A REVIEW OF GRAIN KERNEL DAMAGE:
MECHANISMS, MODELING, AND TESTING PROCEDURES

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HIGHLIGHTS
- Published literature on grain kernel damage during handling is reviewed.
- Types and sources of grain kernel damage are discussed.
- Factors affecting the level of grain kernel damage are outlined.
- Models to predict grain kernel damage and corresponding test devices are summarized.

ABSTRACT. Grain kernel damage during harvest and handling continues to be a challenge in grain postharvest operations. This damage causes physical and physiological changes to grain, which reduces the grain quality and leads to significant yield loss. During harvesting and handling, grain kernels are subject to complex loading conditions consisting of a combination of impact, shear, and compression forces. The main damage mechanisms include impact, which causes external and internal cracks or even fragmentation of the kernel; attrition, which generates fine material; jamming, which deforms and breaks kernels due to high compressive forces; and fatigue, which produces broken kernels and fine material via repeatedly applied loads. Grain kernel damage accumulates as the grain moves through harvesting and handling operations. Harvesting is the major cause of cracks and breakage, while conveying after drying produces fine material. This article provides a comprehensive review of the types of grain kernel damage, sources of grain kernel damage, factors affecting damage, predictive damage models, and the experimental methods used to assess the damage. This review shows that although there is considerable empirical data focused on kernel damage, there is a lack of generalizable mechanics-based predictive models. Mechanics-based models are desirable because they would be useful for providing guidance on designing and operating grain handling processes to minimize kernel damage and thus improve grain quality. In addition, several damage models developed for non-grain particulate materials based on fracture mechanics are reviewed. With some modifications and detailed property analysis, there is potential for adapting the models developed for inorganic materials to predict grain kernel damage.

Keywords. Grain kernel damage, Grain harvesting and handling, Breakage susceptibility, Grain damage prediction.

Cereal grains are the fundamental component of human and livestock diets. Each year, a huge quantity of grains is produced to feed billions of people worldwide. In 2017, the global production of major grains was 1135 million tonnes of corn, 772 million tonnes of wheat, 770 million tonnes of rice, and 353 million tonnes of soybeans (FAOSTAT, 2018). One of the major problems during production is grain kernel damage, which diminishes the quality of the grains and results in postharvest losses. A substantial portion of the produced crop gets damaged despite improvements in planting, mechanical harvesting, and handling techniques. According to the 2016/2017 U.S. Corn Harvest Quality Report (USGC, 2017), the average aggregate broken corn and foreign material (BCFM) was 0.7%. In BCFM-free corn, 4.8% of kernels were chipped and/or cracked, and another 4% of kernels contained internal stress cracks. The total damage was 2.6%, which includes kernels damaged by heat, frost, insects, sprouting, disease, weather, grounding, germs, and mold (USDA, 2013).

Grain kernel damage causes physical and physiological changes in grain kernels that reduce the grain quality, lead to various challenges during downstream processes (e.g., planting, storage, and food processing), and cause significant yield and commercial losses. The specific negative effects of grain kernel damage include:
- Significant mechanical damage to grain kernels leads to a lower grade and typically a price discount.
- Minor damage, such as chipped or hairline fissures on the pericarp, has little effect on grain germinability. However, a large missing fraction of the kernel and/or deep cracks in the endosperm or germ may result in a significant decrease in the germination rate (Sosnowski and Kuzniar, 1999).
Grain kernels with a damaged seed coat are more susceptible to insect infestation and microbiological contamination, which decreases the allowable storage time, causes nutrient loss, and can even result in the presence of toxic compounds if certain types of fungi grow on the kernels (Harein and Meronuck, 1990; Mohapatra et al., 2017).

Grain kernel damage decreases the mechanical strength and increases the breakage susceptibility of the grain. Consequently, more serious physical damage could occur in downstream handling operations (Gunasekaran et al., 1985).

A substantial amount of fine material could be generated in downstream handling operations when the percentage of broken kernels is high (Converse and Eckhoff, 1989; Stroshine, 1992).

Kernel damage also affects the grain’s water absorption rate, which could lead to overcooking or undercooking during grain processing operations, e.g., alkaline processing used for snack food production (USGC, 2017).

The yield of large flaking grits in dry milling and the yield of starch in wet milling are lower for grain with a higher degree of breakage and more stress cracks (Brown et al., 1979; Gunasekaran et al., 1987).

Because grain kernel damage is a critical problem in crop production, a large number of studies have been conducted on various aspects of the problem in past decades. The objectives of this article are (1) to summarize the studies related to the types of damage, sources of damage, and factors affecting the level of damage, which contribute to better understanding of the damage mechanisms; and (2) to review the models for predicting damage of grain and non-grain particles, which could be used to optimize the design and operating conditions of equipment and thus reduce grain kernel damage. The applicability and drawbacks of different models are discussed. To narrow the scope, the focus of this review is mechanical damage of the major grains, i.e., corn, wheat, rice, and soybeans, induced by harvesting and handling operations.

**Types of Grain Kernel Damage**

Mechanical, thermal, and biological damage are the three main types of grain kernel damage. The main interest of this review is mechanical damage. Mechanical damage can be classified into two categories based on the visibility of the damage, i.e., external and internal (Christenbury, 1975; Chowdhury, 1978). External damage includes open cracks in the grain and kernel breakage, while internal damage lies underneath the pericarp and cannot be detected without special instrumentation.

To describe the location of damage better, cross-sectional renderings of corn and rice kernels are provided in figure 1. In general, grain kernels contain a germ or embryo that grows into a whole plant; an endosperm that is rich in protein, carbohydrate, and/or fat to provide sufficient nutrients for the germ to germinate; and a bran and a hull that act as a barrier and protect the grain kernel from outside damage and contamination.

**External Damage**

External damage includes broken, chipped, and scuffed kernels, or kernels with fine cracks on the pericarp that can be visually observed by the naked eye (Chowdhury and Buchele, 1976). Breakage is a major form of external damage in cereal grains. The percentage of broken kernels quantified by sieving or other size-based separation methods is one of the criteria used in determining the grade of grains (USDA, 2013). The size of the sieve chosen for screening depends on the type of grain. For example, a 4.76 mm (12/64 in.) round-hole sieve is used for separating broken corn, and a 1.65 mm × 9.53 mm (0.065 in. × 0.375 in.) oblong-hole sieve is used for separating broken wheat (USDA, 2013). Broken rice kernels are defined as kernels that are less than 3/4 of whole kernels, while the remaining kernels are referred as head rice (USDA, 2009). When evaluating the quality of rice, a sizing device developed by Smith (1955) is commonly used to separate broken rice from head rice. The sizing device consists of inclined plates with indentations that allow only short broken rice to fall into them. The long head rice slides down into the collection box, as it does not fit into the indentations.

The percentage of broken kernels is used to estimate the level of mechanical damage, mainly because the quantification process is simple and fast; however, it does not take all types of mechanical damage into account. Damaged kernels

![Figure 1. Outer layers and internal structures of grain kernels: (a) corn and (b) rice (courtesy of Encyclopedia Britannica, Inc., copyright 1996, used with permission).](image-url)
with cracks or with only a small portion chipped off have a similar size as whole kernels and cannot easily be separated from whole kernels by sieving. Different methods have been proposed, especially for corn and soybeans, to further classify external damage in order to better assess the severity of damage. For corn, a widely used method, developed by Chowdhury and Buchele (1976), quantifies the damage using a numerical damage index. The damage is assessed based on the change in the color of kernels with the application of a fast green dye. The dye only adheres to the starch, while the other parts of the kernels do not react to the application of this dye. According to these authors, the severity of the damage can be classified into five levels:

- **D1**: Broken kernels and fine material that pass through a 12/64 in. round-hole sieve.
- **D2**: Severe damage (broken, chipped, and crushed kernels, with more than 1/3 of the whole kernel missing).
- **D3**: Major damage (open cracks, chipped, and severe pericarp damage, highlighted by green dye).
- **D4**: Minor damage (hairline cracks and spots of pericarp missing, highlighted by green dye).
- **D5**: Sound kernels with no damage.

Figure 2 illustrates the levels of corn kernel damage.

For soybeans, the major concern is seed coat damage (Gagare et al., 2014). The seed coat of a soybean is vulnerable, as it is thin and has low lignin content (lignin contributes to the rigidity of the cell wall) (Capeleti et al., 2005). Without the protection of a seed coat, the fragile radicle (a part of the embryo that develops into the root) beneath the seed coat is exposed to the environment. The germinability greatly decreases if the radicle is damaged (Moore, 1972). The common methods used to evaluate seed coat damage include a ferric chloride test (Gagare et al., 2014) and an indoxyl acetate test (VanUtrecht et al., 2000). These tests check the integrity of the seed coat by staining the soybean with the dye solutions. Furthermore, a tetrazolium test is usually conducted to determine the germination potential of soybeans (Cottrell, 1948). If the seed coat is damaged, the two cotyledons of the soybean tend to split apart under loading (Parde et al., 2002), which is referred to as a split. The term “split” also refers to soybeans with more than 1/4 of the bean removed (USDA, 2013) and/or with cracked cotyledon (Gunasekaran et al., 1988b).

