 7 unknown quantities which must be evaluated, namely:

C_1 = the compressive force exerted by the cupule on kernel g = 1.

C_2 = the compressive force exerted by the cupule on kernel g = 2.

T_1 = the tensile force exerted by the pedicel on kernel g = 1.

T_2 = the tensile force exerted by the pedicel on kernel g = 2.

F_{12} = the compressive-frictional force exerted by kernel g = 1 on kernel g = 2.

F_{21} = the compressive-frictional force exerted by kernel g = 2 on kernel g = 1.

F_{32} = the compressive frictional force exerted by kernel g = 3 on kernel g = 2.

Note that $\vec{F}_{12} = -\vec{F}_{21}$, so that it is possible to solve for each of the unknown forces in terms of H. Furthermore, these can be related to the applied load P.

The Figure 5.14 shows F_{21} and F_{12} for the case where motion is impending between kernels g = 1 and g = 2. In other words, the kernel g = 2 is beginning to shell. The

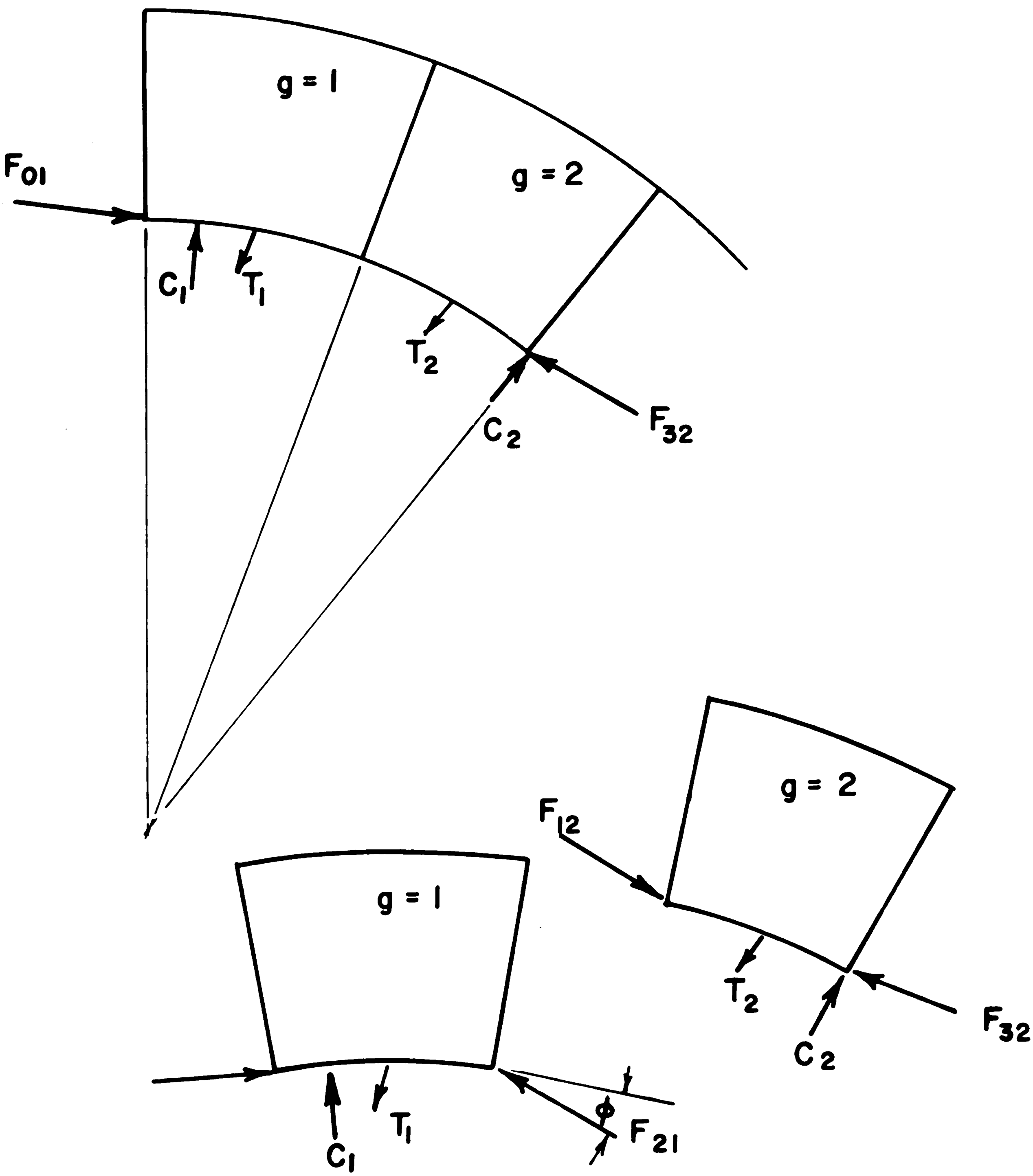


Figure 5.14.--Additional free body force considerations for the case where ejection of kernel g = 2 is imminent. $(1 + \mu^2)H$ is abbreviated F_{01}.

indeterminate condition on kernel $g = 2$ suggested the placing of limits on the force F_{32}. These were determined by assuming a friction angle of 19.8 degrees and considering sliding in both directions, that is kernel $g = 2$ past kernel $g = 3$, or the reverse. Shelling is initiated when either T_1 or T_2 exceeds the ultimate tensile strength of the pedicel.

6. VALIDITY OF THE THEORY

Any theory of shelling can be considered valid if it accurately predicts the response of a corn ear to the kinds of forces that were considered in the formulation. This criterion was stipulated as one of the objectives of this study.

Quasi-static tests were conducted to determine the response of corn ears to radial compressive loading. Loads were applied to the crowns of individual kernels by means of a flat surfaced steel indenter. The indenter was shaped to cover the entire crown of an average corn kernel. Its size and shape (Figure 6.1) permitted a distributed loading of individual corn kernels without disturbance to the adjacent kernels.

In the compressive tests, an entire corn ear was placed on the load cell platform of an Instron model TM testing machine. The Instron model TM is a constant rate of travel testing machine. Load was applied by means of the specially shaped indenter which was mounted in the cross-head.

