IMPACT LOADING OF CORN AND ITS EFFECT ON QUALITY

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ABSTRACT

IMPACT LOADING OF CORN AND ITS EFFECT ON QUALITY

By

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Corn kernels are connected to the cob by pedicels which are fractured during shelling. The phenomena associated with the initiation of corn shelling were investigated by subjecting whole ears to radial compressive impact loading. Impact velocities comparable with combine cylinder peripheral velocities commonly found during field shelling were utilized while testing two varieties of corn. Precautions were taken to reduce biological changes in the samples between the time of collection and the time of testing.

The impact process was recorded by high-speed cinematography. The resulting movies were examined with a movie analyzer to estimate the energy absorbed by corn ears during impact. Study of these movies also revealed shelling is initiated by radial compressive impact loading as a result of inertial forces and the wedging effect proposed by Halyk (1968).

The maximum impact force was measured for every sample tested. Regression analysis showed that for both varieties impact force was increased by increases in ear weight, moisture content or impact velocity. Impact force increased as the harvest season progressed for the Michigan 250 variety, while the opposite was true for the Michigan 500 variety.

Every kernel of all samples tested were inspected and kernels with visible mechanical damage were weighed. Mechanical damage for the Michigan 250 variety increased with: (1) decreases in kernel moisture content or impact velocity or (2) increases in cob moisture content or testing date. For the Michigan 500 variety mechanical damage decreased as the harvest season progressed until November 4, and then it increased as the season progressed. Damage for Michigan 500 also became more severe with increases in kernel moisture content.

Kernels removed by a single impact were weighed. Increases in impact velocity or decreases in cob moisture content or ear weight increased kernel removal for the Michigan 250 variety. Increases in moisture content, testing date, impact velocity or ear weight increased kernel removal for the Michigan 500 variety.

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IMPACT LOADING OF CORN AND ITS EFFECT ON QUALITY

By

Thomas Harold Burkhardt

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1. INTRODUCTION

The most important crop grown in both Michigan and the United States is corn. Average yearly Michigan production of corn during the period of 1964 through 1967 was 92.2 million bushels valued at $104.2 million. Approximately 54.3 percent of this corn was fed on the farm where it was grown with the remainder being marketed as a cash crop. The corn which was sold accounted for six percent of the total Michigan cash receipts from farm marketings (Michigan Department of Agriculture, 1968). The total disappearance of corn in the United States in 1965 was 4.392 billion bushels. Of this total, 76.2 percent was fed to livestock, 15.2 percent was exported and 0.3 percent was used for seed. The remaining 8.3 percent was used for wet process products (4.6 percent), corn meal and grits (2.5 percent), alcohol and distilled spirits (0.7 percent), and breakfast foods (0.5 percent). The grain equivalent of the starches, syrups, sugar, meal, oil, flour and other foods containing corn that shoppers select amounts to about one bushel per person per year. In a recent survey of the largest stores of five food chains in the Washington, D.C. area, 650 different items which contained one or more of the products of the wet milling industry were counted (Liebenow, 1968).

The corn kernel is attached to the cob by means of a structure known as the pedicel (Wolf *et al.*, 1952). During the shelling process pedicels are fractured thereby freeing kernels from the cob. A tangential force applied to kernels at the butt of the ear causes the pedicels to bend until they fail. If a kernel is not located at the end of the ear,

surrounding kernels prevent tangential motion and the corn cannot be shelled in this manner. However, high-speed photography has revealed that when an impact load is applied by the corn harvester near the middle of the ear, shelling is initiated. Thus, there must be forces other than bending which cause shelling. To date, no theory has been developed to explain the phenomena associated with shelling.

When corn was harvested by hand or mechanical picking, the ears were dried before the shelling. Since the advent of harvesting by grain combines equipped with corn heads, shelling takes place at high moisture levels. Mitchell (1956) reported that much of the field shelling is initiated at moisture levels from 25 to 30 percent, while Johnson _et_ _al_. (1963) encountered moisture levels from 20 to 40 percent. Because of these high moisture levels and the high velocity impact loading encountered at the combine cylinder, many kernels are cracked or broken. Consequently, the combine is being blamed for much of the quality loss which takes place between the field and the feeder or processor (Bailey, 1968).
A basic understanding of the shelling process will aid in the development of a new corn shelling process.

2. AN ANALYSIS OF PAST INVESTIGATIONS

2.1 Corn Harvesting

In the eighteenth and nineteenth centuries corn ears were manually picked, husked and tossed into wagons. The cost of hiring men for this tedious operation became an economic burden to the American farmer because of the competition of higher wage levels for non-farm employment. In spite of the difficulties associated with manual corn harvesting, the introduction of mechanical harvesting to general use was a difficult, slow process.

The first patent issued on a corn harvester was on October 8, 1850, to E. Quincy of Lacon, Illinois. The second corn harvester patent was issued just one week later to W. Watson of Chicago, Illinois. Both machines were listed as being able to strip heads from Indian corn. The first patent for a corn picker and husker was issued to L. Devore of Victor, Iowa on August 22, 1871, but the first picker and husker did not appear commercially until 1909 (Aspenwall, 1924; Seferovich, 1961). McKibben (1929) field shelled corn with a grain combine in 1928, at Iowa State College. He reported that prior attempts at field shelling had occurred in Kansas and Nebraska.

American farm equipment manufacturers have since developed reliable corn heads for grain combines, and field shelling with these machines has become a common method for corn harvesting. The farmers of Indiana, Illinois and Iowa used grain combines to harvest 45.1, 38.0 and 12.7 percent of their corn crops, respectively, during the Fall of 1964, and

58.8, 57.0 and 34.6 percent, respectively, during the Fall of 1968. During this same period of time the use of corn pickers dropped from 47.2 to 32.0 percent in Indiana, from 55.0 to 35.0 percent in Illinois, and from 81.2 to 56.6 percent in Iowa. The corn not accounted for in the above figures was harvested with a picker-sheller (Zimmerman, 1968; Anonymous, 1969).

2.2 Corn Quality

The Federal Grain Standards Act of 1916 established the first official federal grade standards. Prior to this legislation more than fifty hometown versions of grain grading were recognized. One such standard was described by Maywald (1968):

> Corn was tested by picking kernels willy-nilly from boxcars, and the kernels were put in a saucer of water. The ones that sank represented a "good" ear of corn, and the ones that floated were "bad" corn.

The current Federal Grade Standards (Table 2.1) are used as the basis for the market price in corn trading. Number Two corn is the standard trading grade for buying and selling corn and the price quotations are based on this grade. When a lot of corn is sold that does not grade Number Two, discounts or premiums which have been established by the purchaser are used to adjust the market price accordingly. Normally the size of the discounts and premiums that a particular buyer offers depends upon (1) the intended use of the corn, (2) the grade factors of other bins of corn available for use in blending and, (3) the prevailing market discounts and premiums (Uhrig, 1968). For example, a lot of Number Three corn which grades Number Two on all factors except moisture would probably be more valuable to a breakfast food manufacturer than would another lot of Number Three corn which graded Number Two on all factors except cracked corn and foreign material.

During this investigation mechanically damaged kernels have been considered to be those broken into several pieces, those cracked but remaining intact, and those with tip caps removed.

TABLE 2.1 GRADE REQUIREMENTS FOR YELLOW CORN, WHITE CORN AND MIXED CORN.*

Grade No.	Minimum test weight per bushel	Maximum limits			
			Cracked corn and foreign material	Damaged kernels	
		Moisture		Total	Heat-damaged
	pounds	- - - - - - - - - -	percentage	- - - - - - - - - -	
1	56	14.0	2	3	0.1
2	54	15.5	3	5	0.2
3	52	17.5	4	7	0.5
4	49	20.0	5	10	1.0
5	46	23.0	7	15	3.0
Sample Grade	Sample grade shall be corn that (a) does not meet the requirements for any of the grades from No. 1 to No. 5, inclusive, (b) contains stones, (c) is musty, sour or heating, (d) has any commercially objectionable foreign odor, or (e) is otherwise of distinctly low quality.				

* From Uhrig (1968)

The first economic losses associated with mechanical damage are the so-called invisible losses, consisting of corn chips and meal that pass out the rear of the combine and the corn tips left in the cobs. If these particles were to remain attached to the kernels, the producer would realize higher returns due to the increased weight of the corn being sold. Byg and Hall (1968) reported these invisible losses to range from an average of 0.8 percent at 20 percent moisture to an average of 2.9 percent at 35 percent moisture.

In his early attempt at field shelling McKibben (1929) recorded mechanical damage of kernels as not excessive with the kernel moisture content at 18.4 percent. However, many researchers have since reported the mechanical damage of kernels to be excessive during field shelling with grain combines. When temperatures are above 55 degrees Fahrenheit and the moisture content is above 13.5 percent at harvest time, shelled corn provides ideal ambient conditions for the growth of molds and fungi (Bailey, 1968). Kernels which lose their tip caps during harvest have exposed germs. According to Bailey (1968) the germ is the first portion of the kernel to be discolored and destroyed by the growth of microflora. Mechanically damaged kernels provide a ready source of food for microflora. Uhrig (1968) states the problem well:

> Corn damaged in the field-shelling process provides ideal growth conditions for molds. Molds produce chemicals (toxins), known as mycotoxins, that are toxic to livestock. One mold scientifically termed aspergillus flavus [sic], produces a compound known as aflatoxin. Aflatoxin seems very dangerous because a small amount can cause pathological changes in poultry, cattle and swine months after aflatoxin feeding has ceased. Meanwhile, the animals may appear in poor health without specific symptoms of a particular disease. The Pure Food and Drug Administration personnel say there is no way to restore moldy corn and, if seized, the corn will not be allowed to be mixed in other grain either for human or animal consumption. This could cause serious losses or even bankrupt grain shippers.

Since mechanically damaged corn provides a source of food for microflora, high moisture corn with high damage will deteriorate more rapidly than high moisture corn with low damage. As microflora grow, foodstuffs are oxidized and carbon dioxide is produced. Saul and Steele (1966) measured carbon dioxide produced by corn to estimate the loss of dry matter, and hence, the deterioration of the corn. At 65 degrees Fahrenheit a sample of corn at 2.0 percent damage and 28 percent moisture required 600 hours for a one percent loss of dry matter. Another sample which had 28.7 percent mechanical damage had a one percent dry matter loss in only 200 hours at the same temperature and moisture level.

Because of its higher rate of deterioration, corn with a high level of mechanical damage needs to be dried more rapidly than corn with a low level of mechanical damage. If the corn is not dried rapidly enough, the grower will receive a lower market price due to the presence of mold. On the other hand if the corn is dried too rapidly, the grower will receive a lower market price due to the presence of heated kernels. In order to properly dry highly damaged corn, equipment with a large capacity is needed. Additional capital outlay for increased drier capacity burdens the grower economically with higher operating expenses (Saul and Steele, 1966). If the crop is dried commercially, these increased costs would be passed on to the grower in the form of a lower market price.

During the shelling process some kernels are cracked internally or externally, but remain as whole kernels. These kernels may be fractured into several pieces during drying or subsequent handling operations. When corn is graded, broken kernels are considered the same as foreign material and their presence lowers the market price. Bailey (1968)

reported that broken kernels cost the American farmer approximately three cents per bushel on all the corn he sells.

These broken kernels cause an additional storage problem as described by Bailey (1968):

> The increase in broken kernels is aggravated by a phenomenon called by the trade a "spoutline". Whenever a stream of particles of varying sizes is poured onto a pile, the smaller particles tend to stay in the center and the larger particles roll or flow down the slope. In corn, about one-third of the mass is voids between the kernels. In the pile, the fines tend to fill these voids and a little more so that the concentration of fines will go to about 35 percent and form a verticle column in the center of the pile.
>
> In this area there is no circulation of air and so any heat developing from mold activity on the high concentration of broken kernels cannot escape but accumulate, causing progressive heating and damage.
>
> Another consequence of these "spoutlines" is the difficulty of obtaining a representative lot of corn, or of making uniform deliveries.

That broken and cracked kernels are not desirable for corn to be processed is apparent; however, it may not be immediately obvious why the presence of broken and cracked kernels in corn to be used for livestock feed is undesirable. It appears that the feeding value of corn will decrease more rapidly during storage when large amounts of mechanically damaged kernels are present. Since the seed coat helps to protect the interior portion of the kernel from the surrounding environment, kernels with fractured seed coats should be more susceptible to any biological activity which would lower their nutrient content. If this is the case, even the grower who feeds all his corn to livestock is affected by mechanical damage.

Mechanical damage lowers the profits of corn growers by invisible losses, accelerated deterioration, increased drying costs and lowered market price.

Several methods have been used in past studies to quantify mechanical damage (Table 2.2). The carbon dioxide, temperature rise and mold growth techniques were all judged to be too time consuming for the scope of this study. In addition to being time consuming, the water absorption and light absorption techniques also have notable system errors. When the germination technique is used, it is extremely difficult to determine whether the viability reduction is due to mechanical damage or some other form such as disease or insect damage.

When corn is graded to determine market price, corn particles which pass through a sieve with round holes twelve sixty-fourths of an inch in diameter are considered to be foreign material (Uhrig, 1968). However, this method does not detect larger partial kernels or cracked whole kernels. These undetected forms of damage probably cause losses during subsequent handling operations. After careful consideration of the various damage measurement techniques, it was decided that the visual separation technique was most appropriate for this study. The kernels were examined individually and separated into three categories:

1. No visible damage.
2. Broken kernels or visible cracks.
3. Tip caps removed.

The sum of categories two and three gives an estimate of total mechanical damage. However, this may be an optimistic estimate since some internal cracking may not be visible.

