

GENOTYPIC DIFFERENCES IN LODGING AND MECHANICAL STRENGTH IN
STALKS AND PEDUNCLES OF PEARL MILLET (Pennisetum glaucum
(L.) R. Br.)

by

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Differences were found in lodging and mechanical strength tests among pearl millets, pearl millet x napier grass (PMxNG) lines, test crosses and sorghum. In 1987 field lodging ranged from 0 to 98%. Test crosses with PMxNG lines lodged worse on average than the millets or sorghum, but they were superior to the millets and sorghum in mechanical stalk strength tests. Field observations showed that most lodging in PMxNG test crosses was due to peduncle breakage. Stalk and peduncle lodging were distinguished in 1988 and peduncle lodging was more critical than stalk lodging. The PMxNG test crosses were superior to the millets and sorghum in rind thickness of basal stalk internodes, which in all genotypes was correlated with stalk crushing strength (0.59* to 0.97**) and stalk breaking strength (0.70** to 0.98***). Sorghum was generally superior in all traits except stalk crushing strength, yield, tillering and peduncle length. Unlike millet increased peduncle length in sorghum had no effect on either stalk or peduncle lodging. Rind thickness and diameter were important in imparting strength to stalks and peduncles. The range of correlations found between traits were 0.49* to 0.84* for rind thickness with diameter of peduncle;

0.74** to 0.86*** for peduncle with stalk diameters; and 0.69** to 0.90* for diameter with length of peduncle. Inconsistencies existed between field lodging and mechanical strength tests. Strong correlations were found (0.77** to 0.96**) between crushing strength and breaking strength but correlations between the stalk and peduncle strength tests were inconsistent. Although there was heterosis for increased stalk and peduncle strength in test crosses, increased height, tillering and yield often gave more lodging. Generally, seed parent 68B (or 68A) per se or in test crosses proved superior to 23DBE (or 23DAE) in peduncle lodging. The best average combiners were lines 86-59110-9 for stalk diameter and rind thickness and 88134 for peduncle rind thickness.

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M.F.P.

TO MY CHILDREN

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INTRODUCTION

The struggle by researchers against crop lodging has persisted for a long time yet despite the abundant knowledge available in this subject, crop lodging is still a major problem in grain cereal production. Lodging is a quantitative trait which results from several factors interacting in an intricate manner (Arnold et al., 1974). Often the genotype X environmental interactions complicate field evaluation and effective selection for lodging resistance (Hess and Shands 1966; Zuber and Loesch 1966; Pendleton, 1954). Factors that could be associated with lodging include high yield levels, poor cultural practices, early maturity, weather, improper nutrient balance, height, inherent structural weakness and their interactions.

Crop lodging has been associated with losses in yield. Norden and Frey (1959) cited Mulder (1954) to have found 60% grain yield losses in cereals, while Zuber and Kang (1978) estimated 5 - 25% annual grain yield losses in maize due to lodging. Pendleton (1954) reported 37% yield losses due to lodging 4 days after heading in spring oats. In winter wheat, yields decreased by a third if lodging occurred 1 to 2 weeks before and 1 to 2 weeks after heading (Laud and Pauli 1956). Wiebel and Pendleton (1964) reported greater decrease (31%) in winter wheat grain yield when artificial lodging was imposed at heading stage than at any other stage thereafter. Lodging has been shown to influence quality. Artificial lodging increased the protein content of the grain in winter wheat (Wiebel and Pendleton, 1964) and in sorghum (Larson and Maranville, 1977) but lodging resulted in low total protein production

and reduced kernel size (Laud and Pauli, 1956). Artificial lodging of soybeans affected quality of seed which varied with date of lodging (Leffel, 1961).