Time dependent behavior of the pedicel and surrounding structure was anticipated. Therefore, loading rates of 0.1,

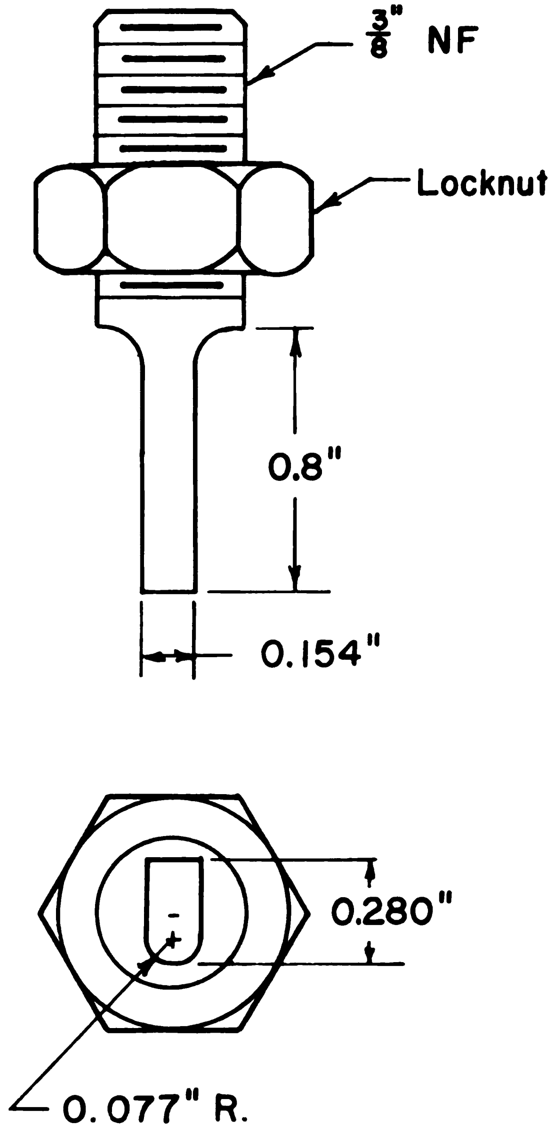


Figure 6.1.--Indenter that was used for applying radial compressive load to individual kernels.

0.1 and 1.0 inch per minute were selected to determine the effect of loading rate on the compressive behavior of the pedicel structure.

Preliminary tests showed that corn ears having a high moisture content (above 15.3 per cent wet basis) would yield information of dubious value to an understanding of the shelling process. The crowns of kernels were crushed when relatively small loads were applied on them. Continuation of loading after crushing of the crown was pointless since the information did not seem related to the shelling process.

On drying to some specific moisture content it appeared that the response of a corn ear to radial compressive loading was completely changed. Application of compressive load to the crown of a kernel no longer caused crushing. Instead, a kernel in the adjacent region would be ejected from the ear (Figure 6.2).

The particular kernel that would be ejected from the ear could be predicted with some accuracy. From the pattern of Figure 5.1 and the theory, either the kernel in the adjacent paired (rather than alternate) row, or one of the two adjacent alternates in the following row (g=2) would be shelled. Shelling in the adjacent alternating row was infrequent and was attributed to some tangential component in the loading.

A typical force-displacement diagram for loading an ear in radial compression is given in Figure 6.3. This reaction could have been predicted by the rigid kernel and cob theory. The initial linear portion of the curve is attributed to the constant rate reaction of the attachment structure in the loaded kernel. As interference from the adjacent kernels comes into play, the curve deviates from the initial straight line. The deviation continues to increase as additional clearances are taken up in the ear.

Data from the compressive tests (Appendix III) were subjected to a multiple linear regression analysis. The parameters usually associated with kernel damage in shelling were considered as independent variables that might affect the force required to initiate shelling. These parameters included moisture content of the kernel, cob moisture content, date of harvest and rate of loading.

A low coefficient of determination for the above analysis indicated that other variables should have been introduced. The theory predicts that the number of rows per ear and some measure of ear looseness or clearance angle should have also been considered.

The rigid material theory predicts that higher loads are required to cause shelling in a loose ear of corn than in one in which the kernels are tightly packed. This factor

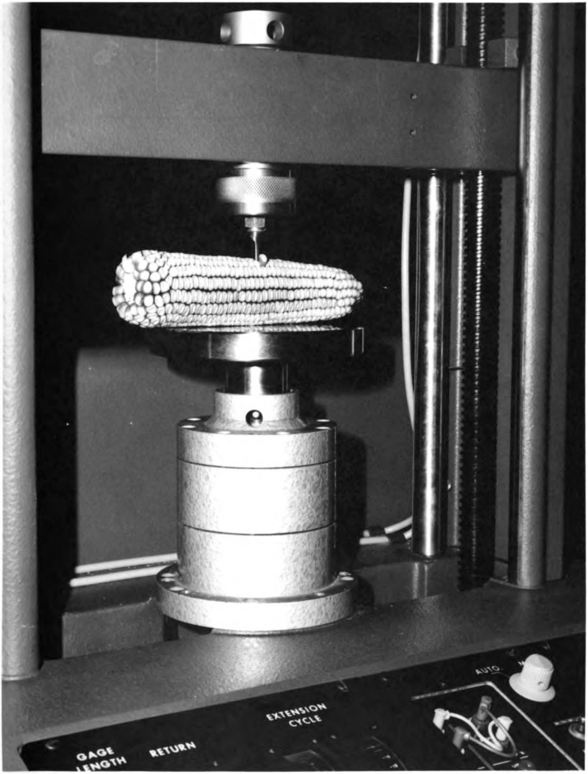


Figure 6.2.--Application of radial compressive load to an ear of corn. Note the ejection of a kernel from an adjacent row. (Photo 67-17)