Researchers have strived to develop automatic methods for detecting external damage with the aid of computer vision systems (Gunasekaran et al., 1988a; Liao et al., 1993; Steenhoek et al., 2001; Gong et al., 2015; Jayas et al., 2016). Although different damage classification criteria have been proposed, in general, damaged kernels are identified based on their variations in size, shape, and color. Compared to manual inspection, automated systems require less labor and produce more consistent and objective results. However, to completely replace manual inspection, more work is needed to develop a portable, robust, high-efficiency, low-cost automated grain quality evaluation system (Gong et al., 2015).

### Internal Damage

Internal damage refers to the fine cracks within a kernel’s endosperm, underneath the pericarp (Gunasekaran et al., 1987). Among all cereal grains, only rice and corn have serious internal damage problems, which are commonly referred as fissures (rice) or stress cracks (corn) (Paulsen et al., 2019). The major causes of internal damage are thermal and moisture stresses induced by rapid changes in ambient temperature and moisture, especially during drying and rewetting processes (Brown et al., 1979; Kirleis and Strosshine, 1990; Cnossen et al., 2003; Iguaz et al., 2006). Internal damage can also occur due to impact during mechanical harvesting and handling processes (Perry and Hall, 1966; Chung and Converse, 1970; Moreira et al., 1980; Sharma et al., 1992).

The formation and propagation of internal stress cracks depend on the kernel’s structure, composition, and variety. Microscopic structural analysis of kernel fissures was conducted by Robutti et al. (1974), Balastreire et al. (1982), and Gunasekaran et al. (1985) for corn, by Wang and Jeronimidis (2008) for wheat, and by Li and Mao (2003) for rice. The microscopic analysis indicated that, in general, a stress crack develops as a single crack and progresses to multiple cracks. Multiple cracks appear as the internal stresses increase (Thompson and Foster, 1963). For corn, cracks usually initiate from internal flaws in the weaker region of the soft endosperm of the kernel (Balastreire et al., 1982). With an increase in stress, cracks propagate through the cell walls around the starch granules toward the hard endosperm and aleurone layer (the outermost layer of the endosperm). The structure and composition of the hard endosperm and aleurone layer make them more resistant to the propagation of stress cracks compared to the soft endosperm. Thus, the crack front narrows when approaching the kernel pericarp and is not visible at the surface of the kernel (Gunasekaran et al., 1985). Rice has a similar crack formation mechanism to corn, i.e., fissures initiate in the endosperm and propagate outward (Li and Mao, 2003). The growth direction of the fissures is generally perpendicular to the longitudinal axis of the rice kernel (Hwang et al., 2009).

With the cracks being internal, evaluation of kernel stress cracks requires special instrumentation. A simple and

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**Figure 2. Levels of corn kernel damage:** D2 = severe damage (top left), D3 = major damage (top right), D4 = minor damage (bottom left), and D5 = sound kernels (bottom right) (Chen, 2019).
widely used method is to examine the kernels individually over a light source, such as a lightbox (fig. 3) (Kirleis and Stroshine, 1990) or a laser (Gunasekaran et al., 1986). The backlight method can be used to quickly estimate the degree of internal damage for corn and rice; however, the method is not applicable to grains that have low transmittance, such as wheat. Similar visualization methods include computer vision systems (Gunasekaran et al., 1987; Yie et al., 1993; Zareiforoush et al., 2015; Ogawa, 2016; Symons et al., 2016), scanning electron microscopy (Gunasekaran et al., 1985), and x-ray microtomography (fig. 4) (Wozniak, 2001; Guelpa et al., 2016; Sood et al., 2016; Shi et al., 2019), which have been adopted by researchers in recent years. Compared to backlighting the kernels, these methods are able to provide more information on the width, length, and location of stress cracks, along with how stress cracks propagate within the kernel. However, these tests are time-consuming and require costly equipment, restricting their widespread use.

**Sources of Grain Kernel Damage**

Many mechanisms can lead to grain kernel damage. Prior to harvest, damage occurs mainly from severe weather conditions and insect infestation (Hill, 2008; Barlow et al., 2015). During harvesting and subsequent handling operations, grain is subject to impact, compaction, and frictional loads that can result in mechanical damage (Srivastava et al., 2006). Another major factor is the drying process used to reduce the kernel moisture content from harvest conditions (18% to 25% wet basis) to safe storage conditions (13% to 15% wet basis) (Loewer et al., 1994; Bucklin et al., 2013). The high-temperature air used for drying grain generates thermal and moisture stress gradients inside the kernels that can lead to internal cracks (White et al., 1980; Iguaz et al., 2006). During storage of damaged kernels, there will be increased fungal growth and accompanying risk of contamination with mycotoxins due to easy accessibility to the exposed starch and other components in the kernels (Shiju, 2010; Fleurat-Lessard, 2017; Neme and Mohammed, 2017).

**Damage Caused by Machines**

Mechanical damage caused during the combine harvesting process has been studied by many researchers (Vas and Harrison, 1969; Waeli and Buchele, 1969; Hall and Johnson, 1970; Brass and Marley, 1973; Pickett, 1973; Newbery et al., 1980; Paulsen and Nave, 1980; Singh and Singh, 1981; Ajllan, 1983; Sharma et al., 1992; Quick, 2003; Špokas et al., 2008). These studies concluded that the harvesting process is the primary source of mechanical damage. To better illustrate the process, an internal view of a combine in an operating state is shown in figure 5. The harvesting process can be divided into four steps: cutting, threshing, separation, and cleaning (Srivastava et al., 2006). Throughout the harvesting process, grain is subjected to impact, friction, and compression loads.

Among the four steps of the harvesting process, threshing is the primary source of mechanical damage (Chowdhury and Buchele, 1978). In a combine harvester, threshing occurs between the cylinder and the concave. Threshing is the process of detaching grain from other parts of the plant by applying mechanical forces that create a combination of impact, shear, and compression (Srivastava et al., 1976). An illustration of the threshing process is shown in figure 6. Even after threshing and before dropping through the concave opening, the detached kernels continue bouncing between the cylinder and concave bar. During this bouncing, the kernels are subjected to impact forces from the cylinder and concave bar and compressive forces from

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**Figure 3.** Corn kernels illuminated by backlight: (a) no stress cracks, (b) single stress crack, and (c) multiple stress cracks (cracks are outlined in red) (Chen, 2019).

**Figure 4.** Corn kernel x-ray images: (a) undamaged and (b) with internal stress cracks (cracks are outlined in red) (Chen, 2019).
Machine parameter settings of cylinder speed, concave clearance, feed rate, and type of threshing unit (rotary or conventional) are the primary factors that affect the level of grain damage. Table 1 provides a summary of the factors that lead to kernel damage during harvesting. Among these parameters, cylinder speed has the largest influence. At higher cylinder speeds, grain is subjected to larger impulsive forces due to impacts with the cylinder, concave, and other kernels (Vas and Harrison, 1969). Compared to cylinder speed, concave clearance has a less significant effect on grain kernel damage. In general, a decrease in concave clearance results in an increase in mechanical damage (Ajillan, 1983; Pickett, 1973; Quick, 2003; Špokas et al., 2008). This trend occurs because a small concave clearance tends to increase the chance that grain kernels are jammed, and the grain kernels may be impacted multiple times in the shelling crescent (the space between the cylinder and the concave) before they exit the threshing chamber. The grain kernel damage level also decreases with an increase in feed rate (Vas and Harrison, 1969; Špokas et al., 2008). At a higher feed rate, plant material inside the machine is denser and cushions the grain from impacts. The type of threshing unit inside the combine also makes a difference in the level of grain damage. Compared to conventional combines, the cylinder speed is lower and the concave clearance is larger in rotary combines, which leads to a lower percentage of damaged grain in rotary combines (Newbery et al., 1980; Wacker, 2005; Srivastava et al., 2006).

In addition to machine parameters, other factors affecting grain damage include the kernel residence time within the shelling crescent and the corn ear orientation during shelling (Young, 1968; Mahmoud, 1972; Mahmoud and Buchele, 1975a; Chowdhury and Buchele, 1978). A longer residence time inside the shelling crescent results in a larger number of impacts and longer loading durations. The level of damage increases almost linearly as the kernels travel farther along the concave (Mahmoud, 1972). Mahmoud and Buchele (1975a) evaluated the effect of corn ear orientation on mechanical damage and found that the tip-in orientation caused a higher level of damage compared to the roll-in orientation.