Lodging of plants in a field is rarely consistent in time and space. Consequently researchers have resorted to using quantitative mechanical methods and techniques that are less dependent on environmental conditions to determine the inherent strength in maize (Albrecht and Dudley, 1987; Beck et al., 1987; Sibale et al., 1987; Berzonsky et al., 1986; Colbert et al., 1984; Foley and Clark, 1984; Donovan et al., 1982; Helms, 1982; Twumasi-Afriyie and Hunter, 1984; Schertz et al., 1978; Undersander et al., 1977; Chang et al., 1976; Arnold et al., 1974; Miller and Myers, 1974; Thompson, 1972, 1965, 1963; Cloninger et al., 1970; Singh et al., 1969; Loesch et al., 1963; Zuber and Grogan, 1961); in sorghum (Schertz et al., 1978; Bashford et al., 1976); in wheat (Miller and Anderson, 1965, 1964; Atkins, 1938; Bartel, 1937) and in barley (Leasure et al., 1948).

Progress has been made using the mechanical methods and techniques in identifying and developing lodging resistant lines in breeding programs in maize and small grain cereals. The author is not aware of any published report and there does not seem to be any in pearl millet [Pennisetum glaucum (L.) R. Br. syn P. americanum (L.) Schum., P. typhoides (Burm.) Stapf & Hubb.] (W.M. Stegmeier, FHBES, KSU, Personal communications).

Grain pearl millet is an important food crop in less fertile sandy soils in tropical regions where drought and nutrient stress are prevalent. Here stiffer stalks would help with thatching and

construction which are additional uses of the residues of the grain crop. Pearl millet also has potential as a summer feed grain crop in warm temperate regions with lower rainfall but would need sufficient lodging resistance to withstand fall weather conditions before and at maturity. The objectives of this study were two-fold:

1. To observe the range of differences for lodging in the germplasm available in the millet breeding program at the University of Nebraska - Lincoln.

The following questions were of principal interest:

- a) Does there exist apparent variability for lodging resistance?
 - b) Could napier grass, Pennisetum purpureum Schum. potentially be a source of stem strength?
2. To see whether any phenotypic or structural characteristics of the crop are associated with reduced or increased lodging, as observed in the field.

LITERATURE REVIEW

TYPES OF LODGING:

The type of lodging in cereal crops depends on where the plant most often breaks or bends, and therefore on the morphology of the crop. Root and stalk lodging are universal but peduncle lodging could be specific to sorghum, millets, wheat, barley, oats and any other crops with terminal inflorescences.

1) ROOT LODGING - occurs when plants lean at an angle, which in maize, Thompson (1972) defined as more than 30° from the vertical but the stems may remain rigid and straight (Pinthus, 1967). Root damage weakens the anchorage of plants. Root lodging usually occurs under storm conditions (Bhamonchant and Patterson, 1964). In maize, Liebhardt and Murdock, (1965) discovered that root lodging resulted from poor brace root development and parenchyma breakdown.

Mechanical methods have been used to measure root strength in maize as a selection criterion for genotypes with superior resistance to root lodging (Beck et al., 1987; Donovan et al., 1982). These methods were found to be faster, more efficient, more accurate and requiring less labour than manual techniques (Beck et al., 1987). Larson and Maranville, (1977) manually forced sorghum plants to a 45° angle at heading over two years and found 15 to 21% yield reduction. Martin and Russell, (1984a) did not find significant differences for root lodging among BSI maize entries although root lodging had highly significant r values with stalk strength/cross section area, stalkrot rating, and rind strength. Recurrent selection for stalkrot [*Diplodia maydis* (Berk.)

Sacc.] and increased European corn borer resistance in BSAA maize synthetic was associated with percent lodging (Nyhus and Russell, 1987). Application of Potassium chloride at 168 kg/ha decreased natural root necrosis in maize (Martens and Arny, 1967b). Experimental results with Black beans (Phaseolus vulgaris L.) led Stoffella et al., (1980) to suggest that a large root biomass might be an important component of lodging resistance.

2) STALK LODGING. In maize stalk lodging results primarily from parenchyma disintegration in the lower portion of the stalk (Liebhardt and Murdock, 1965). Delayed senescence (stay green condition) controlled by a single dominant gene has been associated with improved stalk quality without change in grain maturity (Cavalier, 1984; Duvick, 1984). Gentinetta et al., (1986) described the major effects of delayed senescence in maize as high water and chlorophyll contents in the leaves at physiological maturity; high sucrose content in the stalk during grain filling; and high protein content in the grain. Potassium chloride applied at 168 kg/ha delayed death of maize plants (Martens and Arny, 1967b).