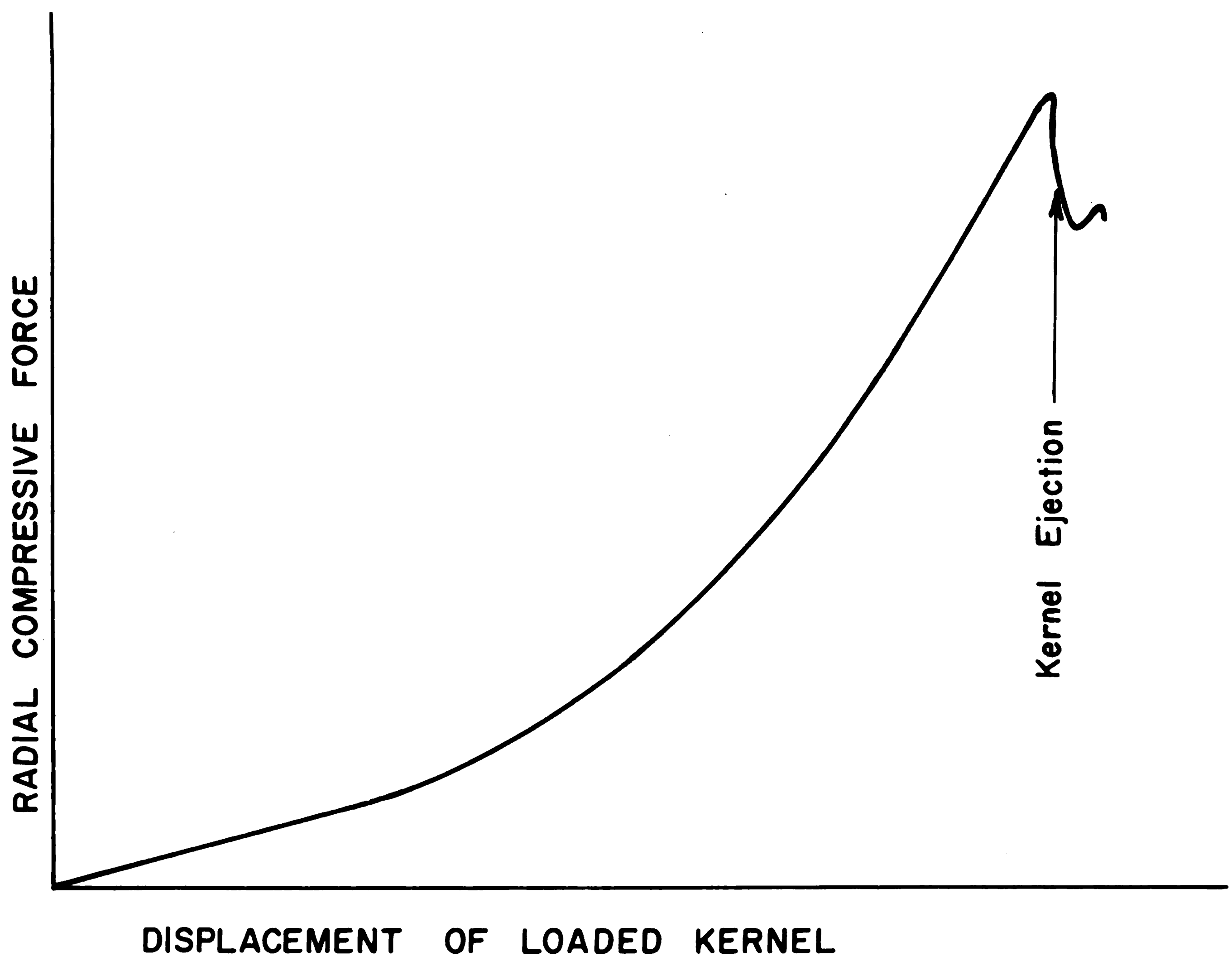


Figure 6.3.--A typical force-displacement curve from the radial compressive tests.

had not been realized prior to the quasi-static compressive tests. However, ear looseness could be simulated by removing one row of kernels from an ear prior to loading.

In several repeated tests it was found that much higher loads are required to cause kernel ejection in an ear after a row of kernels has been removed from it. A typical force displacement record of this is shown in Figure 6.4 for a particular corn ear. The first two tests were conducted on kernels in the same row spaced 13 kernel thicknesses apart. The third test shows the effect on force required to cause shelling when radial compressive load was applied to a kernel after shelling was initiated in the ear. This was done by removing all of the kernels in the row g=3. Although ear looseness was artificially induced, the large difference in required shelling force suggests that ear looseness may be an important factor related to shelling.

6.1 Moisture Content Range for Which the Theory Holds

The main objective of the quasi-static experiments was to determine the moisture content at which shelling can be induced by radial compressive loading. Since moisture contents of the crop on harvesting were such that shelling could not be initiated at the quasi-static load rates, the corn ears were permitted to dry in the laboratory atmosphere until shelling could be achieved in this way.