TABLE 2.2 DAMAGE MEASUREMENT TECHNIQUES*

Test Description	Functional Principle	Change Measured	Test Mode	Principal Advantage	Principal Limitations
Carbon Dioxide Evolution in a Sealed System	Damaged Kernels Support More Biological Activity	Biological	Bulk	Measures Actual Deterioration	Very Dependent on Moisture, Temperature and Oxygen Supply
Temperature Rise in an Insulated Container Due to Heat Evolution	Damaged Kernels Support More Biological Activity	Biological	Bulk	Measures Actual Deterioration	Very Dependent on Moisture, Temperature and Oxygen Supply
Water Absorption by Damaged Kernels	Damaged Seed Coat is More Permeable to Water	Physical	Bulk	No Expensive Equipment	Differences Small Compared to System Errors
Light Absorption By Water Extract from Damaged Kernels	Damaged Seed Coat is More Permeable to Nutrients	Physical	Bulk	Preferential to Germ Damage	Differences Small Compared to System Errors
Fines Created by Standard Handling Treatment	Quality Loss is Proportional to Structural Weakness	Physical	Bulk	Physical Breakage is Most Universal Damage Problem	Moisture Content is Critical

TABLE 2.2 DAMAGE MEASUREMENT TECHNIQUES* (continued)

Test Description	Functional Principle	Change Measured	Test Mode	Principal Advantage	Principal Limitations
Mechanical Separation with Standard Sieve	Particles of Broken Kernels Pass Through Sieve	Physical	Bulk	Rapid	Does Not Measure Total Damage
Visual Separation of Damaged Kernels	Important Damage is Visible	Physical	Discrete	Can Find Even One Bad Kernel	Human Judgment and Fatigue
Germination Loss Due to Physical Damage	Quality is Proportional to Viability	Biological	Discrete	Directly Measures Germ Damage	Time Consuming
Mold Growth in a Controlled Atmosphere	Damaged Kernels Support More Biological Activity	Biological	Discrete	Measures Actual Deterioration	Very Dependent on Moisture, Temperature and Time

* From Agness (1968).

2.3 Shelling Theory

When a corn ear passes between a cylinder and concave bars in a combine harvester, it is subjected to a combination of compressive and tangential forces. In some unknown fashion this combination of forces initiates the shelling process. Once some kernels have been removed, the others probably are removed by tangential forces, which cause the pedicels to fail in bending, thus freeing the kernels from the cob.

The process through which shelling is initiated by a compressive force has not been adequately explained. Johnson et al. (1969) investigated the process of kernel removal by hand-shelling four rows of kernels on opposite sides of corn ears, and subjecting the samples to quasistatic compressive loading. When the load was applied to the exposed cob, no shelling occurred; but loading the unshelled portion of the ear caused shelling. Shelling was also successfully initiated by applying low-velocity impact loading to whole ears.

Halyk et al. (1969) investigated the mechanics of radial compressive shelling under quasistatic and low-velocity impact loading. They reported the initiation of shelling in a region near the point where a radial compressive load was applied to an ear. Under quasistatic loading no shelling was achieved above a kernel moisture content of 15.3 percent w.b. Using a vertical drop-weight tester shelling was achieved with kernel moisture levels of 28 percent w.b. or lower. They developed a model representing the shelling process after reducing the mechanics to the

plane stress case by assuming that:

1. The kernels and cob are composed of a rigid material;
2. The kernel shape closely approximates that of an ordinary truncated wedge; and
3. Pedicel behavior can be approximated by the reaction of an appropriate viscoelastic connector.

It was shown that a kernel displaced radially inward acts as a wedge and causes displacement of the surrounding kernels. As a result of this displacement the pedicel of one of the surrounding kernels is fractured, thereby initiating shelling.

Area under the force-displacement curves from quasistatic loading was used by Halyk et al. (1969) to predict the minumum energy required to induce shelling. This procedure proved successful when the kernel moisture level was below 15.3 percent. Their work was an important step toward the understanding of corn shelling. However, testing needed to be done using impact velocities and kernel moisture levels similar to those encountered during field shelling. Hence, this theory was useful as a foundation for the development of a corn shelling theory suitable for high impact velocities and high moisture levels.

3. OBJECTIVES

When man does not understand a phenomenon, there is sufficient reason for study. However, when a phenomenon has the economic importance of corn shelling, there is even more justification for study. Besides adding to man's understanding, the development of a corn shelling theory could also be helpful to engineers in the development of more efficient corn harvesters. Kaminski (1968) pointed out the need for such information. Accordingly, the objectives of this study were to:

1. Investigate the initiation of shelling of high moisture corn by radial compressive impact loading.
2. Determine the magnitudes of the impact forces and energies applied to an ear during shelling.
3. Study the effects of impact loading on corn quality.

4. APPARATUS AND PROCEDURE

4.1 Description of Apparatus

The impact testing machine employed in this study utilizes a rotary motion similar to that of a pendulum (Burkhardt, 1969). However, mechanical energy is used in lieu of gravity for accelerating the impacting arm. This rotary impact testing machine consists of two major units (Figure 4.1). The primary unit has high rotational inertia and the secondary unit contains an impacting arm with low rotational inertia. When the primary unit has achieved the selected rotational velocity, the two units are coupled by an electric clutch and the impacting arm is forced to rotate. After approximately 330 degrees of rotation, the arm strikes a specimen. The arm is then decelerated by an electric brake and stopped approximately one revolution after impact. The clutch and brake are automatically controlled by an electronic circuit.

Impact force is measured by a quartz load cell mounted between the impacting face and the arm (Figure 4.2). The signal from the load cell is conditioned by a charge amplifier and recorded on a storage oscilloscope. An electronic timer measures the time required for the arm to travel a known distance. The impact velocity can be calculated from this information.

The impact area is surrounded by a collection box to facilitate the retrieval of the specimen after each test. The interior of the box is lined with foam rubber to prevent damage to particles hitting the box.

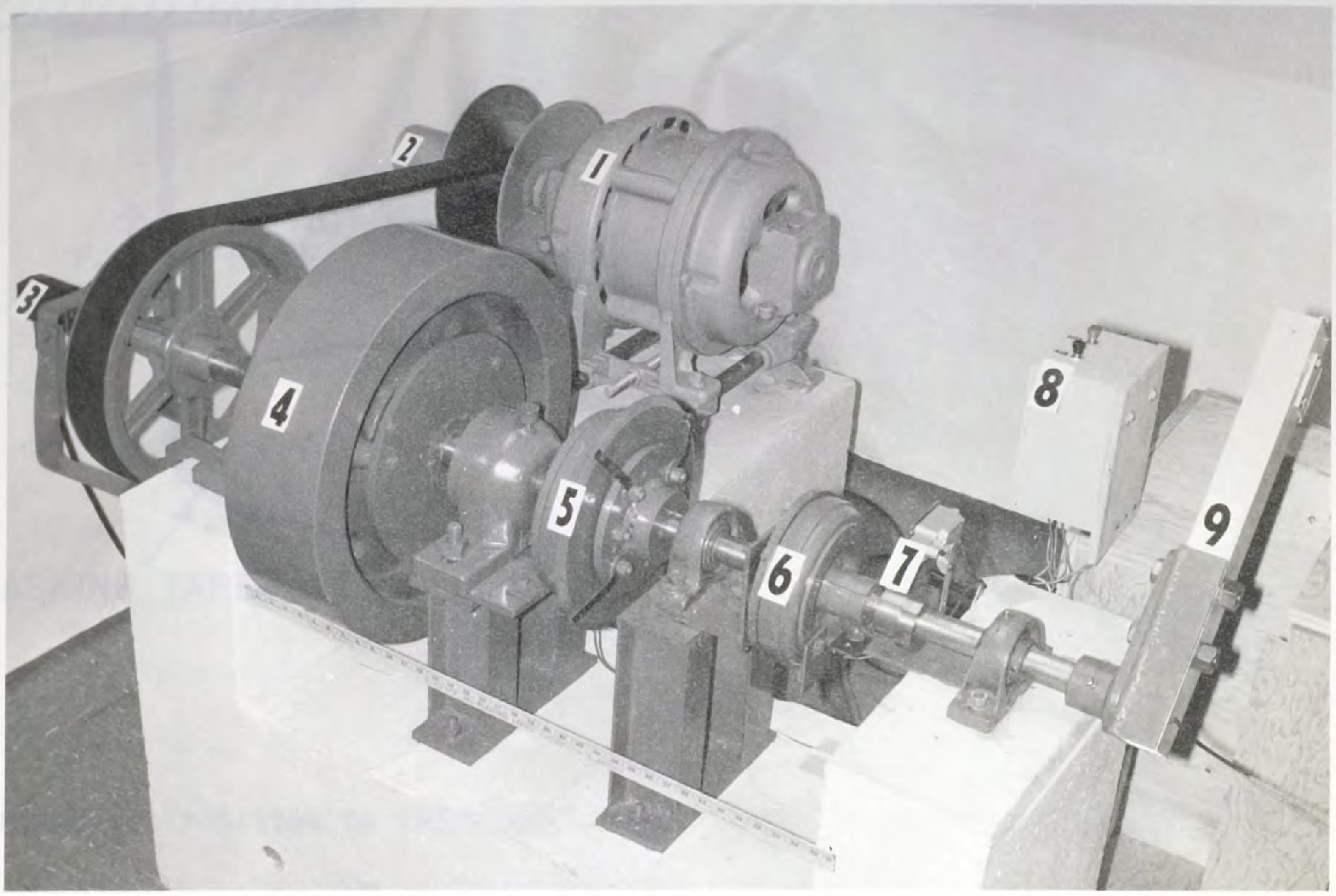


FIGURE 4.1 IMPACT TESTING MACHINE SHOWING THE FOLLOWING COMPONENTS: (PHOTO 68-71.)*

1. ELECTRIC MOTOR
2. VARIABLE SPEED PULLEY
3. TACHOMETER GENERATOR
4. FLYWHEEL
5. ELECTRIC CLUTCH
6. ELECTRIC BRAKE
7. CAM AND MICROSWITCH
8. BRAKE CONTROL SWITCH
9. IMPACT ARM

* Negative filed in Agricultural Engineering Department, Michigan State University.

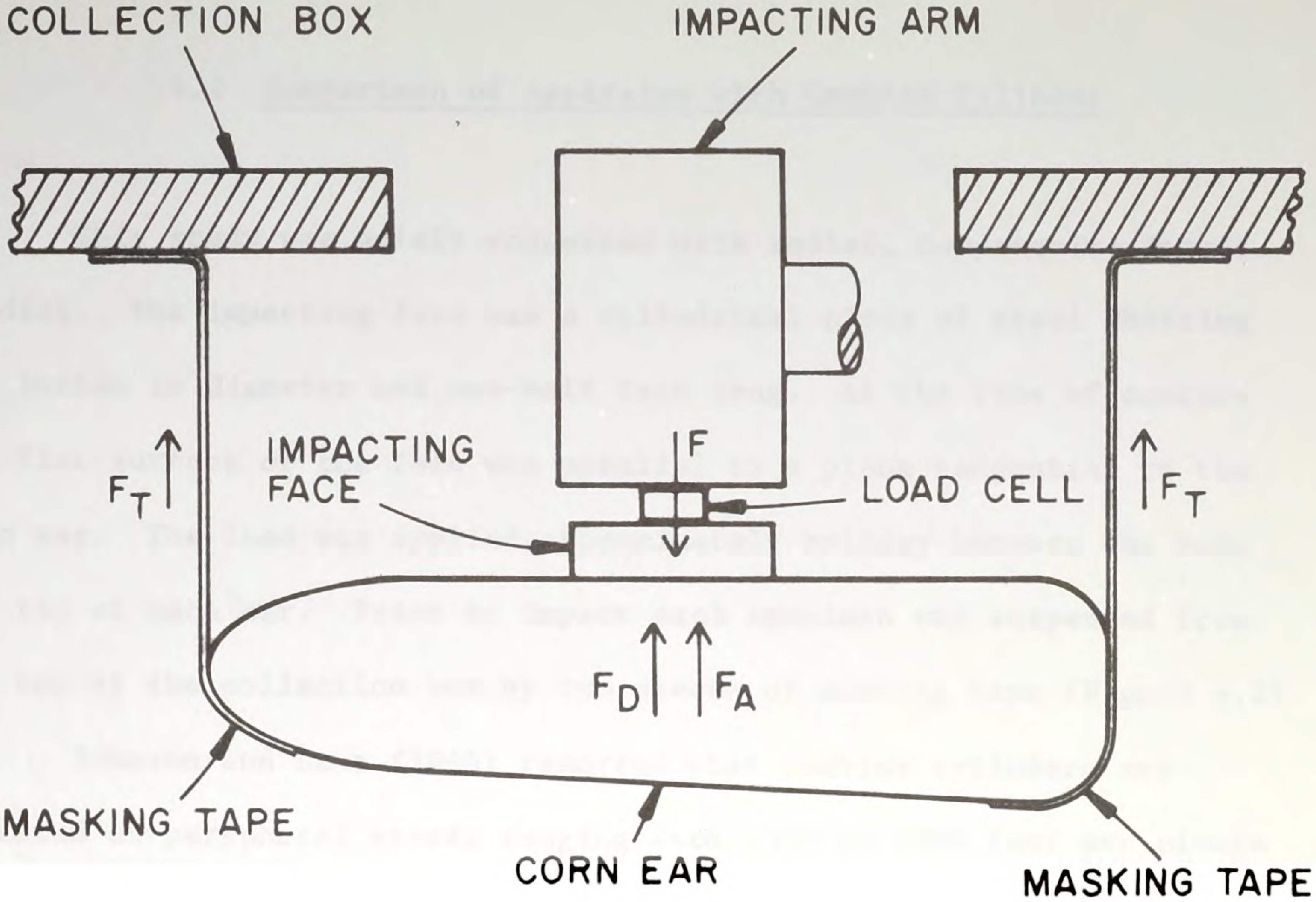


FIGURE 4.2 POSITION OF IMPACTER AND SPECIMEN AT TIME OF INITIAL CONTACT

F = FORCE MEASURED BY LOAD CELL

F_T = FORCE IN TAPE

F_D = DEFORMATION FORCE

F_A = INERTIAL FORCE

4.2 Comparison of Apparatus with Combine Cylinder

This study was solely concerned with radial, compressive impact loading. The impacting face was a cylindrical piece of steel shafting two inches in diameter and one-half inch long. At the time of contact the flat surface of the face was parallel to a plane tangential to the corn ear. The load was applied approximately halfway between the butt and tip of each ear. Prior to impact each specimen was suspended from the top of the collection box by two pieces of masking tape (Figure 4.2).