When studying wind resistance in barley, Grafius (1958) noted that the moment of force about the base of the culm caused by wind on the heads was an important factor in determining lodging. Ever since Zuber and Grogan, (1961) devised a mechanical technique for measuring stalk strength in maize, many morphological characters have been found to impart strength to stalks. Helms (1982) used the potential torque technique on ear height and ear weight as a possible criterion for use in selecting for reduced stalk breakage.

High yield has been associated with high incidence of lodging. This has been attributed to the increased mechanical stress placed on stalks of high yielding genotypes. Investigating the peculiar morphological characteristics of stalks of barren maize plants, Collings (1925) concluded that true barren plants grow taller, more erect, and have a sturdier appearance than do plants bearing ears. Plants which do not produce ears rarely lodge (Campbell, 1964). Broadhead (1973) found that deheaded sorghum plants lodged less and had more side branches than normal plants.

3) PEDUNCLE LODGING. Breakage of sorghum peduncles usually precludes further stalk breakage because the center of gravity is lowered and wind resistance is reduced (Schertz et al., 1978). Bashford et al., (1976) noted that the tissue immediately above the peduncle node was the weakest point on the sorghum plant. Esehie et al., (1977) found that susceptible sorghum types had longer peduncles of smaller diameter. In 1987, the author observed peduncle lodging to be the most serious form of lodging in pearl millet and that peduncles of dwarf pearl millet and sorghum lines were sometimes longer than the rest of the stalks.

FACTORS INFLUENCING LODGING:

1) PLANT POPULATION. New hybrids have higher yield advantage than old ones due, to some extent, to high plant densities which are possible with improvements in stalk quality and other characters.

Nitrogen greatly influenced lodging only when maize plant population exceeded 15,000-20,000 plants/acre (Krantz and Chandler, 1951). Mortimore and Ward, (1964) noted that high corn population densities and late defoliation caused a reduction in sugars. Zuber and

Dicke, (1964) and Thompson (1964) reported that increased corn plant population resulted in a decrease in crushing strength and rind thickness.

An increase in corn population to 32,000 plants per acre decreased yield and increased the barren plants and percent protein of the grain (Pendleton and Seif, 1961). Following selection for high crushing strength in two maize synthetics, Berzonsky et al., (1986) found stalk lodging was not increased at high plant density due to improved stalk quality. Plant population in maize did not affect stalk solids concentration but when pollination and grain development were prevented, total soluble solids in stalks increased until the end of growing season (Hume and Campbell, 1972).

2) PLANT NUTRITION, CONSTITUENTS, AND CULTURAL PRACTICES. Soil fertility has been reported to influence stalk lodging and stalk rots. Nutrient balance is considered important in reduction of lodging and stalkrot (Martens and Arny, 1967b; Parker and Burrows, 1959). Krantz and Chandler, (1951) found lodging to decrease with application of potash on potash deficient soils but lodging was not affected on soils not deficient in potash. High lodging maize strains were associated with high potash and silicon but the reverse was true for strains with low lodging and low ash (Zuber and Loesch, 1966; Zuber et al., 1957).

Investigating the possible mechanisms causing premature breakdown of parenchyma in K-deficient maize stalks, Liebhardt et al. (1968) proposed translocation of compounds from the stalk to the ears as the major causal phenomenon. They found parenchyma breakdown occurred only when an ear was present on the plant. Liebhardt and Munson, (1976)

found 64% of maize lodged in plots receiving no potassium and no chloride or chloride as NH_4Cl , while lodging was only 16% with comparable KCl treatments. They concluded that reduction in lodging was due to Potassium and not chloride. Application of more than 83 lb/acre of K as K_2O on maize did not significantly reduce occurrence of dead stalks and stalk breakage (Josephson, 1962). Lodging-resistant sorghums contained higher total non-structural carbohydrates(TNT) and lower stalk Potassium and protein concentrations (Esechie et al., 1977). Arnold et al. (1974) found Potassium additions reduced the percent of senescent stalks and stalk lodging. Using breaking strength of maize 10 days after mid-silk, Abney and Foley, (1971) found highest inherent stalk strength for resistant and susceptible hybrids on plots receiving Potassium. In a greenhouse hydroponic experiment, the Ca+Mg+K treatment gave the tallest pearl millet and Sudangrass [Sorghum sudanense (Piper) Staph] plants (Shneider and Clark, 1970).