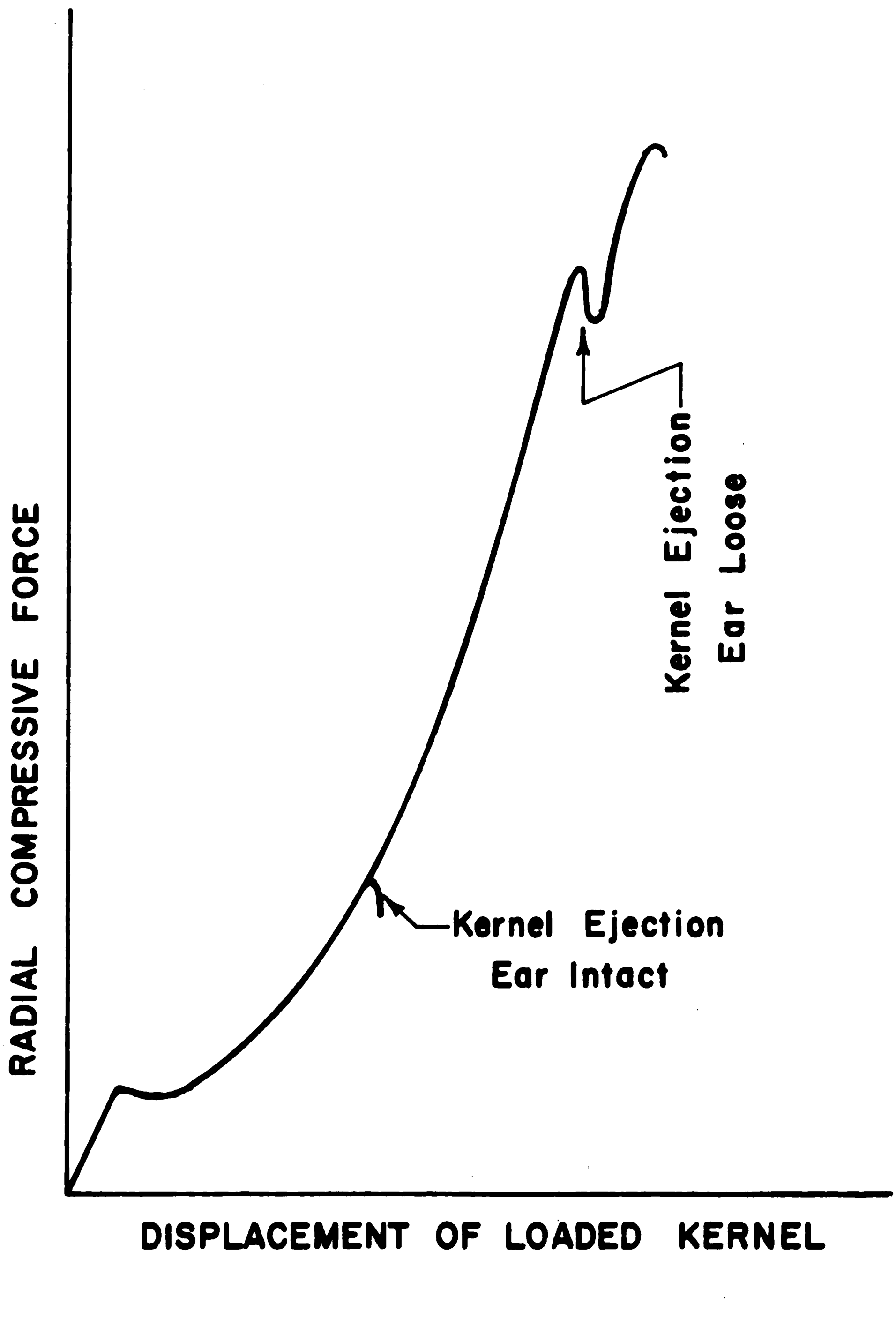


Figure 6.4.--Radial compressive force required to initiate shelling in an ear of corn was considerably lower than the force required to cause shelling after some kernels had been removed from the ear.

The drying rate of the corn ears, which were placed on a tabletop for drying, was such that moisture content of the ears was reduced an average 2.6 per cent per day. Laboratory temperature during the drying period fluctuated between 77°F and 81°F, with relative humidity ranging between 20 per cent and 32 per cent.

The procedure of laboratory drying is not recommended, for it may lead to unnatural moisture relations between the kernel and cob. This procedure was deemed permissible here only because the quasi static loading rates were also unnatural to the shelling process.

It was found that shelling can be induced at quasi-static load rates when the moisture content of the kernels is 15.3 per cent or less; that of the cobs 24.9 per cent or less. Ear moisture averages would be somewhere between these two values.

7. SHORTCOMINGS OF THE THEORY

The theory developed in this study describes the reaction of a corn ear to applied radial compressive loads with a qualified accuracy. In the development, hypothetical assumptions were made to explain the observed behavior of actual corn ears.

7.1 Rigid Material Assumptions

The rigid material assumptions appear very unrealistic as a first impression. However, when considered within the context of the problem, they serve a useful and meaningful purpose by simplifying explanations considerably. The errors which they introduce are probably small.

The hazards associated with these material assumptions are that they conceal many important aspects of the problem. The rigid cob and kernel theory, for instance, precludes shelling by the application of axial load on the cob. This factor is readily apparent because of its physical consequences. What may not be so readily apparent are factors such as interdependence of kernels within a row. The structure of the cupules suggests that such interrelations should exist; that kernels are interdependent. A knowledge of material properties such as Poisson's ratio and bulk modulus is important to an understanding of this interdependence from the materials point of view.

7.2 Assumptions Regarding Compressive Behavior of the Cupule

The compressive behavior of the cupule was assumed to permit pure rotation of kernels about the cob center. Actual measurements of the motion induced in an ear by the application of bending loads to the kernels should be made. These motions are particularly important to a dynamic analysis of the problem.

Structural models similar to those developed by Moustafa (1966) could be an important asset to understanding the stability of attachment of corn kernels to cobs. Such models would remove many of the doubts associated with ideas like sliding spring elements. More importantly, they would aid considerably in extending the theory to include shelling by the application of tangential forces to the ear.

7.3 Ear Looseness Concept

Introduction of the ear looseness concept was required in the rigid material theory. Its importance to the actual problem of shelling by the application of radial compressive loading needs to be ascertained for corn in its various harvest conditions.

The need for an ear looseness concept vanishes when deformable kernels are considered. A study of ear looseness would then correspond to the properties of the kernel material in the directions perpendicular to the length of the kernel. The composition of corn kernels suggests that anisotropic behavior should be expected.

8. EXTENSION OF THE THEORY INTO THE DYNAMIC RANGE

Corn is usually shelled at high rates of loading. Impact velocities between 2500 and 3500 feet per minute are common in cylinder type shellers.

In order that the foregoing theory may have practical value, it must be extendable into the dynamic range. This criterion was one of the objectives established for this study.

A dynamic analysis of the shelling problem requires a knowledge of the dynamic mechanical properties of corn. The lack of such information suggested that a qualitative analysis of shelling by radial impact be considered.

8.1 Low Speed Impact Tests

Corn ears were subjected to low speed radial compressive impact loading. The special indenter used in the quasi static experiments was adapted to a falling weight test apparatus (Figure 8.1). The maximum height of drop available with this apparatus was approximately 5 feet. Minimum weight that could be dropped was 1.25 pounds; maximum weight was 12 pounds.

Using the minimum dropped weight (1.25 pounds) it was noted that shelling could be initiated from drops as low as 0.41 feet. The experiments (Appendix IV) indicated that an average 0.51 foot pounds of energy were required to initiate shelling in dry corn.

The physical results of a drop test can probably be best explained with a photograph. Figure 8.2 shows the result of one drop test in which two kernels were ejected. Although the theory did not predict shelling of kernels in the same row as the load was applied, variations in kernel shape from the idealized model did allow this to occur.