Johnson and Lamp (1966) reported that combine cylinders are operated at peripheral speeds ranging from 2500 to 4000 feet per minute during corn harvesting. In order to cover the range of cylinder peripheral velocities, tests were run at impact velocities of 2500, 3000, 3500 and 4000 feet per minute.

Torsional pendulum tests were performed at the Massey-Ferguson Harvesting Systems Laboratory in Toronto, Canada using a rasp bar cylinder of 22 inches outside diameter. From these tests it was estimated that the cylinder and shaft assembly have a moment of inertia of 36 lb. in. sec^2 (Cooper, 1969). The arm and flywheel of the impact apparatus used in this study have a combined moment of inertia of 60 lb. in. sec^2.

When a combine is used for field shelling at a nearly constant feed rate, the cylinder cannot have a velocity loss each time an individual corn ear is impacted; otherwise, the cylinder would decelerate to an inefficient velocity or a complete stop. Since the rotational inertia of the apparatus used in this study is greater than that of a

typical combine cylinder, there was no measurable velocity loss during impact of a specimen.

The impact forces measured during this study can be represented as follows (Figure 4.2):

$$F = F_A + F_D + 2F_T$$

where:

F = force measured by load cell

F_A = inertial force

F_D = deformation force

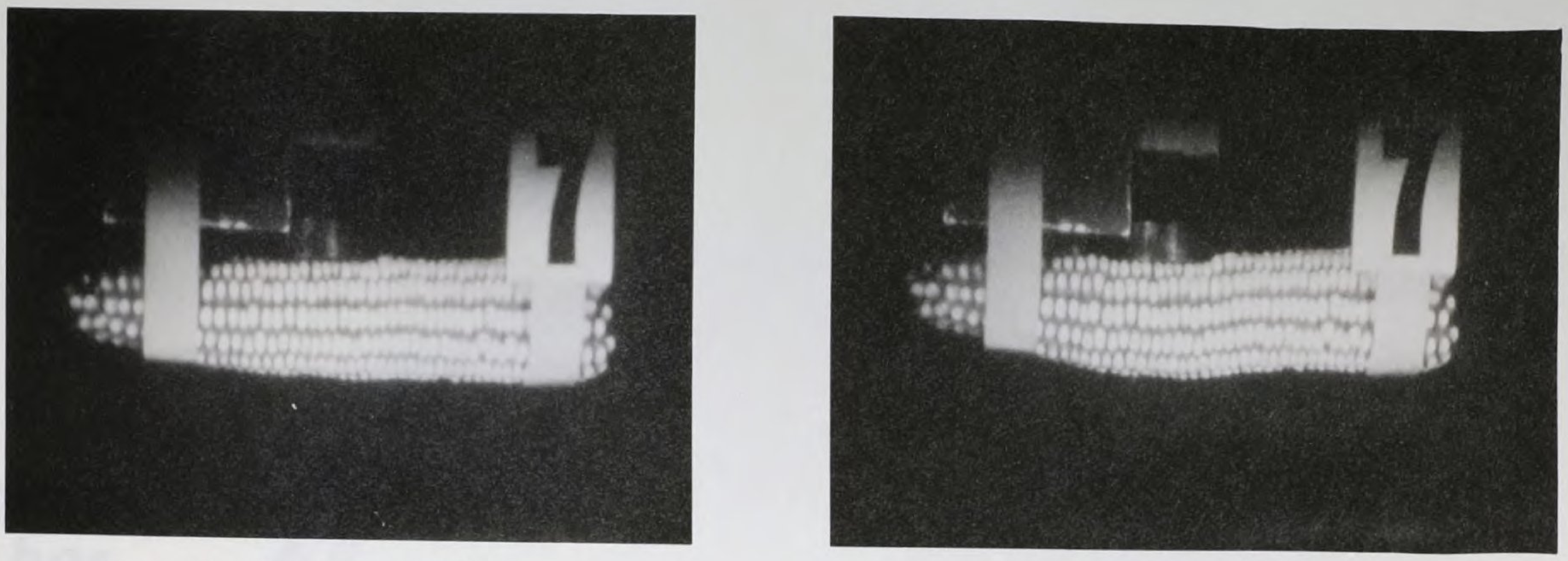
F_T = force in tape

Tensile tests were run using an Instron Model TM testing machine. It was found that for a loading rate of one centimeter per minute (.0328 feet per minute) the masking tape could withstand an average force of approximately 22 pounds before breaking. When the loading rate was increased to 100 centimeters per minute (3.28 feet per minute), the masking tape fractured when the force reached only 2.5 pounds. The tape apparently became more brittle with increased loading rates. During the tests the tape did not adhere well to the moist corn ears and usually slipped free from the specimen without breaking. Since all of the impact forces measured were in excess of 400 pounds and the combined forces in the supporting tape were less than five pounds, the tape forces were considered insignificant.

Examination of the high-speed movies provided further evidence for disregarding the support forces. A series of frames (Figure 4.3) revealed that upon impact the centerline of the ends of the corn ear remained horizontal while the middle of the ear became curved. The curvature of the ear progressed outward until the total ear was deformed. This indicated the force required to accelerate the specimen was large compared to the support force in the tapes. If the support force were large, the whole ear would have curved instantaneously.

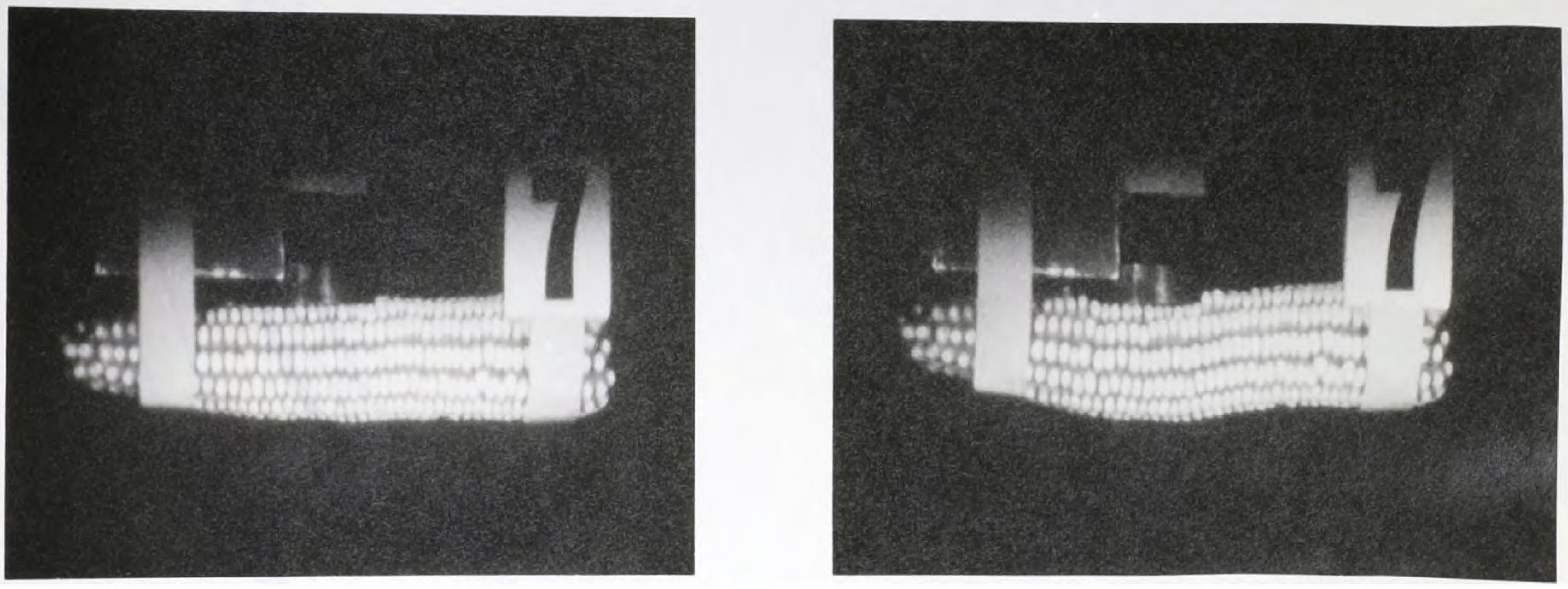
A cross-sectional view of the end of the cylinder-concave area of a grain combine is shown in Figure 4.4. Normally rasp bar cylinders are used for field shelling. Filler plates are added to force passage of the ears between the cylinder and concaves. Otherwise, the ears could pass between the cylinder bars with imcomplete shelling resulting. The center axis of the ear is shown parallel to the axis of rotation of the cylinder. At least one manufacturer currently usus a feeder elevator which introduces the ears oriented in this manner (New Holland, 1969).

The cylinder bar approaches the ear with peripheral velocity, V, and upon impact a force, F_1, is applied by the cylinder bar (Figure 4.5). The cylinder force is opposed by: (1) the concave force, F_2; (2) the deformation force, F_D; and (3) the inertial force, F_A. In this case F_A includes the force required to cause rotational acceleration of the ear as well as the linear acceleration. The complex nature of the loading geometry prevents the writing of a simple equation relating the various forces.



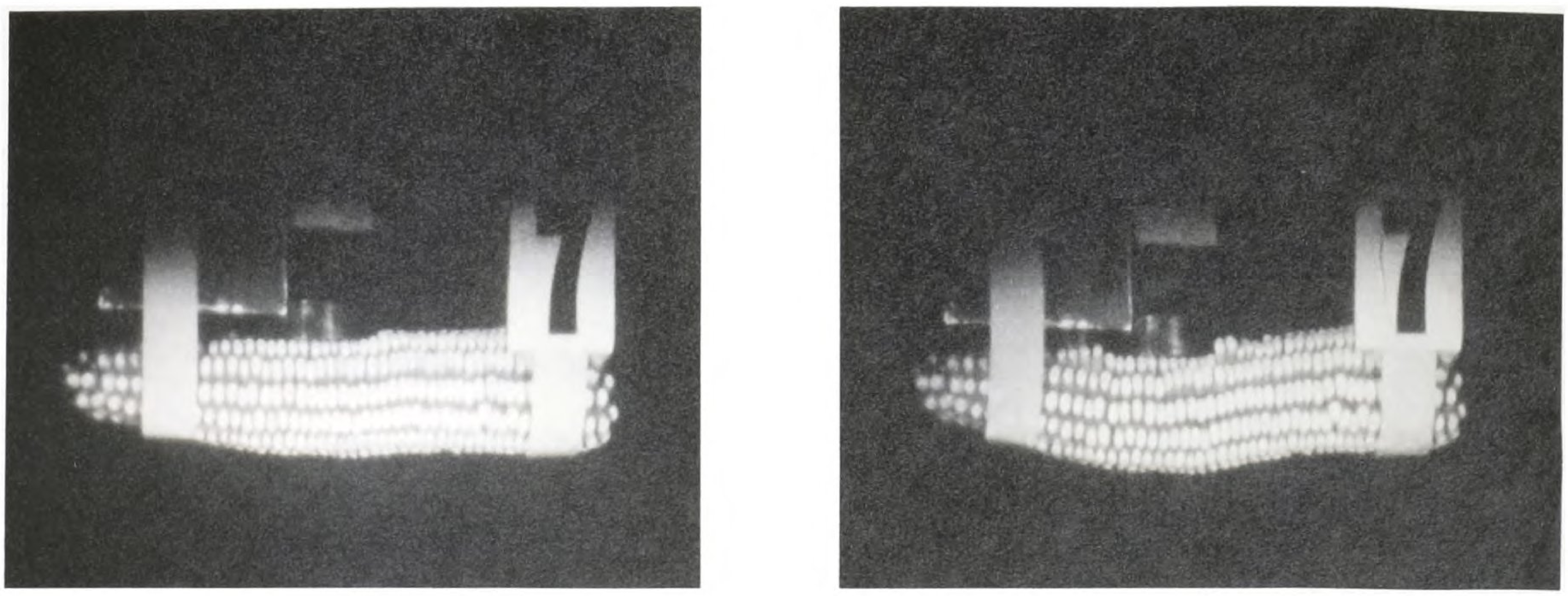
T = 0 microseconds

T = 438 microseconds



T = 146 microseconds

T = 584 microseconds



T = 292 microseconds

T = 730 microseconds

FIGURE 4.3 CORN EAR WEIGHING 0.461 POUND BEING IMPACTED AT 2500 FEET PER MINUTE. KERNEL MOISTURE CONTENT IS 19.6 PERCENT AND COB MOISTURE CONTENT IS 22.4 PERCENT.