Krantz and Chandler, (1951) reported that nitrogen had little tendency to increase lodging in maize. They concluded that high plant populations, low levels of K and varietal differences were more important for lodging than nitrogen. However, incidence of lodging in winter wheat increased with increasing N or P application especially in the fall (Miller and Anderson, 1964). Stalk rot incidence in maize was decreased with increased Potassium sulphate and Potassium metaphosphate (Younts and Musgrave, 1958). A high N:K ratio (200:0) greatly increased severity of internal rot, stalk breakage and premature dying of maize plants (Foley and Wernham, 1957). Stalkrot of maize was less severe under balanced N:P ratio than when less N was present (Otto and

Everett, 1956). Martens and Arny, (1967b) noted on maize that application of Potassium chloride (168 kg/ha) increased stalkrot when stalks were inoculated with Diplodia maydis[(Berk) Sacc.], D. zae[(Schw.) Lev.]. Norberg (1987) found that application of ethephon altered the morphology of the corn plant which led to reduced lodging and less harvestable yield.

Stalk sugar content has been shown to be a factor in lodging resistance (Liebhardt et al., 1968; Campbell, 1964; Mortimore and Ward, 1964). Maize stalks accumulate carbohydrates primarily as sucrose, glucose, fructose and other soluble solids [Hume and Campbell, 1972 citing Loomis (1935)]. By 3 to 4 weeks after anthesis maximum amounts of soluble solids accumulate (Hume and Campbell, 1972; Campbell, 1964; Welton and Morris, 1930) and then rapidly decline during the grain filling stage (McBee and Miller, 1982; Daynard et al., 1969) due to translocation from stalk to grain (Hume and Campbell, 1972). Hume and Campbell, (1972) also noted that plant population did not affect concentration of soluble solids but greatest total accumulation occurred at high plant populations. Prevention of kernel development and low plant population densities in maize maintained or increased the sugars in the pith (Mortimore and Ward, 1964).

Twumasi-Afriyie and Hunter, (1982) found a highly significant negative correlation between stalk lodging and stalk sugar content at maturity in maize. Colbert et al., (1984) were able to significantly increase soluble stalk solids with five cycles of recurrent selection in maize. They also found significant positive correlation between grain yield and soluble solids but grain yield was negatively correlated

with natural stalk lodging.

The degree of lignification in vascular bundle elements and parenchyma cells; the density or pattern of silica deposition in the epidermis; the number of vascular bundles per unit area; and the number of fibers per bundle have been thought to impart strength to plant tissues. Observing lignification and thickness of walls of cells enclosing the vascular bundle sheaths within the central whorl of young sorghum leaves, Blum (1968) was able to characterize genotypes into resistant and susceptible types to sorghum shootfly (Atherigona varia soccata). He also observed different patterns of silica depositions. Schertz and Rosenow, (1977) found prominent differences in the number of cells within lignified walls and in wall thickness in sorghum. Lignification differences occurred in the epidermis, subepidermis and vascular bundles. Selecting for high crushing strength in maize populations, Undersander et al. (1977) found non-significant differences in lignin and cellulose contents of selected versus non-selected populations. Kiesselbach (1949) reported that internode length depends largely on the amount of lignification of the sclerenchyma next to the epidermis and surrounding the peripheral bundles. Murdy (1960) indicated that thick-walled, lignified cells were primarily responsible for stalk strength in maize but Chang and Loesch, (1976) point out that the inherent strength of stalks cannot be attributed to only one anatomical trait. They also found area of lignification was correlated with rind crushing strength responses to selection.