8.2 High Speed Moving Picture Study

High speed moving pictures that have been taken inside the shelling mechanism of a corn harvesting machine can provide information useful to a study of shelling. The sequence of pictures in Figure 8.3 shows the reaction of a corn ear to impact by a cylinder bar. The sequence ends with compression against a concave bar.

The loading of an ear of corn that takes place within a cylinder-type sheller may be purely radial compressive by accident rather than intent. The reaction of the corn ear in the sequence of photos (Figure 8.3) was such that kernels were ejected from the ear near the point of loading. This is in agreement with the results predicted by the quasi-static theory.

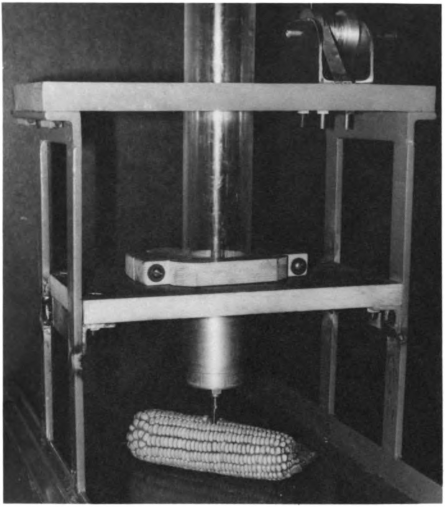


Figure 8.1.--Falling weight test apparatus. Weight with special indenter is shown in the dropped position. (Photo 67-58)

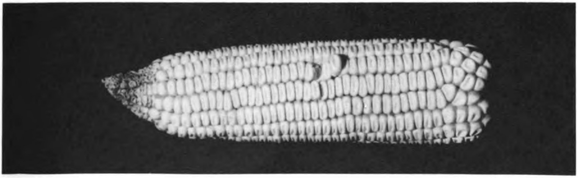
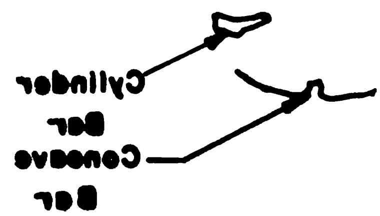


Figure 8.2--Result of a drop test. In this case an 1.25 pound weight was dropped from a 0.5 foot height. Velocity at the beginning of impact was estimated to be 330 feet per minute. (Photo 67-57)


Cylinder
Bar
Concave
Bar

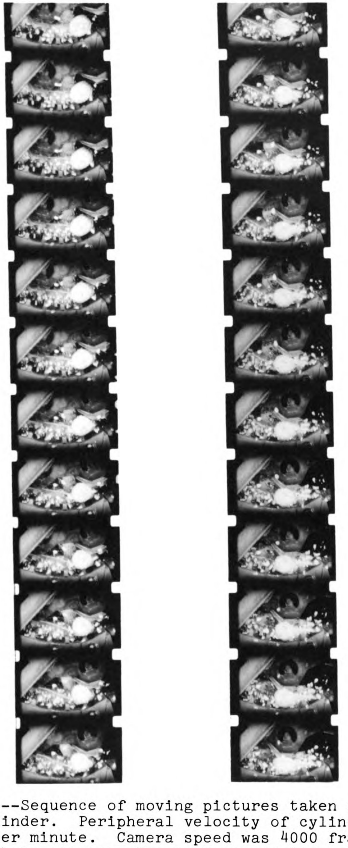


Figure 8.3.--Sequence of moving pictures taken inside a combine cylinder. Peripheral velocity of cylinder was 2600 feet per minute. Camera speed was 4000 frames per second. (Photo courtesy Massey Ferguson Ltd., Toronto)

The vagueness associated with these observations can be dispelled by a dynamic analysis of the problem. Such an analysis should be linked with experiments in which loading can be controlled.

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APPENDICES

APPENDIX I

LITERATURE SURVEY

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LITERATURE SURVEY

A. Survey Procedure

The literature search was initiated by reviewing recent issues of periodicals that normally deal with corn or its production. Included in the list of periodicals were the various series of bulletins, circulars and reports issued by State Agricultural Experiment Stations and the United States Department of Agriculture. Latest issues were reviewed first and the search was pursued in the usual reverse chronological order to the year 1945. In some instances the review was carried to a much earlier date. Notes were made on the articles related to the subject.

The articles located in the periodicals were gleaned for pertinent information. In addition, their lists of references were noted and referred to.

Books on the subject of corn production, plant anatomy and physiology, and harvesting equipment were also reviewed. These were located through the references from the first phase of the study. The author-title and subject indexes of the University Main Library card catalog were also consulted.

The search was concluded by consulting bibliography lists, abstracts and indexes. Keywords always included in this part of the search were: corn, harvest mahcines, maize, shelling, and Zea mays.

B. Periodicals Reviewed--General

Agricultural Engineering
Agriculture
Agronomy Journal
American Journal of Botany
American Midland Naturalist
Biorheology
Botanical Gazette
Cereal Chemistry
Cereal Science Today
Crops and Soils Magazine
Crop Science
Iowa State Journal of Science
Journal of Agricultural Engineering Research
Journal of Agricultural Science
Journal of Agriculture and Food Chemistry
Journal of Applied Mechanics
Journal of Experimental Botany
Journal of Food Science
Journal of the Association of Official Analytical Chemists
Nature
Proceedings of the Royal Society of London (Series A and B)
Stain Technology
The Ohio Journal of Science
World Crops

C. Periodicals Reviewed--U.S.D.A. and Agricultural Experiment Station Literature

The United States Department of Agriculture, together with the State Agricultural Experiment Stations publish many series of pamphlets, circulars, bulletins, handbooks, monographs and leaflets. The material published by the U.S.D.A. could be easily located through the special card catalog in which individual articles are indexed by subject and author.