### DAMAGE CAUSED BY HANDLING

The handling process is another major source of grain kernel mechanical damage. The most common handling equipment used by commercial and farm grain handlers, aggregators, and processors includes belt conveyors; drag chain, flight, or en masse conveyors; screw or auger conveyors; bucket conveyors; and pneumatic conveyors (Labiak and Hines, 1999). Illustrations of these different kinds of conveyors are shown in figure 7. The degree of damage caused by handling equipment is considered to be one of the key factors in evaluating their performance. Thus, various laboratory and field experiments have been conducted by researchers to test the damage induced by different types of handling equipment (Fiscus et al., 1971; Foster and Holman, 1973; Hall, 1974; Johnson, 1984; Misra et al., 1991). However, most researchers limited the scope of their study to quantifying the damage, and few conducted in-
depth studies to understand the grain kernel damage mechanisms. Table 2 provides a summary of the factors influencing damage from handling operations. The major factors, such as conveying speed, conveying distance, and feed rate, are discussed in the following sections.

A bucket elevator uses multiple buckets fixed on a moving belt to haul grain kernels vertically. Fiscus et al. (1971), Foster and Holman (1973), and Hall (1974) experimentally quantified the grain mechanical damage caused by bucket elevators. Their results showed that the percent damage (by weight) was less than 3.2%, and the damage depended on the type of grain and handling conditions. Hall (1974) identified that bucket elevators mainly damage grain during the processes of filling and discharging. This is because the buckets hit the grain at the bottom of the leg (boot section) during filling, and the grain impacts the housing at the top of the elevator (head section) during discharge. When working at a low capacity, the same amount of grain is hit
by the bucket at the boot section more times than when working at a higher capacity. Thus, the damage was higher at a low capacity.

Common screw conveyors consist of three basic components: a screw to move the material; a trough, casing, or housing to contain the material and the screw; and a motor to drive the screw. The major function of a screw conveyor is to elevate and transport bulk material over short to medium distances (Jovanović et al., 2015). This is achieved by pushing the material forward along the axis of the casing with the thrust of the rotating screw (Patel et al., 2012). The sources of damage in screw conveyors can be classified into two categories: (1) kernels shearing at the conveyor inlet where the screw enters the casing, and (2) kernels jamming in the clearance between the screw and the casing (Rademacher, 1981).

Screw conveyor machine or operating parameters that affect the grain damage level are the conveying load, conveying speed, inclination angle, and clearance between the screw and the casing. Increasing the conveying speed generates more damaged grain because, in such a condition, the grain kernels impact the casing wall at higher speed (Bouse et al., 1964; Sands and Hall, 1971; Zareiforoush et al., 2010). Moreover, increasing the speed leads to a decline in conveyor filling percentage, and a greater percentage of the grain is conveyed near the perimeter of the screw (Bouse, 1956). As a result, kernels have a higher probability of being jammed between the screw and the casing. When working at the rated capacity, there is less empty space within the conveyor, and the kernels cannot bounce around and strike the casing wall or screw surfaces (Hall, 1974). The damage during conveying was found to increase significantly if the conveyor was operated below its rated capacity (Misra et al., 1991). The effect of inclination angle on grain damage is inconsistent among reported studies. Experiments with shelled corn tested at 0° and 50° (Sands and Hall, 1971) and with paddy tested at 10°, 20°, and 30° (Zareiforoush et al., 2010) indicated that inclination angle had no significant effect on damage level. However, an experiment with soybeans tested at 15° and 30° suggested that a significant amount of damage was produced when the angle of inclination was steep (Misra et al., 1991). For the effect of clearance on damage, a study showed that grain was more likely to be jammed when the size of the clearance was close to the size of the grain (Roberts and Willis, 1962). Theoretically, little jamming will occur if the clearance is much smaller than the grain size. The critical clearance that should not be exceeded in order to prevent kernels from jamming can be estimated from the grain shape, the roundness of the screw blade edge, and the coefficient of friction between the grain and surface (Rademacher, 1981). The cost of manufacturing goes up when

<table>
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<tr>
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<td>Screw conveyor</td>
<td>Bouse et al. (1964)</td>
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<tr>
<td>Conveying speed and screw-tube clearance</td>
<td>Wheat</td>
<td>Screw conveyor</td>
<td>Roberts and Arnold (1966)</td>
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<tr>
<td>Number of passes and screw-tube clearance</td>
<td>Wheat</td>
<td>Screw conveyor</td>
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<td>Conveying speed, feed rate, and conveying distance</td>
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<td>Screw conveyor</td>
<td>Sands and Hall (1971)</td>
</tr>
<tr>
<td>Shape of grain, size of grain, and screw-tube clearance</td>
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<td>Conveying speed, inclination angle, flight type, and intake length</td>
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<td>Air velocity, conveying distance, wheat variety, and harvest conditions</td>
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<td>Pneumatic conveyor</td>
<td>Zareiforoush et al. (2010)</td>
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<tr>
<td>Air velocity, grain feed rate</td>
<td>Corn</td>
<td>Pneumatic conveyor</td>
<td>Magee et al. (1983)</td>
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<td>Air velocity, grain flow rate, conveying distance, and discharge device</td>
<td>Rice</td>
<td>Pneumatic conveyor</td>
<td>Chung and Verma (1993)</td>
</tr>
<tr>
<td>Type of conveyor, conveying rate, grain variety, moisture content, and drying condition</td>
<td>Corn</td>
<td>Drag chain conveyor</td>
<td>Johnson (1984)</td>
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<tr>
<td>Conveying distance, feed rate, number of passes, and moisture content</td>
<td>Corn</td>
<td>Drag chain conveyor</td>
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<td>Type of conveyor, feed rate, conveying speed, inclination angle, and moisture content</td>
<td>Corn, soybean</td>
<td>Standard screw conveyor, perforated-tube screw conveyor, U-trough screw conveyor, and vertical bucket elevator</td>
<td>Hall (1974)</td>
</tr>
<tr>
<td>Drop height, impact surface, type of spout end, belt speed, type of elevator bucket, feeding method, temperature, and moisture content</td>
<td>Corn, soybean, and wheat</td>
<td>Free falling, drop sprout, grain thrower, and bucket elevator</td>
<td>Fiscus et al. (1971)</td>
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<tr>
<td>Drop height, impact surface, type of spout end, belt speed, type of elevator bucket, feeding method, temperature, repeated handling, and moisture content</td>
<td>Corn, soybean, wheat, and pea bean</td>
<td>Free falling, drop sprout, grain thrower, and bucket elevator</td>
<td>Foster and Holman (1973)</td>
</tr>
<tr>
<td>Type of flow retarder</td>
<td>Corn</td>
<td>Cushion box, spout retarder, and retro-air retarder</td>
<td>Stephens and Foster (1977)</td>
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<td>Type of conveyor, feed rate, number of passes, inclination angle, and moisture content</td>
<td>Soybean</td>
<td>Steel-flighting screw conveyor, screw conveyor with rubber intake, steel-core bristle screw conveyor, rubber-flight conveyor, pneumatic conveyor, and belt conveyor</td>
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</tr>
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the requirement for the clearance accuracy is high, and thus clearances are generally not small. Mechanical damage also decreases with a screw-tube clearance that is much larger than the grain size; however, the conveying capacity for this configuration is low.

The quality of kernels has been found to degrade only slightly during pneumatic handling (Converse et al., 1970; Magee et al., 1983). Grain kernels are broken by high-speed impacts against the conveying tube, especially at elbow sections. The other major cause of damage is crushing of grain at airlock feeders (Mwaro et al., 2012). The major mechanical parameters affecting the damage level are the air velocity and conveying distance. A study on shelled corn damage in pneumatic conveyors reported that dust production and the percentage of fines increased exponentially when the air velocity exceeded a critical speed of 20 m s\(^{-1}\) (Magee et al., 1983; Baker et al., 1986). Converse et al. (1970) studied mechanical damage to wheat in pneumatic conveyors and found that the grain kernel damage increased almost linearly with the conveying distance.