3) PLANT DISEASES. Stalkrots caused by Diplodia zeae(Schw.) Petch.; D. maydis, Colletotricum graminicolum(Ces.) G. W. or Fusarium moniliforme

(Sheld.) have been associated with lodging. Mortimore and Ward, (1964) conceptualised that root and stalkrots are diseases related to the onset of senescence and produce no visible symptoms until physiological maturity. Stalk rot contribution to lodging susceptibility led Loesch et al., (1972) to conclude that stalk strength per se does not assure resistance to stalk lodging.

Conditions associated with susceptibility of maize to stalkrot (Koehler, 1960) were: inherent susceptibility, artificial or natural leaf damage and adequate supply of Potassium with high levels of Nitrogen. Factors that have been implicated in resistance include carbohydrates (De Turk et al., 1936; Holbert et al., 1935); structural constituents (Smith et al., 1938); moisture content (Roberts, 1950; Durrell, 1923); and substances in stalk tissues (Taylor, 1952; Johann and Dickson, 1945). Resistance has been reported to decrease with time (Pappelis and Smith, 1963; Hooker, 1956; McNew, 1937; Durrell, 1923; Burrill and Burrett, 1909) with upper internodes being more susceptible than basal ones (Hooker, 1957, 1956).

Pappelis (1975) found poor correlation between early pith condition ratings and both artificially induced and natural stalk rotting, but they were able to classify maize inbred lines according to their pith condition ratings. Pappelis and Smith, (1963) noted histological observations indicated that spread of D.zeae in maize was limited to dead cells in stalk pith and spread of Diplodia was inhibited by living cells. Cloninger et al., (1970) deduced that stalk rot ratings had limitations in evaluating stalk quality because some maize hybrids could suffer considerable stalkrot yet still retain satisfactory

crushing strength. Mesterhazy (1982) noted that greater rind resistance gave higher stalkrot resistance in maize.

4) INSECT PESTS. European corn borers; shootfly larvae; and wheat stem sawfly larvae have been reported to aid stalk lodging. Twumasi-Afriyie and Hunter (1982) enhanced stalk lodging by infesting maize plants with corn borers. Corn borers provided avenue for fungi entrance and increased stalk rot incidence which aggravated the damage caused by the corn borer (Christensen and Schneider, 1950) and the tunneling in the maize stalk reduced stalk-crushing strength (Zuber and Dicke, 1964). Lebsack and Kosh (1968) successfully used stem-solidness in wheat as an indirect selection for sawfly resistance where solidness is expressed. Their conclusion supported that of Eckroth and McNeal, (1953) and McKenzie (1965). Studying the extent of infestation of stem borers in sorghum, Hsu (1936) found consistent association for borer infestation with colour of grains and weight of plants. White grain varieties had less infestation than varieties with other grain colours.

MORPHOLOGICAL AND ANATOMICAL CHARACTERS ASSOCIATED WITH LODGING:

1) RIND THICKNESS. Magee (1948) defined the rind of the stem as the tough zone of cells which includes the epidermis, hypodermis, and all vascular and non vascular tissues through the lignified portions of the pith parenchyma. Chang et al. (1976) described the maize stalk as consisting of the rind and pith components with the rind contributing more to overall stalk strength. The rind of a maize stalk consists of sclerified cells adjacent to the stalk epidermis (hypodermis), thick-walled parenchyma cells between vascular bundles, and vascular bundles with sclerified bundle sheaths (Murphy, 1960).

Rind thickness has been shown to be highly correlated with actual field lodging (Loesch et al., 1963; Zuber and Grogan, 1961). McRostie and McLachlan, (1942) observed that lodging resistant maize hybrids had more lignification within the rind than lodging susceptible ones. Zuber and Loesch, (1966) found significant negative correlations between ash content and crushing strength, rind thickness, and weight of a 2-inch stalk section while Loesch et al. (1972) noted positive correlation for weight of section and rind thickness with stalk strength. Stem diameter was positively correlated with crushing strength and rind thickness (Zuber and Grogan, 1961). Loesch et al. (1972) reported that D. maydis infection did not affect rind thickness but reduced crushing strength for lodging susceptible crosses. The higher correlation of crushing strength to lodging resistance than rind thickness led Thompson (1963) to conclude that crushing strength was a better measure of lodging than rind thickness but CV values showed higher plant to plant variation for crushing strength than rind thickness. Testing for stalk properties of maize germplasm for five years, Foley and Clark (1984) observed highly significant positive correlation for rind thickness and stalk diameter. There was a significant year effect for rind thickness and accessions with high mean rind thickness came from diverse regions.