The material published by the various State Agricultural Experiment Stations required perusal of bound non-indexed volumes. This part of the search was restricted to series issued by the Agricultural Experiment Stations of the states listed below:

California

Georgia

Illinois

Indiana

Iowa

Michigan

Minnesota

Missouri

Nebraska

Ohio

Wisconsin

D. <u>Abstracts, Indexes and Bibliographies</u>

Agricultural and Horticultural Engineering Abstracts (Discontinued)
Applied Mechanics Reviews
Biological and Agricultural Index
Dissertation Abstracts
Field Crops Abstracts
Plant Breeding Abstracts
Rubbers: RAPRA Abstracts
Science Citation Index
Technical Translations (Discontinued after Dec. 1967)
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APPENDIX II

TENSION EXPERIMENTS

APPENDIX II

TENSION EXPERIMENTS

Experiments were conducted to determine force-elongation characteristics of the pedicels. Corn ears were selected at random from groups harvested within the 1967 crop season. The corn ears were of the single-cross hybrid, variety 402-2x. Date of planting was May 20.

The corn ears were the same ones that were used for the compression tests of Chapter 6 and Appendix III. The compression tests were performed at the 1/6, 3/6 and 5/6 positions along the length of the ear, with origin at the base end. The tension tests were performed on 0.45 inch long sections cut from the 2/6 and 4/6 positions on the ear.

One kernel out of each section was selected for the tension specimen. Kernels in its immediate vicinity were removed (Figure A2.1), to aid in clamping for the tension test.

In order to load the pedicel in tension, the kernels were clamped between coarse sandpaper faces with a clamping force of approximately 6.1 pounds. The cob was clamped between the serrated faces of the Instron type 3C-1 pneumatic grips. Clamping force of the pneumatic grips was less than 23 pounds.

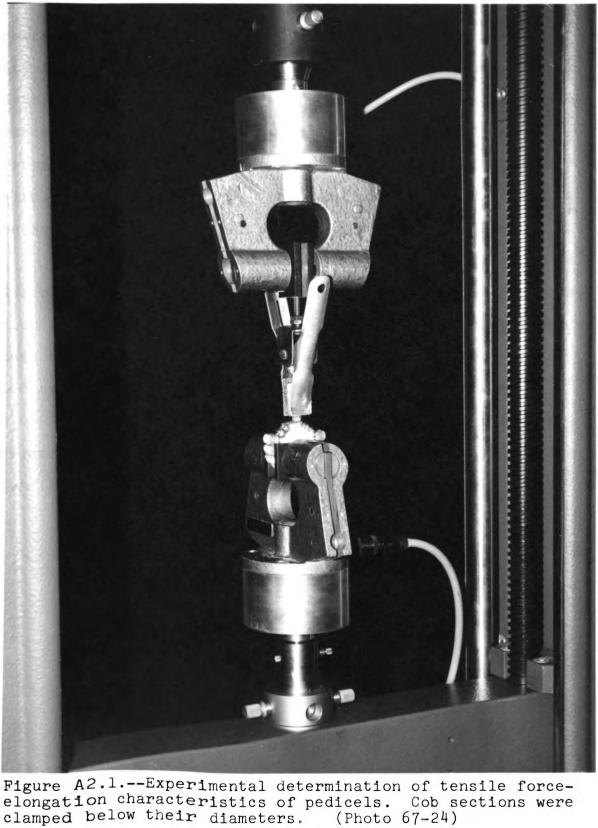

Figure A2.1.--Experimental determination of tensile force-elongation characteristics of pedicels. Cob sections were clamped below their diameters. (Photo 67-24)

The force-elongation characteristics could be described as linear up to the point of fracture. The initial portions of these curves were non-linear, but this was attributed to factors such as straightening of the pedicels, setting of the grips and interference from the cupule. The force-elongation curves were analyzed (Table A2.1) by extending the linear part of the curves to the elongation axis. Pedicel elongation was computed as that distance between the intercept and the elongation at fracture.

The term "elongation error" has been introduced to describe the displacement associated with non-linear elongation of the pedicel. Likewise, the term "force error" was used to indicate the tensile load at which response of the pedicel became linear. Average elongation error was 0.0092 inch. The average force at which pedicel response became linear was calculated as 0.303 pound, for all of the tensile specimens tested.

TABLE A2.1--Analysis of force-elongation curves for pedicel in tension

Date of Harvest	Ear No., Kernel Position	Kernel Moisture, % wb	Loading Rate, inch/min	F-ε Slope, lb/inch	Load at Fracture, lb	Elongation at Fracture, inch	Elongation Error, inch	Force Error, lb
Oct. 5	1C 2/6	13.9	.01	140	4.2	.030	.007	.22
Oct. 5	1C 4/6	13.9	.10	168	5.0	.032	.014	.50
Oct. 5	2C 2/6	13.7	1.00	250	3.9	.019	.016	.55
Oct. 5	2C 4/6	13.7	.01	133	3.4	.027	.012	.35
Oct. 5	3C 2/6	15.3	.10	77	3.8	.049	0	0
Oct. 5	3C 4/6	15.3	1.00	200	4.9	.026	0	0
Oct. 15	1D 2/6	16.4	.01	70	2.6	.038	.009	.25
Oct. 15	1D 4/6	16.4	.10	77	3.5	.043	.023	.40
Oct. 15	2D 2/6	13.4	1.00	167	4.4	.026	.012	.40
Oct. 15	2D 4/6	13.4	.01	125	3.0	.026	.009	.20
Oct. 15	3D 2/6	12.9	.10	117	4.0	.037	.002	.15
Oct. 15	3D 4/6	12.9	1.00	300	4.5	.015	.005	.30
Oct. 25	1E 2/6	16.7	.01	120	3.0	.027	0	0
Oct. 25	1E 4/6	16.7	.10	90	4.2	.047	.011	.30
Oct. 25	2E 2/6	12.1	1.00	225	5.6	.026	.009	.35
Oct. 25	2E 4/6	12.1	.01	190	4.4	.023	.013	.70
Oct. 25	3E 2/6	11.1	.10	100	2.8	.028	.005	.20
Oct. 25	3E 4/6	11.1	1.00	190	4.2	.022	.004	.05
Oct. 25	4E 2/6	11.7	.01	290	4.9	.017	.011	.60
Oct. 25	4E 4/6	11.7	.10	270	4.3	.015	.016	.50
Nov. 4	1F 2/6	15.3	.01	90	3.5	.040	.009	.20
Nov. 4	1F 4/6	15.3	.10	81	3.0	.037	.007	.20
Nov. 4	2F 2/6	14.2	1.00	112	3.7	.032	.015	.40
Nov. 4	2F 4/6	14.2	.01	168	4.7	.028	.009	.40
Nov. 4	3F 2/6	15.6	.10	108	3.7	.036	.017	.40
Nov. 4	3F 4/6	15.6	1.00	106	3.6	.035	.004	.25
Averages				152	3.95	.030	.0092	.303

APPENDIX III

RADIAL COMPRESSIVE LOADING OF CORN EARS: EXPERIMENTAL RESULTS AND ANALYSIS

Results from the radial compressive experiments of Chapter 6 have been summarized in Table A3.1. The term "initial slope" refers to the first part of the curve (Figure 6.3) describing the force-displacement characteristics of the loaded kernel.