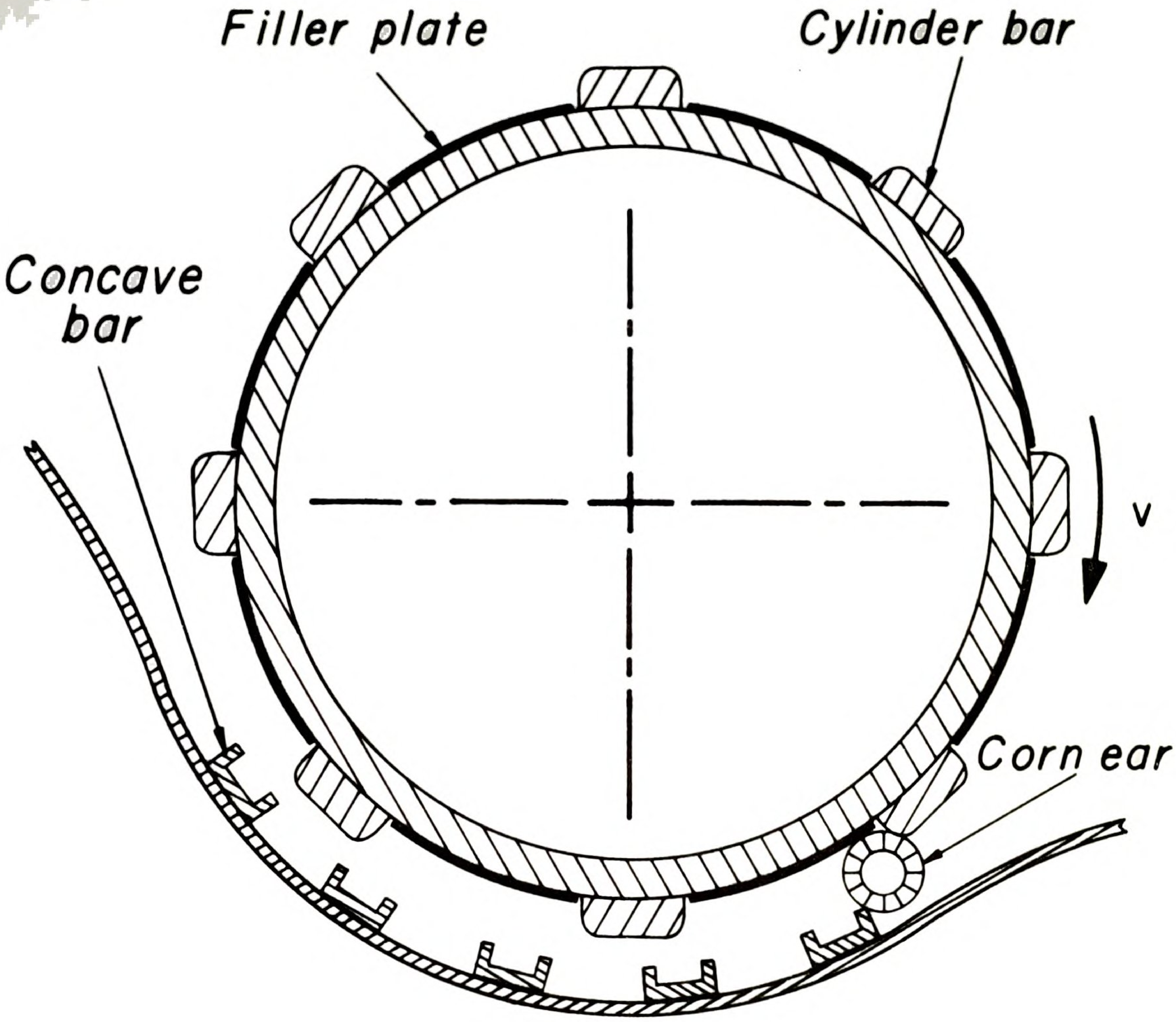


FIGURE 4.4 END VIEW OF CYLINDER - CONCAVE AREA OF A GRAIN COMBINE. THE RASP BAR CYLINDER IS EQUIPPED WITH FILLER PLATES AND IS APPROACHING THE CORN EAR WITH A PERIPHERAL VELOCITY, V.

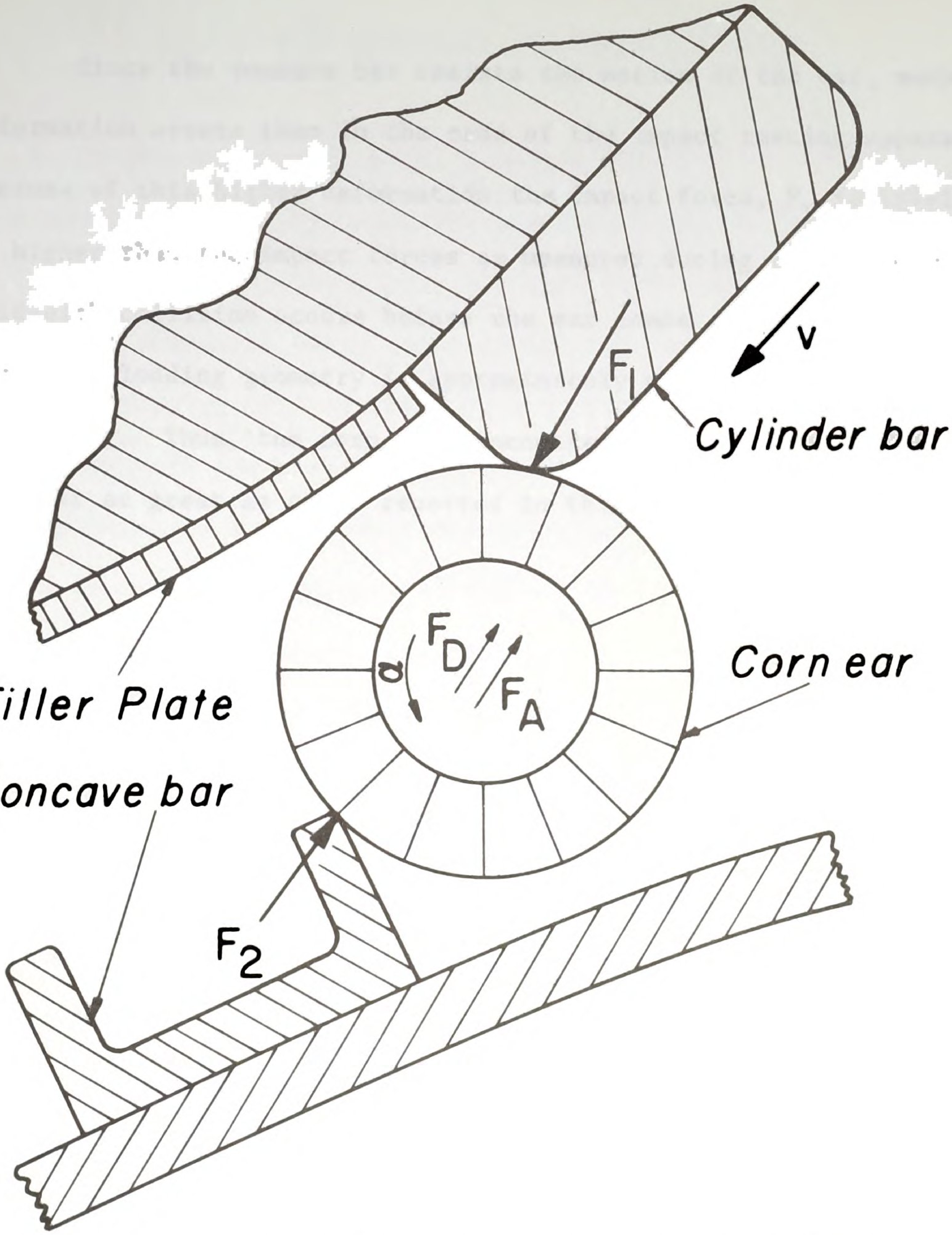


FIGURE 4.5 CORN EAR IMPACTED BY CYLINDER BAR.

V = PERIPHERAL VELOCITY OF CYLINDER

α = ANGULAR ACCELERATION OF EAR

F_1 = CYLINDER FORCE

F_2 = CONCAVE FORCE

F_D = DEFORMATION FORCE

F_A = INERTIAL FORCE

Since the concave bar resists the motion of the ear, much more deformation occurs than in the case of the impact testing apparatus. Because of this higher deformation the impact force, F_1 is likely to be higher than the impact forces as measured during this study. If a "mid-air" collision occurs before the ear comes in contact with the concaves, the loading geometry is approximately the same as that used during this study. Thus, the corn ears encounter forces during field shelling at least as great as those reported in this study.

4.3 Procedure for Quality Studies

Three varieties of corn, Michigan 500-2x (105 day maturity), Michigan 250-2X (85 day maturity) and A509 X MA1334 (83 day maturity), were planted May 24, 1968, on a Michigan State University farm. Flooding because of unusually heavy rains during the month of June ruined approximately eighty percent of the crop and lowered the quality of the remaining twenty percent. As a result of this water damage the ears of the A509 X MA1334 variety were too small and only the other two varieties were used.

In order to simulate field shelling in the laboratory, it was important for the testing equipment to apply impact loads similar to those applied by the combine cylinder. It was also important for the mechanical properties of the samples to be similar to those of corn ears being field shelled. In a real harvesting situation the ears are delivered to the cylinder for shelling only a few seconds after they are collected. The testing equipment used for this study were stationary and could not be moved to the field. Consequently, it was necessary to gather the samples in the field and haul them to the laboratory, resulting in a short time delay between collection and testing.

After a corn ear is detached from its stalk, it is probable that some biological activity takes place. Thus, precautions had to be taken to minimize the biological changes of the samples during the delay between the collection and testing to prevent changes in the mechanical properties of the samples.

One biological change which seriously affects mechanical properties of corn is a change of moisture content. In order to prevent moisture loss of the samples before testing, each ear was manually removed from the stalk with its husk in tact and placed in a plastic bag. The ambient temperature in the corn field was as much as 60 degrees Fahrenheit lower than the laboratory temperature. It was felt that a large temperature rise caused by indoor storage might have accelerated any biological changes initiated by severing the ear from the plant. Consequently, the samples were stored in a shaded area outside the laboratory where the ambient conditions were similar to those found in the field.

Preliminary experiments were conducted on October 8, 1968, to try out the testing procedure. Full scale testing was initiated on October 15. The impact velocities, varieties and testing dates utilized in this study are listed in Table 4.1.

A full scale test consisted of impacting five ears from each of the two varieties at each of four impact velocities for a total of forty ears impacted per test. From the statistical standpoint it would have been more desirable to have used a random selection of the variety velocity treatment combination. At this time, however, the testing equipment was newly developed and its operation procedure was not well known. The changing from one impact velocity to another was rather time consuming at first due to lack of experience of the operators. In an effort to reduce the delay time between collection and testing it was decided to proceed through the impact velocities from slow to fast or fast to slow, thus reducing the time spent changing from one velocity to another. Five ears from each variety were tested at each velocity setting.

TABLE 4.1 SUMMARY OF TESTING PROCEDURE

Testing Date	Impact velocity (feet per minute)	Number of ears tested	Variety
October 8	4000	5	Mich. 250
	4000	5	A509 X MA1334
	4000	5	Mich. 500
October 15	2500	5	Mich. 250
	3000	5	Mich. 250
	3500	5	Mich. 250
	4000	5	Mich. 250
	2500	5	Mich. 500
	3000	5	Mich. 500
	3500	5	Mich. 500
	4000	5	Mich. 500
October 22	2500	5	Mich. 250
	3000	5	Mich. 250
	3500	5	Mich. 250
	4000	5	Mich. 250
	2500	5	Mich. 500
	3000	5	Mich. 500
	3500	5	Mich. 500
	4000	5	Mich. 500
October 29	2500	5	Mich. 250
	3000	5	Mich. 250
	3500	5	Mich. 250
	4000	5	Mich. 250
	2500	5	Mich. 500
	3000	5	Mich. 500
	3500	5	Mich. 500
	4000	5	Mich. 500
November 5	2500	5	Mich. 250
	3000	5	Mich. 250
	3500	5	Mich. 250
	4000	5	Mich. 250

TABLE 4.1 SUMMARY OF TESTING PROCEDURE (continued)

Testing Date	Impact velocity (feet per minute)	Number of ears tested	Variety
	2500	5	Mich. 500
	3000	5	Mich. 500
	3500	5	Mich. 500
	4000	5	Mich. 500
November 12	2500	5	Mich. 250
	3000	5	Mich. 250
	3500	5	Mich. 250
	4000	5	Mich. 250
	2500	5	Mich. 500
	3000	5	Mich. 500
	3500	5	Mich. 500
	4000	5	Mich. 500
November 26	2500	5	Mich. 250
	3000	5	Mich. 250
	3500	5	Mich. 250
	4000	5	Mich. 250
	2500	5	Mich. 500
	3000	5	Mich. 500
	3500	5	Mich. 500
	4000	5	Mich. 500
December 5	2500	5	Mich. 250
	3500	5	Mich. 250
	2500	5	Mich. 500
	3500	5	Mich. 500

After an ear was randomly selected, its husk was manually removed and its weight was recorded. It was then placed in the collection box and held in position by a small piece of masking tape at each end (Figure 4.2). At the time of contact the impacting arm was horizontal and the ear was perpendicular to the arm so the load was applied normal to the middle of the ear.

The sample was retrieved from the collection box after impact and the impact force was recorded. The kernels which had been removed were weighed and the remaining kernels were manually shelled and also weighed. A portion of the manually shelled kernels from the middle of the ear and a portion of the cob were oven-dried at 212 degrees Fahrenheit for 72 hours to determine their moisture content. All moisture contents reported were determined on the wet basis. When there were insufficient kernels left on the middle of the cob for a moisture sample, equal amounts were taken from each end of the ear to estimate the moisture level at the middle. Johnson and Lamp (1966) reported that kernel moisture content is lowest at the ear tip and highest at the butt. Because of this variability the middle moisture level would have been represented less accurately if a moisture sample had been taken from only one end.

The kernels removed by the impact load were inspected and weights were taken of those which had been broken or cracked and those which had lost the tip cap (Figure 4.6).