Grain kernel damage caused by belt conveyors and by drag chain, flight, or en masse conveyors is reported less frequently in the literature as compared to the previously discussed conveyors. Misra et al. (1991) tested the performance of six soybean conveyors, including a steel flight auger, an auger with a rubber intake, a pneumatic conveyor, a rubber belt conveyor, a rubber flight conveyor, and a steel-core bristle auger. Compared with the other types of conveyors, damage caused by the belt and flight conveyors was low (less than 1% by weight). Johnson (1984) quantitatively measured the shelled corn damage caused by drag conveyors and found that the percentage of broken corn increased by less than 1% after conveying for 30 m. The conveyor type (flat bottom and U-trough) and conveying rate had no significant effect on the damage level. Mwaro et al. (2014) determined the damage rates of shelled corn at various moisture contents transported using three different drag conveyors. The percentage of grain breakage ranged from 1.6% to 4.6%, with the highest damage occurring when the conveyor operated below its rated capacity (1/4 of rated capacity). That study indicated that kernel damage was mainly the result of compression between the conveyor flight and casing.

Grain kernels are also subjected to impacts when free-falling or spouting onto a hard surface, such as when unloading grain from a combine into a cart or filling a storage bin. Various drop tests were conducted with shelled corn, soybeans, and wheat (Fiscus et al., 1971; Foster and Holman, 1973). The results showed that mechanical damage to the grain increased with drop height. This is because the kernels gain velocity with increasing drop height, which results in large impact forces (Fiscus et al., 1971). In addition, the velocity of the grain stream could exceed the single-kernel terminal velocity when the drop height was over 15 m (50 ft) because, when the grain stream was dropped as a whole, the drag forces acting on individual kernels were not all the same (Foster and Holman, 1973). Foster and Holman (1973) suggested limiting the drop height to 12 m (40 ft) to reduce free-fall damage. The damage depended on the type of grain when tested at the same conditions.

Wheat was less susceptible to impact damage (percentage damage was less than 0.4%) than soybeans, and soybeans were less susceptible to impact damage than corn. To reduce the damage caused by free-falling and spouting, flow retarders were used to reduce the velocity of the grain stream before exiting the outlet. The effectiveness of a cushion box, spout retarder, and retro-air retarder in reducing damage was studied by Stephens and Foster (1977). It appeared that the flow retarders were able to reduce handling damage; however, the degree of reduction was small.

**DAMAGE CAUSED BY DEHULLING AND MILLING**

Dehulling and milling are the major processes that result in rice breakage (Buggenhout et al., 2013). Dehulling (also called husking) converts rough rice into brown rice by detaching the hull from the kernel. Different from corn and wheat milling, which grinds the grain into flour, rice milling (also called polishing or whitening) converts brown rice into white rice by removing the germ and bran from the endosperm. Rice kernels are subjected to a combination of compression and friction forces during dehulling and milling. These forces separate the endosperm from the bran, germ, and hull. However, the forces induce breakage when the failure strength of the kernel is exceeded. The breakage will become significant if fissures exist in the endosperm because fissures weaken the kernels (Qin and Siebenmorgen, 2005; Iguaiz et al., 2006; Bao, 2019). In addition, it was reported that the percent breakage increases with an increase in the dehulling efficiency (Swamy and Bhattacharya, 1979), mill shaft speed (Yan et al., 2005), and milling duration (Liang et al., 2008).

**OTHER SOURCES OF DAMAGE**

The primary focus of this study is mechanical damage caused by harvesting and subsequent handling operations. However, other sources of pre-harvest and post-harvest damage are discussed briefly in this section.

To increase storage life, grain is dried to a low moisture content before storage in bins. During storage, rewetting (rehydration) can occur due to changes in ambient weather conditions. Many studies have described the kernel damage caused by drying and rehydration (White et al., 1982; Kirkeis and Stroshine, 1990; Wozniak, 2001; Dong et al., 2010). Drying and rewetting generate temperature and moisture gradients within the kernels that create internal tensile stresses (Kunze, 1979). Fluctuations in ambient temperature and relative humidity can induce internal stresses sufficiently large to cause stress cracks (White et al., 1982). The factors affecting stress crack formation were summarized by Gunasekaran et al. (1985) and include drying rate, temperature and moisture gradients, initial and final moisture contents, drying air temperature and airflow rate, and the variety of corn. Improper drying or unfavorable storage conditions can increase grain kernel damage and susceptibility to damage through insect and mold growth during storage (Mohapatra et al., 2017). Damage caused by fungi in stored grains includes generating hot spots that can increase grain temperature up to 64°C (Sinha and Wallace, 1966), producing toxic substances (e.g., aflatoxins, ochratoxins, and fumonisins; Bullerman and
Bianchini, 2007), decreasing germinability, and causing nutrient loss. It was found that the initial contamination level, temperature, moisture content, invasion of pests, and type of storage container are the major factors affecting fungal growth in stored grain (Mohapatra et al., 2017).

**Cumulative Damage**

The damage level of grain increases from harvest to storage. Pierce and Hanna (1985) simulated a sequence of on-farm handling processes, including harvesting, drying, and conveying, and measured the cumulative damage levels and breakage susceptibility after each process. The authors found that the type of damage was highly influenced by the method of handling and processing. Harvesting accounted for 60% of the seed coat damage, while conveying accounted for 65% of the broken corn and fine material. Drying and cooling processes did not directly increase the external damage; however, they contributed to 40% of the breakage susceptibility, which significantly increased the probability of damage in subsequent handling operations.

**Kernel Properties and Loading Conditions Affecting Damage**

In addition to harvest and handling methods, the physical and mechanical properties of the grain kernels, such as moisture content and composition, can affect susceptibility to damage, as well as handling conditions such as grain impact velocity, contact surface type, angle of impact, and kernel orientation of loading. Table 3 summarizes the factors that lead to impact damage of kernels.

**Physical and Mechanical Properties**

Moisture content is one of the most significant factors affecting the level of grain kernel damage. Mechanical properties, such as failure strength, modulus of elasticity, and brittleness, are closely correlated with moisture content. Studies have shown that the breakage susceptibility first decreases with an increase in kernel moisture content and then increases beyond a certain moisture level (Szwed and Lukaszuk, 2007; Shahbazi et al., 2017). Grain kernels at low moisture content are more brittle, less elastic, and have lower rupture energy than kernels at a higher moisture content (Bilanski, 1966; Young, 1968). However, when the kernel moisture exceeds a certain limit, the kernels become too soft to withstand damage (Weller et al., 1990). It has been reported that an optimum moisture content (wet basis) exists for specific types and varieties of grain at which damage would be minimized (Shahbazi, 2011; Shahbazi et al., 2012), e.g., around 22% for corn (Jindal et al., 1979; Quick, 2003), 28% for winter wheat (Szwed and Lukaszuk, 2007), 13% for rapeseed (Szwed and Lukaszuk, 2007), and 17.5% for chickpea (Shahbazi, 2011).

The structure and composition of the grain affect the strength of the grain kernels. For example, soybeans with high lignin content in the seed coat have higher resistance to mechanical damage than soybeans with low lignin content (Capeleti et al., 2005; Kuchlan et al., 2018).

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**Table 3. Summary of factors affecting impact damage.**