Abbreviated forms "b to b" and "alt tip" have been introduced to describe the position of the kernel that was ejected due to the application of radial compressive load on the ear. The positions are relative to the kernel that was loaded. Position "b to b" refers to the nearest kernel in the adjacent aligned row. Two other kernels are equally as near in an adjacent row, but that row is alternating rather than aligned.

The positions of kernels in the row beyond the adjacent aligned row (i.e. g=2) are referred to as alternating since they are not in alignment with the kernels in the loaded row. Kernels alternating towards the tip with respect to the position of the loaded kernel are referred to as "alt tip"; those towards the base are "alt base." Only "b to b" kernels in row g=1 and "alt tip" kernels in row g=2 were ejected from the ears in the quasi-static experiments of this study.

TABLE A3.1--Summary of data from radial compressive tests (quasi-static loading rates)

Harvest Date	Ear No., Kernel Position	Loading Rate, in/min	Number of Kernel Rows	Moisture Content: Kernel, % wb	Moisture Content: Cob, % wb	Initial Slope, lb/in	Displacement of Loaded Kernel at Ejection, in	Force** Req'd. for Rejection, lb	Position of Ejected Kernel
Oct. 5	1C 1/6	.01	18	13.9	14.5	-	-	48	Buckled
	1C 3/6	.10	18	13.9	14.5	55	-	52	Buckled
	1C 5/6	1.00	18	13.9	14.5	78	-	60	Buckled
	2C 1/6	1.00	16	13.7	15.7	38	-	39	Crushed
	2C 3/6	.01	16	13.7	15.7	46	.402*	54	t to t
	2C 5/6	.10	16	13.7	15.7	70	.228	68	t to t
	3C 1/6	.10	18	15.3	24.9	57	-	76	Crushed
	3C 3/6	1.00	18	15.3	24.9	75	.440*	81	t to t
	3C 5/6	.01	16	15.3	24.9	40	-	66	Crushed
Oct. 15	1D 1/6	.01	18	16.4	36.0	17	-	32	Crushed
	1D 3/6	.10	18	16.4	36.0	[illegible]	-	54	Crushed
	1D 5/6	1.00	18	16.4	36.0	[illegible]	-	48	Crushed
	2D 1/6	1.00	14	13.4	16.8	-	-	67	Crushed
	2D 3/6	.01	14	13.4	16.8	60	.340*	50	alt tip
	2D 5/6	.10	14	13.4	16.8	62	.173	34	t to t
	3D 1/6	.10	16	[illegible]	11.9	67	.225	72	t to t
	3D 3/6	1.00	16	[illegible]	11.9	38	.303	[illegible]	alt tip
	3D 5/6	.01	16	[illegible]	11.9	-	-	124	Crushing
Oct. 25	1E 1/6	.01	18	16.7	34.0	-	-	25	Crushed
	1E 3/6	.10	18	16.7	34.0	-	-	34	Crushed
	1E 5/6	1.00	18	16.7	34.0	-	-	47	Crushed
	2E 1/6	1.00	16	12.1	13.0	87	.302*	72	t to t
	2E 3/6	.01	16	12.1	13.0	100	.432*	110	t to t
	2E 5/6	.10	16	12.1	13.0	160	.170	[illegible]	t to t
	3E 1/6	.10	20	11.1	8.6	96	.245*	47	alt tip
	3E 3/6	1.00	20	11.1	8.6	75	.315	74	alt tip
	3E 5/6	.01	20	11.1	8.6	67	[illegible]*	47	alt tip
	4E 1/6	.01	20	11.7	10.9	100	.265	57	t to t
	4E 3/6	.10	20	11.7	10.9	[illegible]	.392*	88	alt tip
	4E 5/6	1.00	20	11.7	10.9	120	.202	41	t to t
Nov. 4	1F 1/6	.01	22	15.3	31.3	-	-	38	Crushed
	1F 3/6	.10	22	15.3	31.3	-	-	47	Crushed
	1F 5/6	1.00	22	15.3	31.3	-	-	41	Crushed
	2F 1/6	1.00	20	14.2	21.8	67	.242	39	alt tip
	2F 3/6	.01	18	14.2	21.8	40	.427	69	b to b
	2F 5/6	.10	18	14.2	21.8	100	.187	47	alt tip
	3F 1/6	.10	18	15.6	30.7	-	-	57	Crushed
	3F 3/6	1.00	18	15.6	30.7	-	-	57	Crushed
	3F 5/6	.01	18	15.6	30.7	-	-	46	Crushed

*Indicates some crushing. **Maximum applied load, where buckling or crushing occurred.

APPENDIX IV

LOW SPEED IMPACT TEST RESULTS

Results of the low speed impact tests of chapter 8 have been summarized in Table A4.1. These data represent an attempt at arriving at minimum energy values required to induce shelling by low speed radial compressive impact.

The destructive nature of these impact tests required the selection of a new test position for each trial. Since any particular trial could not guarantee acceptable results, the procedure adopted was to begin tests on an ear from a minimum expected value. If shelling was not induced, the trial was repeated with height of drop increased by one half inch. New position of the test was removed from the earlier one by a distance of one cob diameter or more. Usually these trials were required on any particular ear.