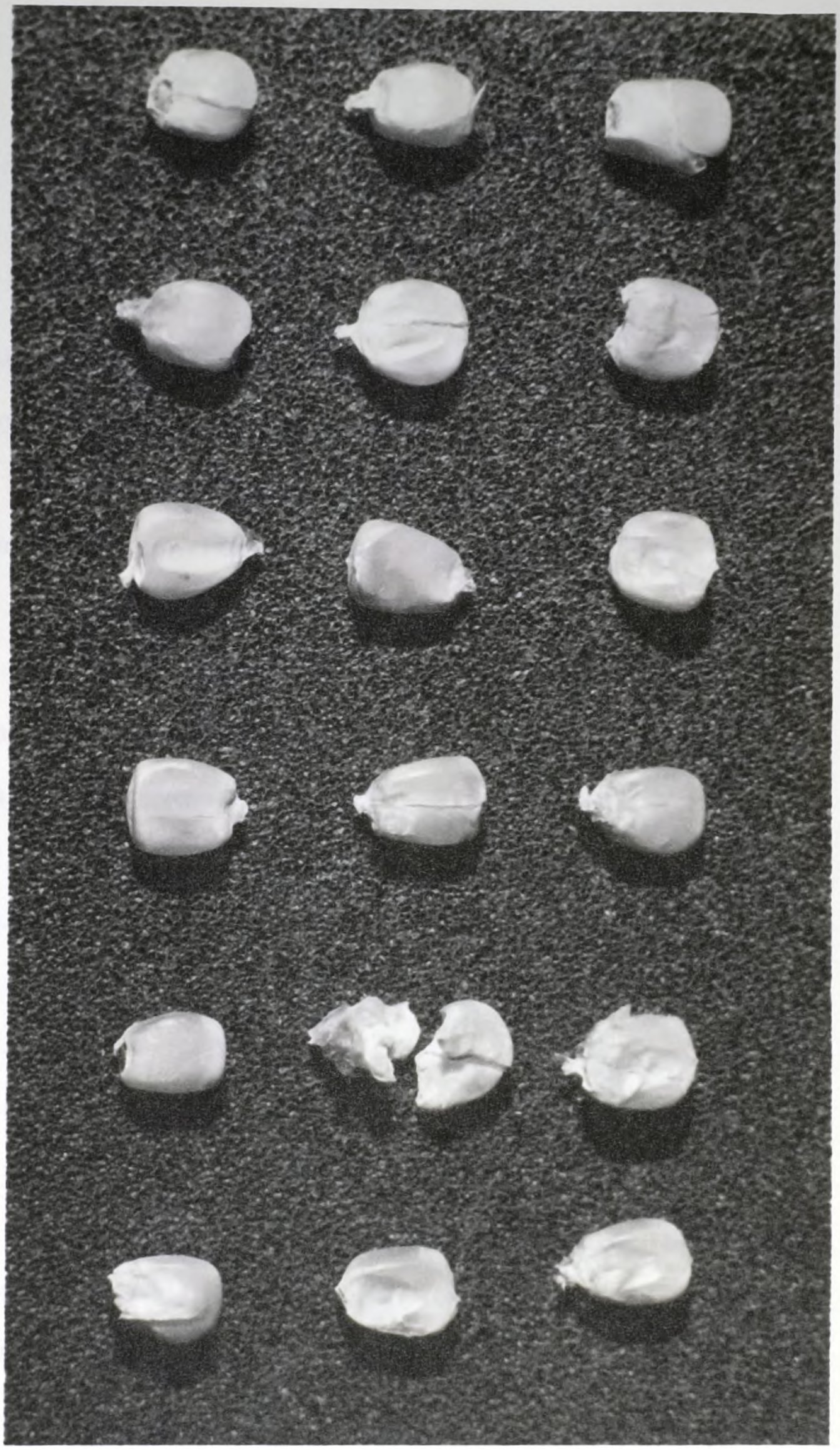


FIGURE 4.6 TYPICAL FORMS OF MECHANICAL DAMAGE FOUND IN THIS STUDY. (PHOTO 68-103)

5. DISCUSSION OF RESULTS

5.1 General Observations

After impact many of the corn ears tested at 2500 feet per minute and 3000 feet per minute exhibited a common pattern of kernel removal (Figure 5.1). Typically a group of kernels three rows wide which were in contact with the impacting face during loading remained attached to the cob. Many of the surrounding kernels were detached. Larger ears also exhibited this pattern of kernel removal, but frequently these cobs were fractured in the middle. As a result, the majority of the larger ears exhibiting this pattern were broken in half during impact.

The small (0.39 pound) ear shown in Figure 5.1 is of the Michigan 250 variety. The kernel moisture content was 21 percent and the cob moisture was 40 percent. An inspection of the exposed cob area following loading at an impact velocity of 3000 feet per minute, revealed that the caps of many of the shelled kernels remained attached to the cob. One kernel at each end of the impact area suffered a broken seed coat.

Most of the Michigan 500 ears and a few of the Michigan 250 ears impacted at 3500 feet per minute and 4000 feet per minute were broken into many pieces. The specimen of Michigan 500 shown in Figure 5.2 was loaded with an impact velocity of 4000 feet per minute; many tip caps remained attached to the cob. The kernel moisture content was 26 percent and cob moisture content 47 percent. The portion of ear in the center of Figure 5.2 has some kernels which were forced into the cob during impact.

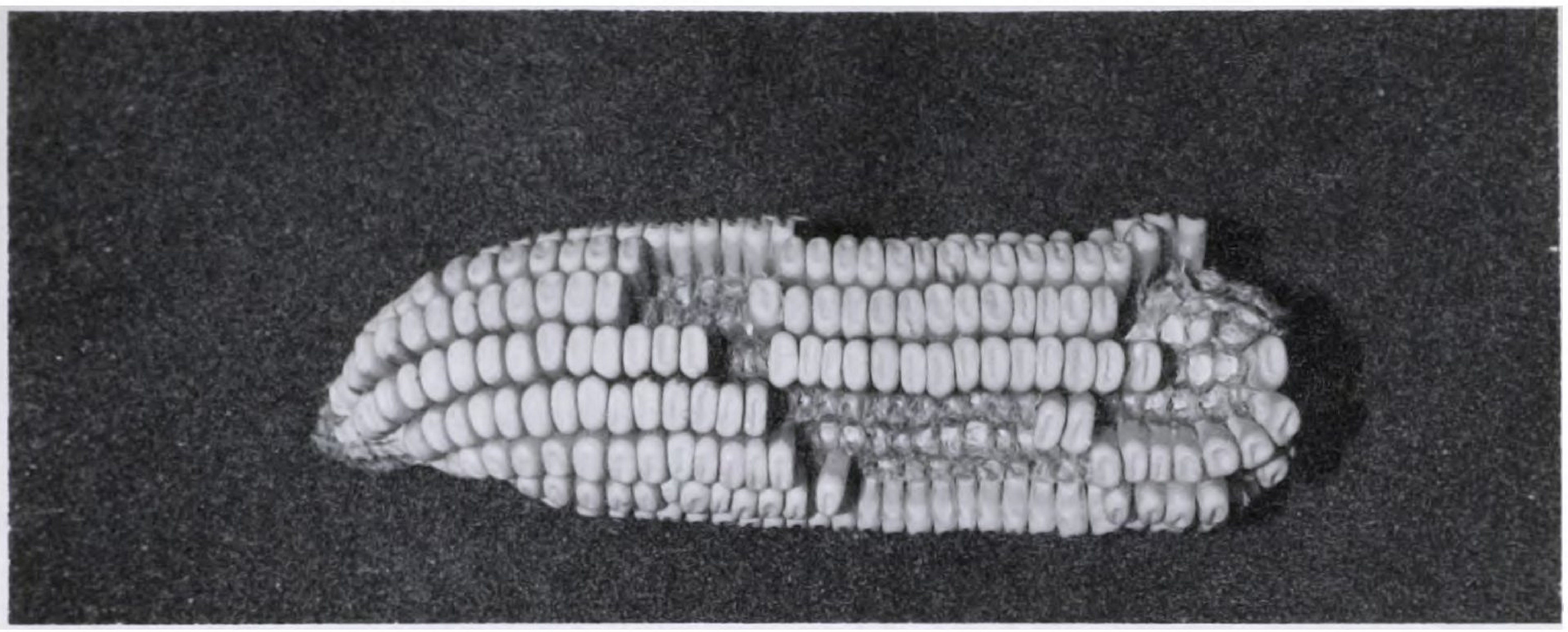


FIGURE 5.1 TYPICAL SHELLING PATTERN FROM LOW-VELOCITY IMPACT AT LOW AND MEDIUM MOISTURE LEVELS.

(PHOTO 68-101)

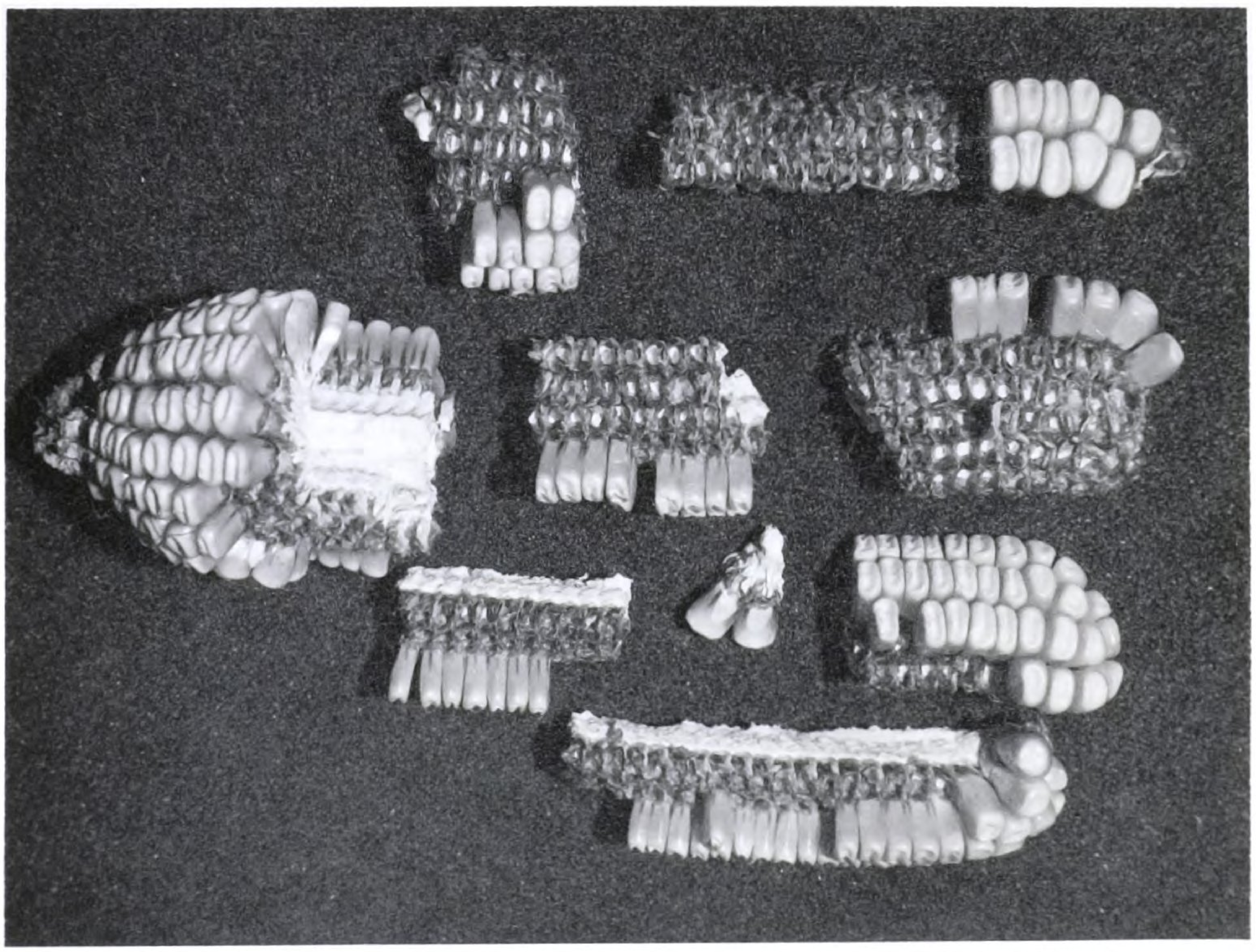


FIGURE 5.2 TYPICAL SHELLING PATTERN FROM HIGH-VELOCITY IMPACT AT HIGH MOISTURE LEVELS.

(PHOTO 68-102)

The kernels shown in Figure 5.3 were shelled from an ear of the Michigan 250 variety by a single impact at 4000 feet per minute. The pile of kernels in the foreground at the right were cracked and broken. The tip caps of the two kernels in the foreground at the left were removed. No visible damage was suffered by the kernels in the large pile. At the time of shelling kernel moisture content was 20 percent.

The corn tested at higher moisture levels was more severely damaged. For example, an ear of the Michigan 500 variety impacted at 4000 feet per minute had a damage level of over 70 percent. (Figure 5.4). Cob moisture content was 47 percent and kernel moisture content was 26 percent. The pile in the foreground consisted of broken or cracked kernels. The tip caps of all kernels in the left pile were removed. At these high moisture levels more tip caps were lost during hand shelling than were lost during shelling by impact loading. Kernels in the right pile were not visibly damaged. Frequently pedicels of kernels attached at the point where the cob fractured remained attached to the kernels during the shelling process. (One such pedicel is shown at the right in Figure 5.4).