<table>
<thead>
<tr>
<th>Factors</th>
<th>Grain Type</th>
<th>Test Method or Device</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content, temperature, and drop height</td>
<td>Pea bean</td>
<td>Free-fall drop test, grain thrower test, bucket elevator test</td>
<td>Perry and Hall (1966)</td>
</tr>
<tr>
<td>Type of handling, drop height, impact angle, impact surface, type of spout end, and feeding method</td>
<td>Corn, soybean, and wheat</td>
<td>Free fall drop test, grain thrower test, and bucket elevator test</td>
<td>Fiscus et al. (1971)</td>
</tr>
<tr>
<td>Type of handling, impact velocity, and contact surface</td>
<td>Corn, soybean, wheat, and pea bean</td>
<td>Free fall drop test, spouting drop test, grain thrower test, and bucket elevator test</td>
<td>Foster and Holman (1973)</td>
</tr>
<tr>
<td>Impact velocity and moisture content</td>
<td>Soybean</td>
<td>Centrifugal impactor</td>
<td>Paulsen et al. (1981)</td>
</tr>
<tr>
<td>Impact velocity and moisture content</td>
<td>Corn</td>
<td>Centrifugal impactor</td>
<td>Singh and Finner (1983)</td>
</tr>
<tr>
<td>Impact velocity and moisture content</td>
<td>Corn</td>
<td>Centrifugal impactor</td>
<td>Sharda (1976)</td>
</tr>
<tr>
<td>Impact velocity and moisture content, impact velocity, impact surface, angle of impact surface, and grain orientation</td>
<td>Corn</td>
<td>Pneumatic projector</td>
<td>Keller et al. (1972)</td>
</tr>
<tr>
<td>Impact velocity and grain orientation</td>
<td>Cottonseed</td>
<td>Static rupture test (seed loading frame), and impact rupture test (pneumatic projector)</td>
<td>Kirk and McLeod (1967)</td>
</tr>
<tr>
<td>Impact velocity, grain size, temperature, grain orientation, and moisture content</td>
<td>Navy bean</td>
<td>Rotating synchronized disks impactor</td>
<td>Moreira et al. (1980)</td>
</tr>
<tr>
<td>Grain orientation and moisture content</td>
<td>Soybean</td>
<td>Rotating synchronized disks impactor</td>
<td>Bartsch et al. (1986)</td>
</tr>
<tr>
<td>Impact velocity and moisture content</td>
<td>Kidney bean</td>
<td>Rotary hammer impactor</td>
<td>Khazaee (2009)</td>
</tr>
<tr>
<td>Impact velocity, number of impacts, and moisture content</td>
<td>Wheat</td>
<td>Rotary hammer impactor</td>
<td>Khazaee et al. (2008)</td>
</tr>
<tr>
<td>Moisture content and impact velocity</td>
<td>Chickpea</td>
<td>Rotary hammer impactor</td>
<td>Shahbazi et al. (2011)</td>
</tr>
<tr>
<td>Moisture content, impact velocity, and grain orientation</td>
<td>Navy bean</td>
<td>Rotary hammer impactor</td>
<td>Shahbazi et al. (2011a)</td>
</tr>
<tr>
<td>Moisture content and impact velocity</td>
<td>Soybean</td>
<td>Rotary hammer impactor</td>
<td>Soosowskis and Kazmiar (1999)</td>
</tr>
<tr>
<td>Impact velocity, moisture content, and grain orientation</td>
<td>Cottonseed</td>
<td>Rotary hammer impactor</td>
<td>Clark et al. (1996)</td>
</tr>
<tr>
<td>Contact surface hardness and grain orientation</td>
<td>Soybean</td>
<td>Rotary bars impactor</td>
<td>Evans et al. (1990)</td>
</tr>
<tr>
<td>Moisture content and impact energy</td>
<td>Wheat, triticate seed</td>
<td>Drop weight impactor</td>
<td>Shahbazi et al. (2012)</td>
</tr>
<tr>
<td>Moisture content and impact energy</td>
<td>Pinto bean</td>
<td>Drop weight impactor</td>
<td>Shahbazi et al. (2011b)</td>
</tr>
<tr>
<td>Impact velocity and moisture content</td>
<td>Corn</td>
<td>Grain impact system</td>
<td>Ajayi and Clarke (1997)</td>
</tr>
<tr>
<td>Grain size and moisture content</td>
<td>Corn</td>
<td>Rigid hammer mill</td>
<td>Jindal et al. (1979)</td>
</tr>
<tr>
<td>Impact velocity and moisture content</td>
<td>Bambara nut</td>
<td>Slingshot impactor</td>
<td>Baryeh (2002)</td>
</tr>
</tbody>
</table>
example is rice chalkiness. Rice chalkiness, mainly caused by high temperature during the ripening period (Miyahara et al., 2017), is the white opaque area in the endosperm (Ogawa, 2016). The chalkiness portion consists of loosely packed starch granules with many air spaces in between the granules that decrease the strength of the kernels (Ashida et al., 2009). As a result, kernel breakage becomes serious during dehulling and milling when chalkiness exists (Patindol and Wang, 2002).

Other physical properties, such as temperature, size, and shape, also have some influence on grain kernel damage (Keller et al., 1972). At low temperatures, grain is more brittle, so handling induces more damage in winter than in summer (Fiscus et al., 1971; Jindal et al., 1979; Kim et al., 2002). Large kernels are more easily damaged than small kernels. Kendall (1978) explained that the stress required for crack propagation increases when the particles become smaller. In addition, larger kernels have more mass and, consequently, are subject to greater force during impact (Hoki and Pickett, 1973). Experimental work has proven this effect of size on kernel damage for corn (Jindal et al., 1979), soybeans (Paulsen et al., 1981), and navy beans (Hoki and Pickett, 1973). For rice, the percent breakage is highly correlated with the kernel thickness (Jindal and Siebenmorgen, 1994). Three-point bending tests indicated that the breaking force was higher for thicker kernels than for thinner kernels (Siebenmorgen and Qin, 2005).

**IMPACT VELOCITY, IMPACT ANGLE, IMPACT SURFACE, AND KERNEL ORIENTATION**

Impact damage is one of the major causes of grain breakage during harvesting and handling operations. The level of impact damage is mainly influenced by the impact velocity, kernel orientation, angle of impact, and surface on which the impact occurs.

Grain impact velocity, which is related to machine parameters such as type of threshing unit (conventional or rotary), cylinder rotational speed, and conveying speed, is a significant parameter influencing the level of damage. Kernels impacting at a higher velocity are subjected to a higher impact load, which consequently leads to more damage. Empirical relationships correlating impact velocity and damage level have been developed for various kinds of grain through single-kernel impact experiments (Bilanski, 1966; Perry and Hall, 1966; Keller et al., 1972; Hoki and Pickett, 1973; Singh and Finner, 1983; Khazaei et al., 2008). For corn and soybeans, the impact damage becomes significant when the impact velocity is higher than 10 m s⁻¹ (Moreira et al., 1980; Bartsch et al., 1986). For navy beans, as the impact velocity increased from 5 to 15 m s⁻¹, the percentage of damaged beans increased from 0.17% to 32.88% (Shahbazi et al., 2011b). As a result, a commonly used method for reducing harvesting and handling damage is to reduce the operating speed or feed rate of the equipment; however, the capacity of the equipment will also be reduced. In practice, an operating condition that maximizes the capacity and minimizes the grain kernel damage must be determined by trial and error.

The angle of impact, i.e., the angle between the direction of grain movement and the impact surface, also plays a role in damage level. Keller et al. (1972) reported that reducing the angle of impact reduced kernel damage; however, the decrease in damage depended on the type of contact surface. For instance, reducing the angle of impact from 90° to 45° reduced kernel damage by 25% on steel and urethane surfaces, while the reduction on a concrete surface was less. The effect of angle of impact varies with the grain type because the kernel shape, structure, and composition differ from one variety to another. Impact damage at different kernel orientations was studied by various researchers for corn (Moreira et al., 1980), soybeans (Bartsch et al., 1986; Evans et al., 1990), navy beans (Hoki and Pickett, 1973), barley (Bilanski, 1966), oats (Bilanski, 1966), and cottonseeds (Clark et al., 1969). Taking soybeans as an example, impacting on the radicle resulted in a decrease in kernel germination rate, while impacting on the cotyledon caused minor damage (Bartsch et al., 1986; Evans et al., 1990). Impact tests considering the influence of contact surface type showed that kernels impacting on a concrete surface experienced more damage than kernels impacting on steel, and grain-on-grain impact caused less damage than impacting on concrete and steel surfaces (Fiscus et al., 1971; Keller et al., 1972; Foster and Holman, 1973; Evans et al., 1990). These results demonstrate that kernels impacting on rougher and less resilient surfaces experienced increased damage.

**MODELS FOR PREDICTING PARTICLE DAMAGE**

**DAMAGE MODELS FOR GRAIN KERNELS**

A property commonly used to indicate the damage resistance of grain kernels is the fracture force or energy. The fracture force or energy is measured using a uniaxial compression test under quasi-static loading conditions (Arnold andMohsenin, 1971). During the test, individual kernels are slowly compressed between two parallel plates until the kernels fail (ASABE, 2012). The fracture force or energy values for various types of grains, e.g., corn (Tarighi et al., 2011; Babic et al., 2013; Seifi and Alimardani, 2014), wheat (Gorji et al., 2010; Babic et al., 2011; Baslar et al., 2012), soybean (Paulsen, 1978; Liu et al., 1990), and rice (Lu and Siebenmorgen, 1995; Bagheri and Dehpour, 2011), are available in the published literature. With a high aspect ratio, rice kernels are susceptible to damage caused by bending forces. Several studies have determined the fracture force of rice using a three-point bending test in addition to a compression test (Lu and Siebenmorgen, 1995; Bagheri and Dehpour, 2011).

The fracture force or energy measured with compression and bending tests provides a good estimation of the static strength of the grain kernels; however, it is not suitable for predicting impact damage. Compared to quasi-static compression and bending, the instantaneous loading rate of impact is much higher (Li et al., 2017). To evaluate the resistance of grains to impact damage, a grain quality indicator called breakage susceptibility was introduced by researchers. Breakage susceptibility refers to the potential for breakage of grain kernels subjected to impact loading dur-
ing handling (AACC, 2010). From the 1960s to the 1980s, various types of breakage susceptibility testers were developed to simulate impact loading during handling (Watson and Herum, 1986; Lowell, 1990), among which the Stein breakage tester (Miller et al., 1981) and the Wisconsin breakage tester (Singh and Finner, 1983) are the two most widely used designs. For these tests, a certain amount of sample kernels are fed into the tester and “propelled to impact against a metal surface and/or other kernels in a controlled manner” (Stroshine, 1992). Breakage susceptibility is then quantified as the percentage of broken kernels of the sample during handling (Paulsen and Hill, 1983). Breakage susceptibility can guide the end use of grain. Grain with high breakage susceptibility is suggested for local use with gentle handling, while grain with low breakage susceptibility can be used for export, which requires repeated handling (Paulsen and Hill, 1977).