Table A4.1--Summary of data from low speed impact tests

Harvest Date	Ear Number, Kernel Position	Number of Kernel Rows	Height of Drop, inches	Energy Applied, foot pounds	Kernels Shelled: number, position
October 25	1E 2/6	16	5.3	0.54	none
	1E 3/6	16	5.8	0.60	1, g=1
	1E 4/6	16	6.1	0.63	1, g=1
	2E 2/6	16	5.9	0.61	1, g=1
	2E 4/6	16	6.0	0.62	1, g=1; 1, g=0
	3E 2/6	18	5.2	0.54	1, g=1
	3E 4/6	18	5.3	0.55	1, g=1
	4E 2/6	16	5.2	0.54	1, g=0; 1, g=1
	4E 3/6	16	5.3	0.55	none
	4E 4/6	16	5.3	0.55	none
	5E 2/6	16	5.3	0.55	2, g=1
	5E 4/6	16	5.4	0.56	2, g=1
	6E 2/6	16	5.1	0.53	2, g=1
	6E 4/6	16	5.2	0.54	3, g=1
November 4	1F 1/6	18	6.1	0.63	2, g=1
	1F 3/6	18	5.2	0.54	none
	1F 4/6	18	6.2	0.64	1, g=1
	2F 1/6	18	6.0	0.62	1, g=1
	2F 3/6	18	6.1	0.63	2, g=1
	2F 5/6	18	6.3	0.66	1, g=0; 2, g=1
	3F 2/6	16	5.9	0.61	1, g=1
	3F 4/6	16	6.2	0.64	1, g=1
	4F 2/6	20	6.2	0.64	1, g=1
	4F 3/6	20	5.3	0.55	1, g=1
	4F 4/6	20	5.4	0.56	1, g=0; 2, g=1; 2, g=2
	5F 2/6	22	5.2	0.54	none
	5F 3/6	22	6.0	0.62	2, g=2
	5F 4/6	22	4.9	0.51	3, g=2
	6F 2/6	18	5.0	0.52	1, g=1
	6F 4/6	18	5.0	0.52	1, g=0; 1, g=1

APPENDIX V

EXPERIMENTS TO DETERMINE VALIDITY OF HYPOTHESIS THAT KERNEL THICKNESS IS A FUNCTION OF ITS POSITION ALONG THE LONGITUDINAL AXIS OF THE CORN EAR

A. Model

The model selected for this study was

$$t_i = \frac{A}{i}$$

where,

t_i = thickness of any kernel i in a particular row.

i = period under consideration in the sequence 1, 2, 3, . . . Represents position of kernel from base of ear.

A = a constant.

B. Procedure for Obtaining Data

Several ears of variety 402-2x single cross hybrid corn were selected at random from a lot of ears harvested on October 15, 1967. The corn was planted on May 20, 1967.

Kernel thickness was considered to be that exterior dimension that is obtained by measuring the kernel in a direction parallel to the longitudinal axis of the corn ear. It is usually the smallest of the three dimensions commonly measured on corn kernels.

Thickness measurements were made by means of a micrometer caliper. The caliper was equipped with a ratchet attachment. Results were recorded so that kernel thickness could be related to its position, as counted from the base of the ear.

C. Data Analysis

The form of the model,

$$t_i = \frac{A}{i} = Ai^{-1}$$

suggested the use of the convenient computer STAT series LS Routine prepared by the Michigan State University Agricultural Experiment Station. The LS Routine is based on the equation:

$$Y = a + bX$$

If a=0, similarity of the above equation to the model becomes readily apparent. Although the LS Routine could be modified to force a to zero, no such attempt was made. This decision was consistent with the general idea of finding a suitable, yet simple, approximation.

D. Results of the Analysis

The statistical analyses have been summarized in Table A5.1. Coefficients of determination varied from zero to .87 indicating that the model can be a good one for "uniform" ears. Its failings should also be considered.

It is instructive to take the derivative of the equation,

$$t_i = Ai^{-1}$$

with respect to i. Rate of change of kernel thickness with respect to position, dt_i/di, is not linear as can be seen from

$$\frac{dt_i}{di} = -Ai^{-2}$$

An evaluation of this factor and others suggested the need for a more profound analysis of the problem of simple mathematical description than the objectives of this study demanded.

TABLE A-5.1--Summary of regression equations describing kernel thickness as a function of its position along the ear.

Ear No., Row No.	a	b	R^2	F	N*
1,1	.137	.172	.68	62.6	32
1,2	.148	.052	.04	1.018	30
1,3	.134	.199	.55	28.9	26
2,1	.156	.186	.38	18.4	32
2,2	.170	.092	.06	1.913	33
2,3	.154	.162	.48	28.0	32
3,1	.184	.002	.00	0	25
3,2	.168	.189	.40	14.0	23
3,3	.167	.208	.54	26.1	24
4,1	.154	.261	.49	36.2	39
4,2	.155	.209	.87	254	39
4,3	.152	.284	.48	30.3	35
5,1	.177	.225	.30	1176	24
5,2	.177	.212	.56	28.9	25
5,3	.181	.170	.25	6.87	23
6,1	.155	.112	.19	4.81	22
6,2	.142	.286	.54	21.9	21
6,3	.143	.166	.28	8.70	24

*N denotes total number in sample.

R^2 denotes coefficient of determination.

APPENDIX VI

GLOSSARY

Bract -a somewhat modified leaf associated with the reproductive structures of a plant.

Cupule -designates the depression or alveolus on the cob near the base of which the paired spikelets are attached. It has also been called cucullate depression, corneous cupule or alicole.

Glume -one of the two empty bracts at the base of the spikelet in grasses.

Herbal -a book in which plants are named, described, and often pictured.

Lemma -the lower of the two bracts enclosing the flower in the spikelet of grasses. Also called the flowering glume.

Palea -the upper bract that, with the lemma, encloses the flower in grasses.

Pedicel -one of the ultimate single flower bearing divisions of a peduncle.

Peduncle -a stalk that bears a flower or flower cluster.

Period -an interval, especially one established by repeated or regular recurrence.

Rachilla -a small or secondary rachis; the axis of a spikelet of a grass or sedge.

Rachis -the elongated axis of an inflorescence.

Spikelet -one of the small few-flowered bracteate spikes that make up the compound inflorescence of a grass or sedge.

Viscoelastic-having both viscous and elastic properties
in appreciable degree.