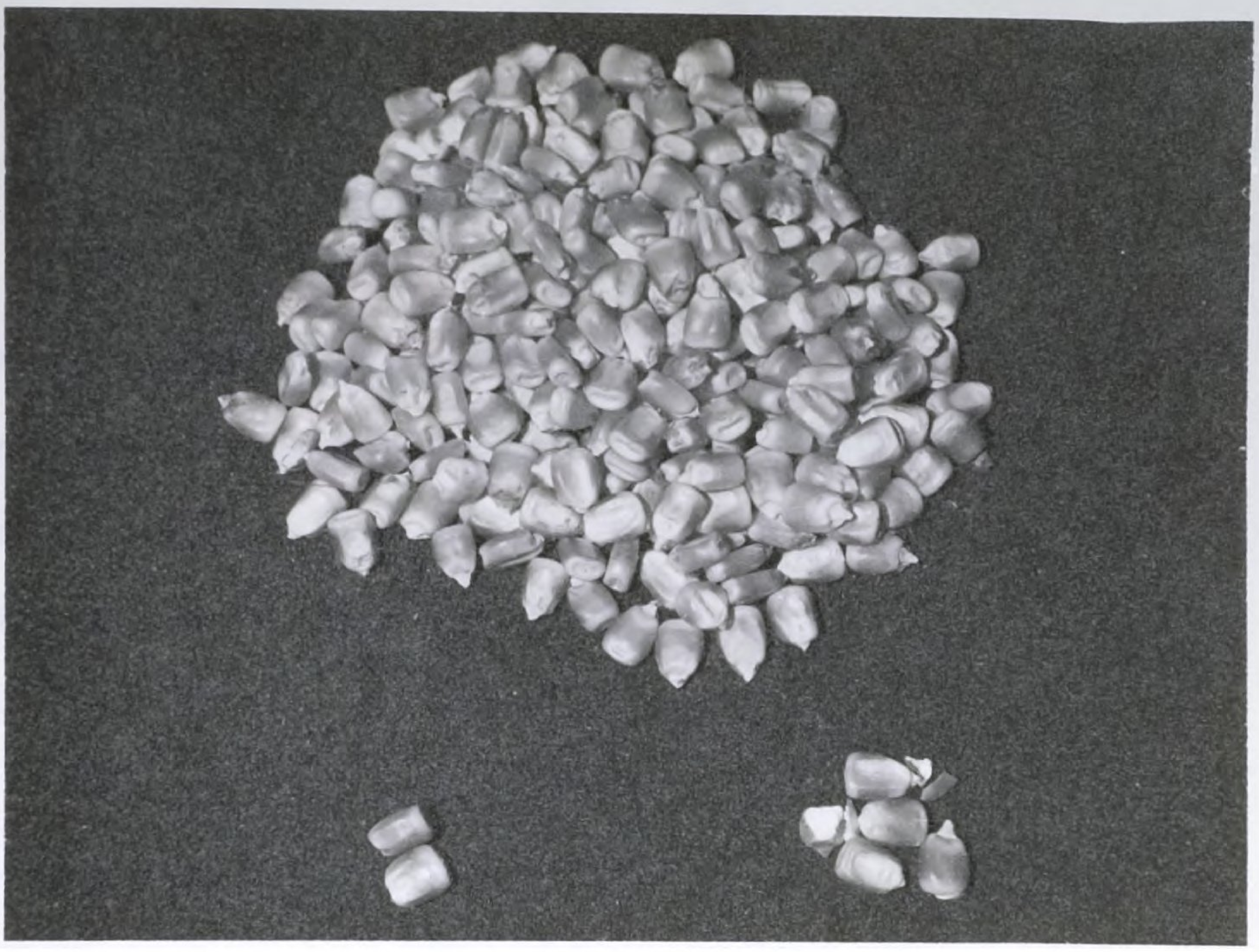


FIGURE 5.3 KERNELS REMOVED FROM AN EAR OF THE MICHIGAN 250 VARIETY WITH A SINGLE IMPACT AT 4000 FEET PER MINUTE. UPPER PILE - SOUND KERNELS. LOWER LEFT - TIP CAPS REMOVED. LOWER RIGHT - CRACKED AND BROKEN KERNELS. (PHOTO 68-98)

FIGURE 5.4 KERNELS REMOVED FROM AN EAR OF THE MICHIGAN 500 VARIETY WITH A SINGLE IMPACT AT 4000 FEET PER MINUTE. LOWER PILE - CRACKED AND BROKEN KERNELS. UPPER RIGHT - SOUND KERNELS. UPPER LEFT - TIP CAPS REMOVED. (PHOTO 68-99)

5.2 Regression Analysis Models

Important relationships among the measured parameters were estimated by means of regression analysis. The "Multiple Regression Program" used for this analysis was run on an International Business Machine Corporation Model 7044 computer at the Computer Center, University of California, Davis. A sub-routine was written for making the appropriate transformations while reading in the raw data. Estimates of the regression coefficients were determined by standard matrix inversion tenchiques.

For studying kernel removal the following general second order statistical model was used:

$$Y = \beta_o + \beta_1 X_1 + \ldots\ldots + \beta_6 X_6 + \beta_{11} X_1^2 + \ldots\ldots + \beta_{66} X_6^2 + \beta_{12} X_1 X_2 + \ldots\ldots + \beta_{56} X_5 X_6 + \varepsilon \quad [5.1]$$

where:

Y = percent kernels removed by a single impact (observed value)

X_1 = cob moisture content (percent w.b.)

X_2 = kernel moisture content (percent w.b.)

X_3 = weight of ear (pounds)

X_4 = impact velocity (feet per minute)

X_5 = testing date (day of year)

X_6 = impact force (pounds)

ε = error of observation

β_i and β_{ii} are regression coefficients.

This model can be written as:

$$\hat{Y} = b_o + b_1X_1 + \ldots\ldots + b_6X_6 + b_{11}X_1^2 + \ldots\ldots + b_{66}X_6^2 +$$

$$b_{12}X_1X_2 + \ldots\ldots + b_{56}X_5X_6 \qquad [5.2]$$

where:

$\hat{Y}$ is an estimator of Y

b_i are estimators of β_i

b_{ij} are estimators of β_{ij}

After calculating the values of the b_i and b_{ij} the percent of kernels removed by a single impact is expressed as a function containing twenty-eight terms. The term with the lowest standard partial regression coefficient, and hence, the last important term, was dropped from the model and then the data were reprocessed. This procedure was repeated until all regression coefficients were significantly different from zero at the 95 percent level. In this manner a less cumbersome function was obtained and the important coefficients were estimated with greater precision.

The kernel removal model for the Michigan 250 variety was determined to be:

$$\hat{Y} = -95.6 + 0.0809X_4 - 9.23 \times 10^{-6}X_4^2 - 49.8X_3 - 0.340X_1 \qquad [5.3]$$

By taking the partial derivatives of $\hat{Y}$ with respect to the X_i, it can be determined how a change in one parameter will affect $\hat{Y}$. In this case an increase in cob moisture content, X_1, or ear weight, X_3, will reduce the amount of kernel removal. For the range of velocities

used in this study an increase in impact velocity is accompanied by an increase in kernel removal. The kernel moisture content, impact force and testing date did not significantly affect the kernel removal.

The kernel removal model for the Michigan 500 variety is as follows:

$$\hat{Y} = -78.5 - 1.77X_1X_3 + 2.76X_2X_3 + 1.85X_1 - 0.0247X_1X_2 + 4.93 \times 10^{-3}X_4X_5 \qquad [5.4]$$

Determination of the consequences of parameter changes in this model is not as straight forward because of the cross-product terms. The rate of change in kernel removal due to a unit change in cob moisture content is a function of kernel moisture content and ear weight. In this and similar cases the partial derivatives were evaluated by substitution of the mean values for the included parameters. As an example:

$$\frac{\partial \hat{Y}}{\partial X_1} = 1.85 - 1.77X_3 - .0247X_2 = .106$$

for: $X_3 = .566$

$X_2 = 30.8$

An increase in kernel moisture, cob moisture, impact velocity, or testing date was accompanied by an increase in kernel removal. A decrease in ear weight reduced the kernel removal while impact force had no significant effect.

According to Halyk (1968) shelling can be initiated more easily when ears have small spaces between rows of kernels than when ears have large spaces. During the testing it was noted that the small ears of

the Michigan 250 variety were more tightly packed with smaller spaces between kernel rows than were the large ears. Hence, it was not surprising that the regression analysis showed that for Michigan 250 the smaller ears shelled more easily than the larger ears.

For the range of impact velocities studied, both varieties shelled more easily with increased velocity. This result agrees with Morrison (1955) that combine-type cylinders shell corn more effectively with increased peripheral velocities.

Burrough and Harbage (1958) reported shelling became more effective as the harvesting season progressed. Testing date had the same influence on the Michigan 500 variety, but had no significant effect on the Michigan 250 variety.

According to Johnson and Lamp (1966) shelling effectiveness increases as the kernel moisture (or cob moisture) decreases. For the Michigan 250 variety the cob moisture content had the same effect, but the kernel moisture content had no significant effect. Both kernel moisture and cob moisture had opposite effects on kernel removal for the Michigan 500 variety. An increase in either moisture level significantly increased the kernel removal. The difference appears to stem from the fact that the moisture levels were much higher for the Michigan 500 variety than for Michigan 250. Many seed coats of the Michigan 500 kernels were broken leaving tip caps attached to the cob, whereas the impact affected very few of the Michigan 250 kernels in this manner. Even though the kernel removal improved with increased moisture levels, the mechanical damage increased to levels which would make field shelling impractical.

The regression analysis for total mechanical damage (kernels visibly cracked and broken plus kernels which lost the tip caps) utilized the same dependent variables, X_i, as used previously for kernel removal. The resulting damage model for the Michigan 250 variety is as follows:

$$\hat{Y} = 3.38 + .251X_1X_2 - .0672X_1^2 - .00193X_2X_4 + 1.14 \times 10^{-4}X_4X_5 - 0.0112X_2X_5 \qquad [5.6]$$

where:

$\hat{Y}$ = total mechanical damage (expressed as a percent of the kernels removed by a single impact)

Total damage is increased by (1) decreases in impact velocity, X_4, or kernel moisture level, X_2; or (2) increases in cob moisture level , X_1, or testing date, X_5. Ear weight, X_3, and impact force, X_6, had no significant effect on total damage.

The subsequent damage model was developed for the Michigan 500 variety:

$$\hat{Y} = 3680 - 20.9X_5 + .0285X_5^2 - 29.7X_2 + .107X_2X_5 \qquad [5.7]$$

Cob moisture level, X_1, ear weight, X_3, impact velocity, X_4, and impact force, X_6, had no significant influence on total damage. Increases in kernel moisture content, X_2, are accompanied by increases in damage. The rate of change in damage with respect to a unit change in testing date, X_5, reaches a minimum at November 4. Before this date damage decreases with an increase in testing date, but after this date the opposite is true.

That Michigan 250 suffered less damage at high impact velocities than at low velocities seemed strange initially. However, after careful consideration of the available information, this result does not appear so unusual. Since the collection box was lined with foam rubber, only the kernels which come in contact with the impacting face can be broken or cracked, the most prevalent form of mechanical damage for this variety. Since kernel removal was significantly improved by increases in impact velocity, increasing the impact velocity reduced the percentage of shelled kernels which could be damaged by coming in contact with the impacting face.

Earlier it was shown that kernel removal for the Michigan 250 variety was hampered by increases in cob moisture levels. These shelling difficulties due to cob moisture increases were accompanied by greater incidence of damage.

Kernel moisture level had an opposite effect on damage for the two varieties. Using the data from these tests there is no way to determine whether this discrepancy was due to the differences in average moisture level or varietal differences. The damage level increased as the harvest season progressed for Michigan 250 and after November 4 for Michigan 500.

For studying the effect of several parameters on impact force the following statistical model was used:

$$\hat{Y} = b_0 + b_1X_1 + \ldots.. + b_5X_5 + b_{11}X_1^2 + \ldots.. + b_{55}X_5^2 + b_{12}X_1X_2 + \ldots.. + b_{45}X_4X_5 \qquad [5.8]$$

where:

$\hat{Y}$ = estimator of Y

Y = maximum impact force (pounds)

X_1 = cob moisture content (percent w.b.)

X_2 = kernel moisture content (percent w.b.)

X_3 = weight of ear (pounds)

X_4 = impact velocity (feet per minute)

X_5 = testing date (day of year)

b_i and b_{ij} are estimators of the regression coefficients

After elimination of unimportant terms using the system described above, the impact force model for Michigan 250 was found to be:

$$\hat{Y} = 4000 - 437X_2 + .826X_2X_5 + 4.25X_2^2 - .0232X_5^2 + 5.22 \times 10^{-5}X_4^2 + 855X_3 \qquad [5.9]$$

Cob moisture, X_1, was the only parameter which had no significant influence on impact force. Increases in ear weight, X_3, impact velocity, X_4, or testing date, X_5, caused an increase in impact force. The rate of change of impact force with respect to a unit change in kernel moisture, X_2, reached a minimum within the range of moisture levels studied. For example, on day 317 the force decreased with an increase in moisture level up to 20.6 percent. Above that level increases in moisture content caused an increase in impact force. For days 289, 303 and 331 the critical moisture levels were 23.3, 22.0 and 19.2 percent, respectively.

The impact force model determined for Michigan 500 was:

$$\hat{Y} = 366 - 4890X_3 + 15.8X_3X_5 + 45.6X_1 - .173X_1X_5 + 27.7X_3X_2 + 4.53 \times 10^{-5}X_4 \qquad [5.10]$$

Impact force increased with: (1) a decrease in cob moisture, X_1, or testing date, X_5, or (2) an increase in kernel moisture, X_2, ear weight, X_3, or impact velocity, X_4.

Before the impacting face and corn ear collide the ear is at rest. For a perfectly plastic collision the final velocity of the specimen would be equal to the impacting velocity, and for a perfectly elastic collision the final velocity would be twice the impacting velocity. Since the collision is neither perfectly plastic nor perfectly elastic, the final velocity of the ear must be a constant multiple of the impacting velocity and that constant must be a real number greater than one and less than two. Because of this relationship, increasing the impacting velocity will increase the final velocity of the ear. This, in turn, will increase the acceleration the ear undergoes.

According to Newton's Second Law of Motion an external force, $\overset{>}{F}$, is required to change the velocity of a body of mass, m, with an acceleration, $\overset{>}{a}$, where:

$$\overset{>}{F} = m\overset{>}{a} \qquad [5.11]$$

The regression for both varieties showed that an increase in ear weight or impacting velocity increased the maximum impact force.

The testing date had opposite effects on impact force for the two varieties. Increased force followed increased testing date for Michigan 250 and decreased testing date for Michigan 500. The testing date was

more highly correlated with kernel moisture and ear weight for Michigan 500 than for Michigan 250. Interaction of the parameters could have caused the discrepancy in results.

For the investigator accustomed only to quasistatic loading, the effect of kernel moisture level on impact force may seem contrary to nature: force should be greater for a dry ear than for a wet ear. However, since corn is a viscoelastic material, force becomes a function of displacement rate as well as displacement. Increasing the moisture level increases the dependence of the force upon loading rate because the material becomes more viscous and less elastic under stress. Thus, the indicated influence of moisture level on impact force and the influence of impact velocity on force can be substantiated.

Earlier it was indicated that a decrease in cob moisture caused an increase in impact force for Michigan 500; the opposite of the effect of changes in kernel moisture. Kernel and cob moisture were positively correlated; however, a one percent change in cob moisture resulted in a -7.9 percent change in impact force while a one percent change in kernel moisture resulted in a 15.7 percent change in force. Since kernel moisture had more influence than cob moisture, the net result is that an increase in ear moisture caused an increase in impact force for Michigan 500. Cob moisture had no significant influence on impact force for Michigan 250.

6. SOME THEORETICAL ASPECTS OF CORN IMPACT

6.1 Extension of Corn Shelling Theory to Dynamic Range

Prior to this study the investigations attempting to explain corn shelling have utilized quasistatic and low-velocity impact loading. No researcher has reported the use of impact loading at velocities comparable to the cylinder peripheral velocities commonly found during field shelling.