Nevertheless, breakage susceptibility only provides an estimation of the relative damage level. Actual damage during handling depends on the severity and number of the operations, which cannot be predicted using breakage susceptibility (Stephens and Foster, 1976). To correlate the damage probability of grain kernels with the impact velocity and/or number of impacts, many studies developed empirical models using single-kernel impact tests. A summary of a number of empirical models for grain impact damage is given in table 4. Researchers have conducted a series of impact damage tests on different grain types and varieties, including mung bean seeds (Shahbazi et al., 2011c), wheat (Khazaei et al., 2008; Shahbazi, 2012; Shahbazi et al., 2012), triticale seeds (Shahbazi et al., 2012), pinto beans (Shahbazi et al., 2011b), lentil seeds (Shahbazi et al., 2012), kidney beans (Shahbazi et al., 2012), and corn (Shahbazi et al., 2012).

Table 4. Summary of empirical models for predicting grain impact damage.

<table>
<thead>
<tr>
<th>Grain Type</th>
<th>Parameters Tested</th>
<th>Apparatus</th>
<th>Impact Condition</th>
<th>Regression Model</th>
<th>Moisture Content (% w.b.)</th>
<th>Speed (m/s or rpm)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton seed</td>
<td>F</td>
<td>Pneumatic impactor</td>
<td>Single kernel</td>
<td>PD = αV^β</td>
<td>6, 10, 14</td>
<td>15.24, 20.32, 25.4, 30.48, 40.64</td>
<td>Kirk and McLeod (1967)</td>
</tr>
<tr>
<td>Soybean and shelled corn</td>
<td>F</td>
<td>Free-fall drop test</td>
<td>In bulk</td>
<td>PD = αV^β</td>
<td>Soybean: 11, 12.5; Corn: 13, 15</td>
<td>12.29, 15.87, 18.54</td>
<td>Foster and Holman (1973)</td>
</tr>
<tr>
<td>Rapeseed and wheat</td>
<td>MC</td>
<td>Rotary hammer impactor</td>
<td>Single kernel</td>
<td>PD = b0 + b1MC + b2MC^2</td>
<td>Wheat: 8, 12, 16, 20, 24, 28, 32; Rapeseed: 5, 7, 9, 11, 13, 15</td>
<td>-</td>
<td>Szwed and Lukaszuk (2007)</td>
</tr>
<tr>
<td>Wheat and triticale seed</td>
<td>MC, N and V</td>
<td>Drop weight impactor</td>
<td>Single kernel</td>
<td>PD = b0 + b1MC + b2MC^2</td>
<td>Wheat: 8, 12, 16, 20, 24, 28, 32; Rapeseed: 5, 7, 9, 11, 13, 15</td>
<td>-</td>
<td>Shahbazi et al. (2012)</td>
</tr>
<tr>
<td>Navy bean</td>
<td>V, VMC and kernel orientation</td>
<td>Rotary hammer impactor</td>
<td>Single kernel</td>
<td>PD = b0 + b1MC + b2MC^2</td>
<td>Wheat: 8, 12, 16, 20, 24, 28, 32; Rapeseed: 5, 7, 9, 11, 13, 15</td>
<td>-</td>
<td>Shahbazi et al. (2011a)</td>
</tr>
<tr>
<td>Bean seed after drying</td>
<td>N and MC</td>
<td>Centrifugal impactor</td>
<td>In bulk</td>
<td>PD = b0 + b1N + b2MC</td>
<td>14, 17, 21</td>
<td>1,000, 1,500, 2,000, 2,500</td>
<td>Ptasznik et al. (1995)</td>
</tr>
<tr>
<td>Shelled corn</td>
<td>N and MC</td>
<td>Centrifugal impactor</td>
<td>In bulk</td>
<td>PD = b0 + b1N + b2MC + b3MC^2</td>
<td>8.5, 13.9, 18.9, 24.1, 29.2; 2,000, 2,500, 3,000, 3,500, 4,000</td>
<td>2,000, 2,500, 3,000, 3,500, 4,000</td>
<td>Singh and Finner (1983)</td>
</tr>
<tr>
<td>Shelled corn</td>
<td>N and MC</td>
<td>Centrifugal impactor</td>
<td>In bulk</td>
<td>PD = b0 + b1N + b2MC + b3MC^2</td>
<td>9.3, 14.1, 28</td>
<td>1,500, 2,000, 2,500, 3,000, 3,500</td>
<td>Sharda (1976)</td>
</tr>
<tr>
<td>Chickpea</td>
<td>V, VMC</td>
<td>Rotary hammer impactor</td>
<td>Single kernel</td>
<td>PD = b0 + b1MC + b2MC + b3MC + b4MC^2</td>
<td>7.5, 10, 12.5, 15, 17.5, 20</td>
<td>5, 7.5, 10, 12.5, 15, 17.5, 20</td>
<td>Shahbazi et al. (2011)</td>
</tr>
<tr>
<td>Kidney bean</td>
<td>V and MC</td>
<td>Rotary hammer impactor</td>
<td>Single kernel</td>
<td>PD = b0 + b1V + b2MC + b3MC + b4MC + b5MC^2</td>
<td>5, 10, 15, 20</td>
<td>5, 7.5, 10, 12</td>
<td>Khazaei (2009)</td>
</tr>
<tr>
<td>Wheat</td>
<td>V, VMC, and n</td>
<td>Rotary hammer impactor</td>
<td>Single kernel</td>
<td>PD = b0 + b1V + b2MC + b3MC + b4MC + b5MC + b6MC^2</td>
<td>7.5, 12, 15.3, 19, 23.3</td>
<td>5, 10, 15, 20, 25, 30</td>
<td>Khazaei et al. (2008)</td>
</tr>
<tr>
<td>Corn before shelling</td>
<td>V, cob MC, V, and n</td>
<td>Rotary hammer impactor</td>
<td>Impact testing machine</td>
<td>PD = b0 + b1VX + ... + b5VX + b6VX + b7VX + ... + b12VX</td>
<td>6, 10, 14</td>
<td>12.7, 15.24, 20.32</td>
<td>Burkhardt and Stout (1974)</td>
</tr>
</tbody>
</table>

Note: PD = percent damage (%), i.e., the amount of damaged kernels divided by the total amount of kernels used in the test; V = impact velocity (m/s), i.e., the linear velocity when the kernel was impacted; N = number of rotations (rpm), i.e., the impeller speed of a centrifugal impactor; MC = grain kernel moisture content (% wet basis); n = number of impacts; and α, β, and b are constants determined by empirical data.
prediction was close to the experimental result of 30 m s\(^{-1}\). It is challenging to compare models because the experiments used to generate the model data used different test apparatuses, grain varieties, velocities, and moisture contents. However, despite these limitations, empirical models have improved researchers’ understanding of the factors that influence grain kernel damage. Moreover, these studies have greatly improved the development and refinement of the apparatuses used to generate kernel damage, e.g., centrifugal impactor (Cooke and Dickens, 1971; Shar- da, 1976; Paulsen et al., 1981; Singh and Finner, 1983; Ptaszni k et al., 1995), pendulum impactor (Srivastava et al., 1976), the pneumatic impactor (Kirk and McLeod, 1967), rotary arm impactor (Sosnowski and Kuzniar, 1999; Szwed and Lukaszuk, 2007; Khazaei et al., 2008; Shahbazi, 2011), slingshot impactor (Baryeh, 2002), and drop bar impactor (Shahbazi et al., 2012).

While empirical models are built on direct observation, measurement, and extensive data, mechanistic models describe the process based on an understanding of physics (Tham, 2007). Over the last decade, attempts have been made to develop mechanistic models for predicting grain kernel damage during handling processes. For example, grain kernel damage has been modeled using the finite element method (FEM) (Segerlind, 1984) to give detailed force and deformation analysis of kernels. In FEM, the kernel is divided into a collection of connected elements, each of which follows a specified stress-strain relationship. The deformation of the system of elements is determined numerically from Newton’s laws. Xu et al. (2013) used FEM to simulate impact between a threshing tooth and a single rice kernel. Based on a stress analysis in a single kernel, the critical velocity corresponding to the critical tensile stress (minimum stress that causes permanent plastic deformation or cracks) was predicted to be 29.5 m s\(^{-1}\). The simulation prediction was close to the experimental result of 30 m s\(^{-1}\). Another study modeled the compression of individual and bulk Jatropha curcas seeds in a container (Petru et al., 2012, 2014). The results of the model indicated that the coefficient of friction between seeds and between a seed and the container played a significant role in the initial stage of the pressing process. The authors observed that the information provided by the FEM model is useful for optimizing the design of oil pressing machines to increase energy efficiency.

In recent years, the discrete element method (DEM) has become a useful tool for studying the mechanics and dynamics of grain systems. In DEM simulations, the dynamics of every kernel is modeled (Cundall and Strack, 1979). At each time step in the simulation, kernel-kernel and kernel-boundary contacts are detected, the contact forces are then calculated based on a contact force model, and the kernel accelerations are found using Newton’s laws. These accelerations are then integrated in time to determine new kernel states. DEM has been used to investigate grain damage, including modeling of compression damage of rapeseed (Raji and Favier, 2004), damage of sorghum and wheat in a vertical screw conveyor (McBride and Cleary, 2009), breakage of corn in drag chain conveyors (Mwario et al., 2014), and wheat breakage during milling (Patwa et al., 2016). The lattice element method (LEM) is an intermediate approach between DEM and FEM and can be used to study the fracture of heterogeneous materials. LEM has been used to model the fragmentation of protein and starch components within wheat endosperm (Topin et al., 2009; Chichti et al., 2016).

Compared to empirical models, mechanistic models can provide deeper insight, can be applied to a greater variety of systems, and can be used to reduce experimental testing (Tham, 2007). However, developing mechanistic models requires a fundamental understanding of the significant physics of the system. In addition, developing and running mechanistic models can be time-consuming.

### Damage Models for Non-Grain Materials

The science of comminution studies the size reduction of solid particles with a specific interest in damage propagation. Various models have been developed and used to predict the damage of inorganic particulate materials, such as rocks and minerals, on the basis of fracture mechanics. In this section, several damage models developed for inorganic materials are reviewed. With proper assumptions and modifications, some of these models may be adapted to predict the damage of grain kernels.

#### Impact Models

Although grain kernel impact damage is undesirable, impact-induced breakage of ore and rock is crucial in size reduction processes, and thus it is widely studied in the science of comminution. The degree of impact damage is usually expressed as a function of impact velocity (\(v\)) or specific kinetic energy (\(v^2/2\)). Different forms of breakage probability models for single impacts were summarized by Rozenblat et al. (2012) and include the logistic model (Petukhov and Kalman, 2004), Weibull model (Djamarani and Clark, 1997; Kapur et al., 1997; Salman et al., 2002; Cheong et al., 2004), lognormal model (Pocock et al., 1998), and power law model (Duo et al., 1996). These models were developed to better predict particle fragmentation during size reduction and pneumatic conveying processes.

A commonly used analytical impact model, developed by Ghadiri and Zhang (2002), predicts the single-impact attrition of particles with a semi-brittle failure mode. The model proposes that the fraction of material removed per impact (\(\xi\)) is:

\[
\xi = \alpha \frac{\rho v^2 l H}{K_c^2} \tag{1}
\]

where \(\alpha\) is a proportionality constant that is independent of the material properties and particle size, \(\rho\) is the particle density (kg m\(^{-3}\)), \(v\) is the impact velocity (m s\(^{-1}\)), \(l\) is the characteristic particle size (m), \(H\) is the particle hardness (Pa), and \(K_c\) is the fracture toughness of the particle.
(N m⁻¹²). The proportionality constant (α) can be determined from a single-particle impact test (Zhang and Ghadiri, 2002). The model was validated by comparing experimental test data collected using the impact device shown in figure 8. Particles made of ionic single crystals were fed into the device individually and accelerated by compressed air to a specific speed. The particles impacted perpendicularly against a rigid target, and the mass loss of the particles was measured.

Using dimensional analysis, Vogel and Peukert (2005) derived a fracture mechanics model to predict breakage probability ($P_B$):

$$P_B = 1 - \exp\left[-f_{\text{Mat}} x k \left(E_m - E_{m,\text{min}}\right)\right]$$

(2)

where $f_{\text{Mat}}$ is a material strength parameter (kg J⁻¹ m⁻¹), $x$ is the initial particle size (m), $k$ is the number of impacts, $E_m$ is the mass-specific impact energy (J kg⁻¹), and $E_{m,\text{min}}$ is the minimum specific impact energy below which breakage does not occur (J kg⁻¹). The material parameters $f_{\text{Mat}}$ and $E_{m,\text{min}}$ can be determined by single-particle comminution experiments using the impact device developed by Schöntert and Marktscheffel (1986), as shown in figure 9. During the test, a single particle is fed into the disk-shaped rotor by the vibration feeder. The rotor accelerates the particle to a specified speed through centrifugal force. At the end of the radial channel in the rotor, the particle is released into an evacuated grinding chamber and then impacts on the sawtooth-shaped target ring at an angle of 90°. A large number of particles (2500 particles for each test condition) were tested to acquire statistically reliable breakage probability parameters.

Shi and Kojovic (2007) proposed a modified Vogel-Peukert model to predict the breakage index, $t_{10}$ (cumulative percentage passing 1/10 of the initial size), instead of the breakage probability of particles. The advantage of $t_{10}$ is that it can be used to predict the full size distribution of the fragments. The parameter $t_{10}$ can be expressed as follows:

$$t_{10} = M \left(1 - \exp\left[-f_{\text{Mat}} x k \left(E_m - E_{m,\text{min}}\right)\right]\right)$$

(3)

where $M$ is the maximum $t_{10}$ value achievable in a single breakage event (%), and $E_m$, $E_{m,\text{min}}$, $f_{\text{Mat}}$, $x$, and $k$ are the same as in equation 2. The model was validated using the data from drop weight tests with eight types of ore (Banini, 2000). The average $R^2$ value was 0.98, indicating that the model fit the data well.

Wear Model

In addition to the damage caused by direct impact, shear also causes a significant amount of wear damage to particles (Ouwerkerk, 1991). Wear damage occurs during industrial processes such as fluidized bed drying and coating, cyclone separation, sandblasting, stirring, and bulk materials handling (Bemrose and Bridgewater, 1987). Meng and Ludema (1995) and Zmitrowicz (2006) reviewed the various wear models developed for solid materials. Meng and Ludema (1995) reported over 300 prediction equations for friction and wear, and they classified these equations into three categories: empirical relationships, contact-mechanics-based equations, and models based on material failure mechanisms. Zmitrowicz (2006) provided an updated summary of wear relationships along with a description of different wear patterns, including abrasion, plowing, erosion, cavitation, corrosion, and fatigue.

In these models, the Archard wear model (Archard, 1953) is widely used for granular materials. When the deformation of the material is in the plastic range, the worn volume ($W$, m³) is proportional to the applied load ($P$, N) and is independent of the apparent area of contact:

$$W = Ks \frac{P}{P_m}$$

(4)

where $K$ is an empirically determined wear coefficient, $s$ is the sliding distance (m), and $P_m$ is the flow pressure (Pa), which is approximately equivalent to the hardness ($H$) of the softer contacting surface. A wide range of materials has been tested using a pin-on-disk system, as shown in figure 10, to acquire the $K$ value and validate the model (Archard and Hirst, 1956). The test setup includes a pin and a flat circular disk positioned perpendicular to the pin. During the test, the pin presses against the disk at a specific load, and the disk revolves around its center. The amount of wear on the pin can be quantified by its volume loss.

Based on empirical analysis on the attrition of catalyst particles in a fluidized bed system, Gwyn (1969) expressed particle attrition as a simple time-dependent power law relationship:
attrition rate with Ouwerkerk (1991) modified Gwyn’s formula to correlate good predictions at large shear strains (Bridgwater, 2007).

The study found that a better fit was acquired when correlating shear cell, were used for particle attrition experiments. The three devices, a fluidized bed, screw pugmill, and annular model with the goal of improving prediction accuracy.

where 

\[ W = K_p t^m \]  

(5)

where \( W \) is the weight fraction attrited (kg), \( t \) is the attrition time (s), \( m \) is a constant independent of particle size, and \( K_p \) is a parameter that is a function of the initial particle size. The relationship is usually applied by replacing time \( t \) with shear strain (\( \Gamma \)). Although the model generally fits the data well, it lacks a theoretical explanation and fails to give good predictions at large shear strains (Bridgwater, 2007).