Halyk *et al*. (1969) reported that a kernel with moisture level below 15.3 percent subjected to compressive loading acted as a wedge and caused shelling of one of the surrounding kernels. By using a vertical weight-drop machine they found this wedging effect to hold for kernel moisture levels of 28 percent or lower.

During this study kernel moisture levels as high as 43.6 percent were encountered. Radial compressive impact loading at 2500, 3000, 3500 and 4000 feet initiated shelling on all of the ears tested regardless of moisture content. The amount of kernels removed by a single impact was found to depend upon moisture content, ear weight, impact velocity and testing date. The nature of this dependence is discussed in Section 5.2.

The pedicels of kernels on the top half of the corn ear and on the outside of the contact area were subjected to a tensile force during impact (Figure 4.2). This tensile force was the inertial force due to the cob's accelerating downward away from the top kernels.

When the pedicel of one kernel fractures to initiate shelling, forces applied to that kernel must be great enough to exceed the maximum tensile strength of the pedicel while overcoming the frictional forces between kernels. Thus far, two mechanisms for applying tensile force to the pedicel during impact have been described. The wedging effect originally reported by Halyk (1968) causes tensile stress in pedicels of kernels adjacent to the loaded area because of tangential displacement of the adjacent kernels. Pedicles of the top kernels were also subjected to a tensile force because of the kernel's resistance to downward acceleration. The tensile forces resulting from these two actions is greatest near the loaded area of the ear. It was observed that the first kernels removed were always adjacent to the loaded area. Shelling is initiated during radially inward impact loading because of the inertial forces on the shelled kernels and the wedging effect.

The reflected tensile stress wave discussed in Appendix III could also be a factor in the initiation of shelling; however, the stress wave propagation route and velocity through the ear must first be determined.

6.2 Analysis Utilizing High-Speed Movies

The result of impacting five corn ears tested at 2500 feet per minute showed the cob of each specimen broken into two pieces; and approximately 50 kernels shelled with the remaining kernels still attached to the cob halves. The high-speed cinematography techniques used to record these tests are described in Appendix I. The movies were analyzed with Vanguard Instrument Corporation Model M-16C motion analyzer to determine the kinetic energy of the specimens.

The movies were projected on the screen of the motion analyzer one frame at a time. The coordinates of the center of mass of every particle were recorded for each frame. Since the ear halves were rotating after impact, the coordinates of two points on each half were also recorded to measure angular displacement. Only the kernels shelled from the camera side of the ear were visible, so it was assumed there was one kernel not in view for each visible kernel. Consequently, the kinetic energy determined for the visible particles was doubled to compensate for the kernels not in view.

A Hewlett-Packard Model 9100A calculator was programmed to calculate the linear and angular velocities of the particles. The coordinates measured on the analyzer screen were adjusted to reflect the true displacements. Between frames number one and two the average linear velocity, v, of the center of mass of a given particle can be expressed as:

$$v = \left[(x_1 - x_1')^2 + (y_1 - y_1')^2 \right]^{1/2} / T \qquad [6.4]$$

where:

(x_1, y_1) are the adjusted coordinates from frame number one.

(x_1', y_1') are the adjusted coordinates from frame number two.

T is elapsed time between frames one and two.

The data need not be adjusted for determining the angular velocity: if (x_1, y_1) and (x_2, y_2) are coordinates of two points on a rigid body in frame one and (x_1', y_1') and (x_2', y_2') are coordinates of the same points in frame two, then the average angular velocity, ω, of the body between frames one and two can be written as:

$$\omega = \Theta / T \qquad [6.5]$$

where:

$$\Theta = \arccos\,[(2d^2 - c^2) / 2d^2]$$

$$c^2 = (y_2 - y_1 - y_2' + y_1')^2 + (x_2 - x_1 - x_2' + x_1')^2$$

$$d^2 = (y_2 - y_1)^2 + (x_2 - x_1)^2$$

T is elapsed time between frames one and two.

To determine the kinetic energy of the ear halves after impact the linear and angular velocities were calculated over a group of fifteen successive frames. The average of these values was used to calculate the linear and rotational kinetic energies. Only linear kinetic energy was determined for the shelled kernels. The kinetic energy of all the particles was totaled to estimate the total kinetic energy of the ear.

6.3 Energy Considerations

When two bodies collide at a high relative velocity, some of the original kinetic energy is transformed into heat energy during the collision and absorbed by the bodies. If the total kinetic energy lost by both bodies during collision can be determined, this value can be used to estimate the energy absorbed by the bodies. However, in the case of this study this type of energy balance could not be run to determine the energy absorbed by the corn during impact. The impact tester was powered by an electric motor to prevent a loss of velocity of the impacting arm while in contact with the arm.

Haliday and Resnick (1963) discussed the topic of impact and some of their results were used to estimate the energy absorbed by the corn during impact. If a body of mass m_1 traveling at a velocity u_1 and a body of mass m_2 traveling at a velocity u_2 impact with a perfectly elastic collision, the velocities after the collision can be written as:

$$v_1 = \left(\frac{m_1 - m_2}{m_1 + m_2}\right) u_1 + \left(\frac{2m_2}{m_1 + m_2}\right) u_2 \qquad [6.6]$$

$$v_2 = \left(\frac{2m_1}{m_1 + m_2}\right) u_1 + \left(\frac{m_2 - m_1}{m_1 + m_2}\right) u_2 \qquad [6.7]$$

If m_2 is considered to be negligible in comparison to m_1, and m_2 is initially at rest, equations 6.6 and 6.7 reduce to:

$$v_1 = u_1 \qquad [6.8]$$

$$v_2 = 2u_2 \qquad [6.9]$$

If the corn ear is considered to be m_2, this precise situation existed during the impact. For a perfectly elastic collision at 2500 feet per minute the ear should have moved downward with a velocity of 5000 feet per minute after impact. A corn ear traveling at this velocity and weighing 0.468 pound would have a kinetic energy of 50.6 ft-lbs.

High-speed movies were analyzed for five corn ears with average kernel and cob moisture contents of 20.5 percent and 27.9 percent, respectively, and weighing an average of 0.468 pound. The kinetic energy measured for these ears averaged 17.2 ft-lbs after impact. The observed kinetic energy differed from the theoretical value because the collision was inelastic and not perfectly elastic. The discrepancy of 33.4 ft-lbs from the theoretical value of 50.6 ft-lbs is considered to be the energy dissipated during impact. Negligible amounts of energy were absorbed by the supporting tape and impacting machine. An insignificant portion of energy was also used to form sound waves. Hence, the energy discrepancy of 33.4 ft-lbs is an estimate of the energy absorbed by the ear during impact.

7. CONCLUSIONS

7.1 Findings of This Study

Whole corn ears were tested to investigate the initiation of corn shelling by radial compressive impact loading. It was found that radial compressive impact loading would initiate shelling on corn ears with kernel moisture levels as high as 43.6 percent and impact velocities as low as 2500 feet per minute.

Halyk (1968) reported that a kernel displaced radially inward by quasistatic or low velocity impact loading acted as a wedge and shelled one of the surrounding kernels. During this study this wedging effect was also shown to be valid for impact velocities ranging from 2500 to 4000 feet per minute and is illustrated in Figure 4.3. Under the loading configuration utilized by Halyk (1968) the acceleration of the cob was insignificant and was disregarded. However, in this study the cob was accelerated downward away from top kernels not in contact with the impacter (Figure 4.2). Consequently, the shelling observed in this study was initiated by forces resulting from the wedging effect and the downward acceleration of the cob.

High-speed movies were utilized to determine the kinetic energy of five corn ears with average kernel and cob moisture contents of 20.5 percent and 27.9 percent, respectively, and weighing an average of .468 pound. This information was used to estimate that these ears absorbed an average of 33.4 ft-lbs of energy during impact.

The maximum impact force was measured for every sample tested. A regression analysis showed impact force was dependent on kernel moisture content, ear weight, impact velocity and testing date for both varieties. Cob moisture content had a significant effect on impact force for only the Michigan 500 variety.

The percentage of kernels removed by a single impact was shown by regression analysis to depend on cob moisture content, ear weight and impact velocity. Kernel moisture content and testing date significantly affected kernel removal for the Michigan 500 variety.

Regression analysis showed mechanical damage of both varieties was influenced by kernel moisture content and testing date. Cob moisture content and testing date had a significant effect on mechanical damage for only the Michigan 500 variety.

7.2 Recommendations for Future Studies

Several ideas which could be the subject of other investigations have arisen during the preparation of this thesis. The effect of storage conditions and time between collection and testing of samples should be studied for important grains. No researcher has reported an investigation of the dependence of feeding value of corn upon mechanical damage and storage time. As stated in Appendix III determination of the stress wave propagation velocity and route could reveal the role of reflected tensile waves in corn shelling.

A study in cooperation with the Crop Science Department could utilize the impact testing equipment to evaluate the resistance of corn

varieties to mechanical damage and the ease with which they can be shelled. It appears this could be a valuable part of a corn breeding program.

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APPENDICES

APPENDIX I

HIGH-SPEED CINEMATOGRAPHY

APPENDIX I

HIGH-SPEED CINEMATOGRAPHY

The high-speed movies utilized in this study were obtained with a continuous-type 16mm Fastax camera using Kodak Type 7278 TRI-X reversal film in a 100-foot roll. A Wollensak-Fastax Goose Control Unit synchronized the actions of the camera and the testing apparatus.

The large amount of preparation time before filming and the high cost of purchasing and processing the film inspired the recording of useful information on each roll of film. To achieve this the impact had to occur after the film was accelerated to a desired framing rate and before the end of the film passed through the camera. For proper coordination of the equipment, it was necessary to obtain the following information:

1. Elapsed time between activation of start switch and initial contact between impacting face and specimen;
2. Time required for impact;
3. Time required for film to reach desired velocity;
4. Time required to run 100 feet of film through camera;
5. Time available for filming impact process.

By measuring the appropriate distance on the trace of a storage oscilloscope, it was possible to determine the time which elapsed between activation of the start switch and initial contact between the impacting face and the specimen. For an impact velocity of 2500 feet per minute,

the elapsed time was 0.42 second. Using the same method it was found that the time required for impact was much less than one millisecond. This was not a critical parameter since it was so much smaller than the other parameters being considered.

The rate of film passing through the camera was controlled by the magnitude of the voltage supplied to the camera motors by the Goose Control Unit. The camera manufacturer provided curves from which the pertinent data was estimated. For example, on the first filming, the voltage setting was adjusted to 40 volts. From the curves it was estimated 3.3 seconds would be required to accelerate the film to the desired velocity and 5.0 seconds would be required to run the 100 feet of film through the camera.

During the filming the manual start switch on the impact apparatus was replaced by a normally open contact switch on the control unit. The "four position" switch was set at position number three. The event timer was set at 2.9 seconds and the camera timer was set at 5.0 seconds. Under this adjustment the impact apparatus was automatically started 2.9 seconds after the camera was started,and the camera was stopped after running 5.0 seconds. This setting provided an average framing rate of 1860 frames per second during the impact process.

The timing for stopping the camera was quite important. Premature stopping would have caused the camera to masticate film that was not on the take-up reel. Late stopping would have caused the take-up reel to rotate at a high speed with the end of the film striking the interior of the camera and breaking off small pieces of film.

The camera was located four feet from the specimen. A 50mm lens was used with a f/4.0 aperture setting. The impact velocity was 2500 feet per minute. The first attempt at high-speed cinematography proved successful.

For another filming on the same day, an average framing rate of 4100 frames per second was achieved by using the following adjustments:

1. Voltage to camera - 90 volts.
2. Event timer - 0.93 second.
3. Camera timer - 2.0 seconds.
4. Aperture setting - f/2.7.

The camera was then moved to six feet from the specimen to increase the field of view. An average framing rate of 6470 frames per second was achieved using the following adjustments:

1. Voltage to camera - 200 volts.
2. Event timer - 0.30 second.
3. Camera timer - 1.0 second.
4. Aperture setting - f/2.7.
5. Lens - 50 mm.

An average framing rate of 6830 frames per second was achieved by changing the event timer to 0.38 second. In both cases the light meter reading was 1800 foot-candles. This amount of light was barely adequate, and an increased amount would have improved the quality of the movies. For lighting this intense it is very easy to burn a biological specimen or dry it excessively. Consequently, the lamps cannot be lighted for a period longer than necessary.

The light colored corn ears showed up very well against the dark background. The impacting face should have been painted a lighter color

because it did not show up very well.

For any reader who is contemplating the use of high-speed cinematography the following information should prove useful:

1. There should be at least one object of known size in the field of view to use as a reference.
2. There should be a method for determining the framing rate.
    a. A light flashing at a known rate.
    b. An object moving at a known constant velocity.
    c. A timer in the field of view.
3. There should be one point which is stationary throughout the filming sequence to use for removing the error of camera movement.
4. A number should be placed in the field of view for later identification.
5. The objects to be studied should be a light color against a dark background.
6. Read the directions carefully.

APPENDIX II

STATISTICAL METHODS

APPENDIX II

STATISTICAL METHODS

The data collected in this study were used to estimate the coefficients of six different regression models. In Section 5.2 effects of changes in the dependent variables on the independent variable for each model were discussed. However, no mention was made of the t-tests and analysis of variance tests carried out during the regression analyses.

For the sake of illustration consider the following regression model:

$$\hat{Y} = b_4X_4 + b_{44}X_4^2 + b_3X_3 + b_1X_1 + b_o$$

where:

$\hat{Y}$ = percent of kernels removed by a single impact

X_4 = impact velocity (feet per minute)

X_3 = ear weight (pounds)

X_1 = cob moisture content (percent w.b.)

b_4, b_{44}, b_3, b_1, b_o are estimates of the regression coefficients, β_4, β_{44}, β_3, β_1, β_o.

An analysis of variance was carried out to test the hypothesis that the dependent variable, $\hat{Y}$, is unrelated to the independent variables, X_4, X_3, X_1, in a linear or quadratic fashion (H_o: $\beta_4 = \beta_{44} = \beta_3 = \beta_1 = 0$). This analysis is summarized in Table A2.1. The calculated F value was significant at the 95 percent level. Thus, it was possible to conclude with at least 95 percent confidence that at least one of the regression coefficients was different from zero.

To determine which of the regression coefficients were different from zero t-tests were utilized. For example, it was hypothesized that the independent variable, X_1, was unrelated to the dependent variable $\hat{Y}$ (H_1: $\beta_1 = 0$). The calculated t value was significant at the 95 percent level. Thus it was possible to conclude with at least 95 percent confidence that β_1 was different from zero. The same procedure was used to determine that β_3, β_4 and β_{44} were also different from zero.

The regression parameters for the six models are summarized in Tables A2.1 through A2.6. All of the t and F values listed are significant at the 95 percent level. The standard partial regression coefficients were calculated for all of the parameters of every model. For a given model the most important parameter had the partial regression coefficient with the largest absolute value. The next most important parameter had the second largest partial regression coefficient. The parameters were listed in the tables in descending order of importance as indicated by the absolute values of the partial regression coefficients. The ranges of parameters for which the models are valid are listed in Table A2.7.

TABLE A2.1 SUMMARY OF REGRESSION ANALYSIS PARAMETERS

Y = Percent of kernels removed by a single impact
Variety - Michigan 250 Coefficient of determination = .6110

Parameter	Regression Coefficient	Standard Partial Regression Coefficient	T-Value
X_4	.0809	2.80	3.37
X_4^2	-9.23×10^{-6}	-2.08	-2.50
X_3	-49.8	-.281	-4.71
X_1	-.340	-.219	-3.66
Constant	-95.6	-	-2.51

Analysis of variance due to regression

Source	d.f.	S.S.	M.S.	F
Regression	4	21,742.05	5,435.51	50.3
Error	128	13,840.41	108.13	-
Total	132	35,582.46	-	-

TABLE A2.2 SUMMARY OF REGRESSION ANALYSIS PARAMETERS

Y = Percent of kernels removed by a single impact
Variety - Michigan 500 Coefficient of determination = .6887

Parameter	Regression Coefficient	Standard Partial Regression Coefficient	T-Value
X_1X_3	-1.77	-1.87	-4.40
X_2X_3	2.77	1.65	3.92
X_1	1.85	1.40	3.81
X_1X_2	-.0247	-1.10	-3.15
X_4X_5	4.93×10^{-5}	.819	16.4
Constant	-78.5	-	-5.54

Analysis of variance due to regression

Source	d.f.	S.S.	M.S.	F
Regression	5	10,217.07	2,043.41	56.6
Error	128	4,617.28	36.07	-
Total	133	14,834.35	-	-

TABLE A2.3 SUMMARY OF REGRESSION ANALYSIS PARAMETERS

Y = Mechanical damage (percent of kernels removed)
Variety - Michigan 250 Coefficient of determination = .1257

Parameter	Regression Coefficient	Standard Partial Regression Coefficient	T-Value
X_1X_2	.251	4.91	2.78
X_1^2	-.0672	-2.97	-2.41
X_2X_4	-.00193	-1.83	-3.36
X_4X_5	1.14×10^{-4}	1.25	3.19
X_2X_5	-.0112	-.613	-2.06
Constant	3.38	-	.210

Analysis of variance due to regression

Source	d.f.	S.S.	M.S.	F
Regression	5	4,271.43	854.29	3.65
Error	127	29,718.90	234.01	-
Total	132	33,990.33	-	-

TABLE A2.4 SUMMARY OF REGRESSION ANALYSIS PARAMETERS

Y = Mechanical damage (percent of kernels removed)
Variety - Michigan 500 Coefficient of determination = .4655

Parameter	Regression Coefficient	Standard Partial Regression Coefficient	T-Value
X_5	-20.9	-15.4	-4.04
X_5^2	.0285	13.2	3.89
X_2	-29.7	-6.45	-3.66
X_2X_5	.107	5.83	4.05
Constant	3680.	-	4.07

Analysis of variance due to regression

Source	d.f.	S.S.	M.S.	F
Regression	4	31,322.05	7,830.51	29.0
Error	129	34,553.67	269.95	-
Total	133	65,875.73	-	-

TABLE A2.5 SUMMARY OF REGRESSION ANALYSIS PARAMETERS

Y = Maximum impact force (pounds)
Variety - Michigan 250 Coefficient of determination = .7103

Parameter	Regression Coefficient	Standard Partial Regression Coefficient	T-Value
X_2	-437.	-5.01	-3.98
X_2X_5	.826	2.77	2.95
X_2^2	4.25	2.08	3.78
X_5^2	-.0232	-.913	-2.57
X_4^2	5.22×10^{-5}	.738	15.0
X_3	855.	.302	5.92
Constant	4000.	-	3.65

Analysis of variance due to regression

Source	d.f.	S.S.	M.S.	F
Regression	6	6,427,380.9	1,071,230.1	51.5
Error	126	2,620,919.2	20,800.9	-
Total	132	9,048,300.1	-	-

TABLE A2.6 SUMMARY OF REGRESSION ANALYSIS PARAMETERS

Y = Maximum impact force (pounds)
Variety - Michigan 500 Coefficient of determination = .6048

Parameter	Regression Coefficient	Standard Partial Regression Coefficient	T-Value
X_3	-4890.	-2.55	-2.17
X_3X_5	15.8	2.40	2.21
X_1	45.6	1.18	2.00
X_1X_5	-.173	-1.15	-2.29
X_3X_2	27.7	.568	2.98
X_4^2	4.53×10^{-5}	.544	9.57
Constant	366.	-	2.00

Analysis of variance due to regression

Source	d.f.	S.S.	M.S.	F
Regression	6	7,629,196.6	1,271,530.0	32.4
Error	127	4,986,157.2	39,261.1	-
Total	133	12,615,353.8	-	-

TABLE A2.7 RANGE OF PARAMETERS FOR WHICH REGRESSION IS VALID

		Michigan 500	Michigan 250
Cob Moisture Content (percent)	minimum	25.6	15.4
	maximum	72.7	56.2
Kernel Moisture Content (percent)	minimum	18.1	14.2
	maximum	43.6	30.0
Ear Weight (pounds)	minimum	.256	.248
	maximum	.853	.710
Maximum Impact Force (pounds)	minimum	440	350
	maximum	2000	1640
Total Mechanical Damage (percent)	minimum	2.06	0.28
	maximum	100.00	93.99
Kernel Removal (percent)	minimum	2.3	8.2
	maximum	54.6	80.4

APPENDIX III

STRESS WAVE PROPAGATION

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STRESS WAVE PROPAGATION

Stresses and deformation in a viscoelastic body under quasi-static conditions of loading can be determined by applying the theory of viscoelasticity. These calculations are based on the assumptions that the deformations due to applied external forces have reached their static values and the body is in equilibrium. In such analysis inertial forces due to deformation or motion are neglected. These methods are suitable when the external forces are applied for a period of time longer than that required to establish equilibrium and make the necessary experimental observations. However, when external forces are applied for only a few microseconds, inertia stresses attain values of importance and the stresses and deformations may be analyzed in terms of stress wave propagation.

The impact loading of corn ears discussed in this thesis caused stresses and deformations which may require stress wave considerations. Moisture content significantly affected response of the corn to impact loading, suggesting the possibility of modeling corn ears as viscoelastic material. The complex geometry of corn ears and the viscoelastic modeling of corn cause the mathematics of this problem to be very difficult and outside the scope of this thesis. However, a discussion of a procedure for developing necessary descriptive equations is in order.

The corn ear can be considered as consisting of cylindrical layers of isotropic material with the glumes, lemmas and paleas represented by

viscoelastic compressive elements and the pedicels by viscoelastic tensile elements (Figure A3.1). Conceivably a viscoelastic model could be developed for each layer in the model by experimentation.

To arrive at a governing partial differential equation for stress wave propagation, Kolsky (1963) considered the stress wave problem for a continuous elastic body through application of Hooke's Law, strain-displacement equations and the following equations of motion:

$$\begin{aligned}
\rho \frac{\partial^2 u}{\partial t^2} &= \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + \frac{\partial \sigma_{xz}}{\partial z} \\
\rho \frac{\partial^2 v}{\partial t^2} &= \frac{\partial \sigma_{yx}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \sigma_{yz}}{\partial z} \\
\rho \frac{\partial^2 w}{\partial t^2} &= \frac{\partial \sigma_{zx}}{\partial x} + \frac{\partial \sigma_{zy}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z}
\end{aligned} \qquad [A3.1]$$

where:

ρ = mass density of the medium

u = displacement in the x-direction

v = displacement in the y-direction

w = displacement in the z-direction

t = time

σ_{xy} = stress (The first letter in the suffix denotes the direction of the stress and the second letter defines the plane in which it is acting.)

For wave motion in a viscoelastic media the appropriate constitutive equation must be used in place of Hooke's Law to arrive at a governing partial differential equation for each cylindrical layer of the corn ear model.

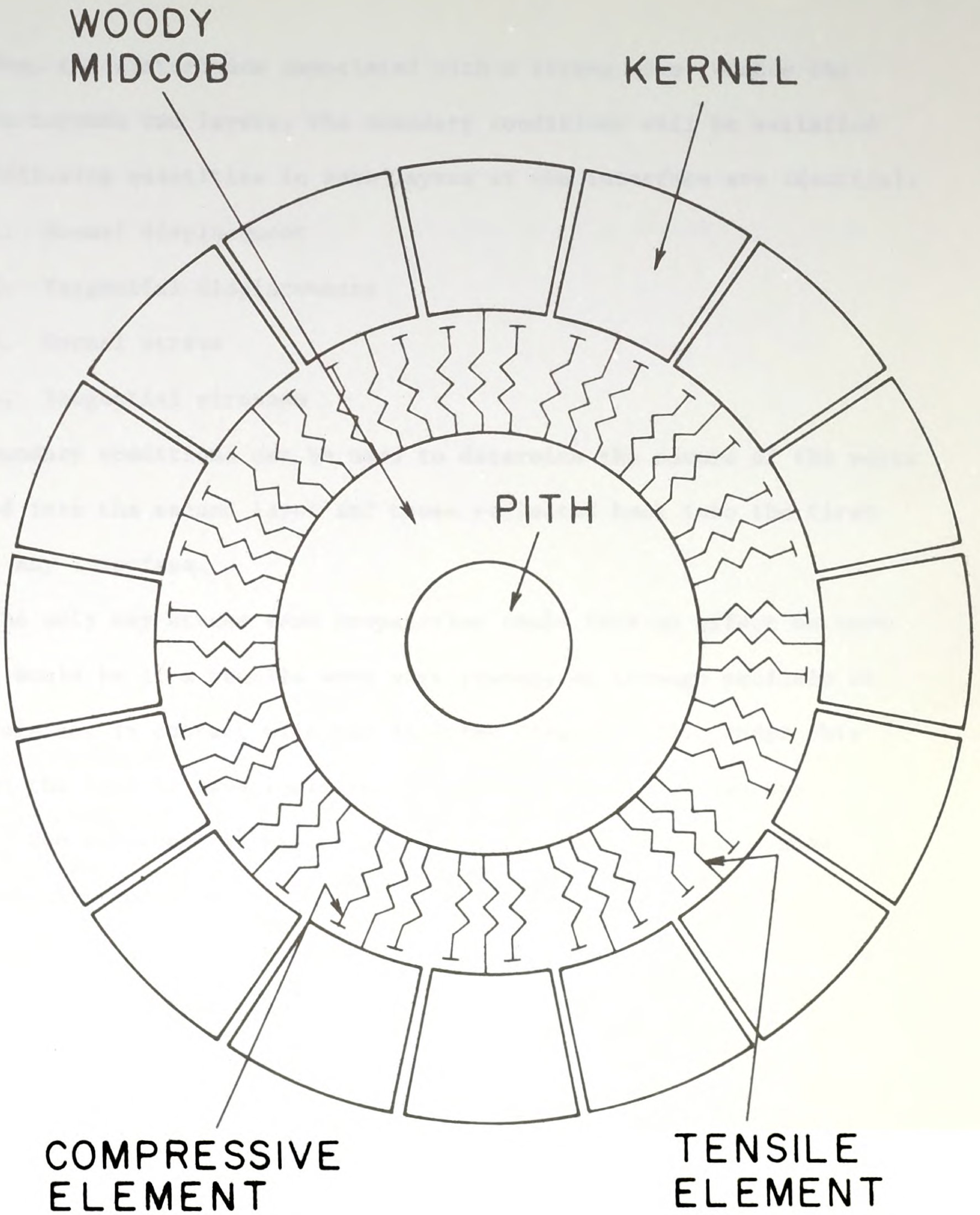

FIGURE A3.1 THEORETICAL MODEL OF EAR CROSS SECTION. TENSILE ELEMENT REPRESENTS PEDICEL. COMPRESSIVE ELEMENT REPRESENTS GLUMES, LEMMAS AND PALEAS.

When the disturbance associated with a stress wave reaches the interface between two layers, the boundary conditions will be satisfied if the following quantities in both layers at the interface are identical:

1. Normal displacement
2. Tangential displacements
3. Normal stress
4. Tangential stresses

These boundary conditions can be used to determine the nature of the waves refracted into the second layer and those reflected back into the first layer at any interface.

The only way stress wave propagation could have an effect on corn shelling would be if a tensile wave were propagated through pedicels of top kernels not in contact with the impacter (Figure 4.2). Under this condition the tensile wave would help fracture pedicels of the top kernels. The mathematical manipulation described above could answer three pertinent questions:

1. Could a tensile wave be reflected from one of the interfaces to the top of the ear?
2. Would the propagation velocity be sufficient to allow a tensile wave to reach the top pedicels while the impacting face is still in contact with the ear?
3. Would the amplitude of such a wave be great enough to be an important force in the initiation of corn shelling?

If the answers to any or all of these questions is no, stress wave propagation would not be an important factor in corn shelling.

Determination of the wave propagation velocity and route through a corn ear and the effect of stress waves on corn shelling would be an interesting topic for a future study. However, in the development of improved corn harvesting equipment the value of such a study is rather questionnable at this time.