To account for the effect of applied normal stress (\( \sigma \)), Ouwerkerk (1991) modified Gwyn’s formula to correlate attrition rate with \( \Gamma \sigma \). The model has been found to provide a good fit to the experimental data (Ghadiri et al., 2000):

\[ W = a \left[ \Gamma \left( \frac{\sigma}{\sigma_{ref}} \right)^2 \right]^b \]  

(6)

where \( a \) and \( b \) are stress-dependent constants, and \( \sigma_{ref} \) is a reference stress level (Pa).

Neil and Bridgwater (1999) further studied the Gwyn model with the goal of improving prediction accuracy. Three devices, a fluidized bed, screw pugmill, and annular shear cell, were used for particle attrition experiments. The study found that a better fit was acquired when correlating the attrition rate with \( \Gamma \sigma \), where \( \phi \) is an empirically determined constant. In addition, they combined the Gwyn formula with the Schuhmann function, \( W = W_f(s/dt)^2 \), to better describe the mass-size distribution:

\[ W_f = A \left( \frac{\sigma \Gamma \phi}{\sigma_{SCS}} \right)^b \]  

(7)

where \( d \) is the average initial particle diameter (m), \( d_f \) is the diameter of the largest particle (m), \( W \) is the mass of degradation product having a size less than \( d \) (kg), \( W_f \) is the mass of degradation product having a size less than \( d_f \) (kg), \( G \) is the Schuhmann size distribution modulus, \( A \) (kg) and \( \beta \) are empirical constants, and \( \sigma_{SCS} \) is the side-crushing strength of a single particle (Pa). The model was further validated by Bridgwater et al. (2003) with annular shear cell tests. The authors proved the validity of the model for different particle shapes under a wide range of stresses and strains. However, Ghadiri et al. (2000) pointed out that the model worked well only when fine debris was considered and not when large fragments were included in the model.

**Fatigue Model**

Fatigue damage may occur when a particle is subjected to repeated loading and unloading. The fatigue damage of particles was examined by Jensen et al. (2001) using DEM modeling. In their DEM simulation of particle damage, Jensen et al. (2001) defined a critical energy density \( (W_0, \ J \ m^{-2}) \), and a total energy that the particle can absorb before breakage \( (W_{imax}, \ J) \):

\[ W_{imax} = W_0 V_i \]  

(8)

where \( V_i \) is the volume of particle \( I \) (m³). The authors proposed a particle damage criterion in which a particle breaks only when the accumulated work done to particle \( i \) \( (W_i) \) is equal to or greater than \( W_{imax} \). The particle remains undamaged if \( W_i < W_{imax} \). The value of the critical energy density \( (W_0) \) that gave the best correlation with the DEM simulations was compared to experimental results using quartz sand and calcareous sand grain breakage (Hoteit, 1990). The simulation and the experimental values showed good agreement with each other.

Several fatigue models were developed based on the Vogel-Peukert model. These models assume that no particle damage occurs when the specific input energy is less than the minimum specific impact energy \( (E_{m,min}) \). When the work done on a particle is larger than the \( E_{m,min} \), the particle damage probability increases with the cumulative effective energy:

\[ \sum_i (E_i - E_{m,min}) \]  

where \( E_i \) is the impact energy in the \( i \)th collision of the particle. An incremental breakage model based on the Vogel-Peukert model was developed by Delaney et al. (2013) to predict rock size and shape distributions during comminution in autogenous (AG) and semiautogenous (SAG) mills. The probability of a rock remaining intact decreases until the rock breaks. A modified model was developed to describe the daughter size distribution, \( t(k) \):

\[ t(k) = A(k) \left[ 1 - \exp \left( b(k) \sum_i (E_i - E_{m,min}) \right) \right] \]  

(9)

where \( A(k) \) and \( b(k) \) are coefficients calibrated from drop weight tests.

Capece et al. (2014) modified the Vogel-Peukert model to fit a typical milling process (e.g., a ball mill), during which a particle is impacted multiple times with different impact energies. The total number of impacts \( (k) \) in equation 2 is replaced with:

\[ \sum_{l=1}^{L} f_{coll,l} t^l, \text{ such that} \]

\[ P_B = 1 - \exp \left[ -f_{mat} \sum_{l=1}^{L} f_{coll,l} (E_{m,l} - E_{m,min}) t^l \right] \]  

(10)
where $f_{coll,i}$ is the collision frequency ($s^{-1}$), $t$ is the milling time, and $E_{m}, E_{m,\text{min}}, f_{\text{tar}}, x,$ and $P_{b}$ are the same as in equation 2. The model can be used to quantify milling performance with particle size interactions.

A limitation of the Vogel-Peukert model and associated models is that they do not include parameters that explicitly account for the effect of material weakening due to repetitive impacts (Tavares, 2009). A fatigue model proposed by Tavares (2009) assumes that the stiffness of the particle decreases under repeated loading events. This weakening effect can be described by a variable $(D)$ called the degree of damage. The degree of damage generated in the $n$th loading event $(D_{n}^*)$ is calculated as:

$$D_{n}^* = \left[ \frac{2\gamma}{2\gamma - 5D_{n}^* + 5} \right]^{\frac{2\gamma}{5}}$$

(11)

where $\gamma$ is a damage accumulation coefficient calculated from impact or quasi-static compression tests, $E_{k,n}$ is the specific impact energy at the $n$th impact event (J kg$^{-1}$), and $E_{n-1}$ is the specific fracture energy of the particle before the $n$th impact (J kg$^{-1}$). The diminishing stiffness leads to a decrease in the specific fracture energy. The relationship between the specific fracture energy before $(E_{n-1})$ and after $(E_{n})$ loading event $n$ is as follows:

$$E_{n} = E_{n-1}\left(1 - D_{n}^*\right)$$

(12)

If the loading energy for a given loading event is larger than the specific fracture energy, the particle will be broken. When implementing the model, equations 11 and 12 need to be solved simultaneously for $D_{n}^*$ with an iterative procedure.

A different approach to modeling fatigue damage is to calculate the decrease in particle strength (Rozenblat et al., 2013) expressed in terms of a breakage force. The reduced compression strength after $n$ loading events is modeled by:

$$F' = F_{m}\left[1 + \frac{P_1}{\exp\left(P_3 - P_2\left(F_{p}^*\right)^{\frac{1}{3}}\right)}\right]^{\frac{3}{2}n}$$

(13)

where $F'$ is the new compression strength (N), $F_{m}$ is the initial compression strength (N), $F_{p}^*$ is the ratio between the applied normal compression stress and initial compression strength, and $P_1$, $P_2$, and $P_3$ are model parameters evaluated by functions of the system and material properties. When implementing the model, $P_1$ can be assumed to be a constant, while $P_2$ and $P_3$ can be determined by fitting single-particle impact test data.

CONCLUSIONS

This article reviewed various aspects of grain kernel mechanical damage during harvesting and handling operations. The topics examined included the types of damage, sources of damage, factors affecting damage, and models used to predict damage. Single-kernel damage tests using lab-built devices have been used to study the effects of loading conditions and of physical and mechanical properties of the grain on damage level, while bulk material damage tests using actual harvesting and handling equipment have been conducted to study the effects of operational settings on damage level.

Predicting grain kernel damage is challenging for several reasons. First, kernel damage processes are complex, with the underlying mechanisms remaining unclear or impractical to model precisely. Second, grain kernels are irregularly shaped, anisotropic, heterogeneous, and nonlinear viscoelastic materials. Moreover, their properties may change due to moisture content or biological activity (Sarig, 1991). Third, harvesting and handling operations create diverse loading conditions, which are hard to model exactly. Fourth, grain kernel damage can take different forms, e.g., different types of external and internal damage. Lastly, measuring and quantifying damage is challenging. There is no common agreement on how to quantify the severity of damage, and measuring the damage level can be time-consuming, depending on the method.

Various empirical models have been developed with regression analysis to correlate the damage level with the influencing factors. However, these models are essentially curve fits to considerable experimental data, which are often not generalizable and typically do not give insight into the physics of grain damage. According to this review, only a few studies have attempted to develop mechanics-based damage prediction models for cereal grains. More effort is needed in developing, applying, and validating mechanics-based models because such models would be helpful in designing and operating harvesting, handling, and processing equipment to reduce damage and improve grain quality.

Particle damage has been studied extensively for minerals, soils, composites, and pharmaceuticals, which have relatively homogeneous properties, but the damage prediction models for those materials have not been widely extended to grain kernels. There is potential for adapting the models developed for inorganic materials to predict grain kernel damage. However, application of those models to grain kernels would require modifications and assumptions to overcome the variability in kernels due to variety, physical characteristics, chemical composition, etc. Appropriate adoption of such models would help in developing improved mechanistic models using modeling techniques such as FEM, DEM, and LEM.

ACKNOWLEDGEMENTS

The authors would like to thank CNH Industrial for financial support.

63(2): 455-475 469
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