Miller and Myers (1974) obtained significant negative correlations between pith cell death ratings and each stalk quality components of crushing strength, rind thickness, rind puncture, and weight of a 5.1 cm internode section in both maize populations studied. Potassium additions increased crushing strength and rind thickness while

nitrogen and phosphorus had little influence on the two characteristics (Arnold et al., 1974). A significant inbred line x year interaction for crushing strength and rind thickness led Zuber and Loesch (1966) to suggest the need to measure these traits for more than one year.

2) PLANT HEIGHT AND STALK CHARACTERISTICS. Plant height is affected by genotype, climate and soil conditions (Pendleton and Seif 1961). In oats large culm diameter, thick culm wall, short internodes, short height, and long leaf sheath have generally been associated with lodging resistance (Norden and Frey, 1959). Investigating the morphological characters and lodging in oats, Bhamonchant and Patterson, (1964) found significant negative correlations between lodging resistance and plant height, lengths of first two internodes, lowest internode, and length of exertion of peduncle. In the same study, lodging resistance was significantly and positively correlated with diameters of second and lowest internodes, but was not significant for length of peduncle and number of nodes. Independent genetic and environmental variances for plant height were realised in oat crosses studied in F2 to F6 generations (Frey, 1959). Significant correlations existed between breaking strength of oat straw and weight of straw broken and height of culm (Davis and Stanton, 1932).

In sorghum larger diameters of basal internodes and peduncles, shorter peduncles, shorter plant height, higher weight of 5cm basal and peduncle stalk sections and thicker rind were associated with lodging resistance (Esechie et al., 1977). Inbreeding depression resulting from one generation of selfing in pearl millet composites had little effect on plant height and days to flowering (Rai et al., 1985). Significant

increase in grain yield following selection for high stalk-crushing strength in maize was associated with increased plant height for MoSQA and in undesirable increase in ear height, plant height, and delay in maturity for MoSQB synthetic (Berzonsky et al., 1986).

3) NUMBER, SIZE, AND DISTRIBUTION OF VASCULAR SYSTEMS. Sass (1955) described the anatomy of maize and Maiti and Bisen (1980) the anatomy of pearl millet. Studying the vascular system of maize, Hershey and Martin (1930) observed that about 40 days after planting approximately 90% of the vascular bundles have been formed. Increasing plant population from 1 to 3 plants per hill to 15 plants per hill caused about 50% reduction in the number of vascular bundles of the first and second internodes. McRostie and McLachlan (1942) noted that the number of vascular bundles within the lignified area in the rind was positively correlated with lodging resistance. Correlations of 0.66-0.72 were observed between number of vascular bundles and stem diameter. The number and size of vascular bundles in small stems were reduced by 36% and 27-30%, respectively (Martin and Hershey, 1935). Heimsch et al. (1950) reported a progressive decrease in number of vascular bundles from lower to higher internodes, but the number in lower internodes was not constant. On the other hand Weaver (1946) reported that at maturity the average cross section areas of internodes below the 13th were the same, and there was a progressive decrease in size and number above the 13th internode toward the apex.

McRostie and McLachlan (1942) noted that the extent of lignification of maize stem tissue and number of vascular bundles in the third internodes were about one fourth less than that of the first

internodes. They reported high correlations between diameter of internodes and diameter of vascular bundles. Bundles were progressively smaller in successively lower internodes but an associated increase in sheath sclerenchyma and thickness of fiber cells.

Murdy (1960) described the strengthening system of a maize plant as consisting of thick-walled, lignified cells found in three stem tissues, viz, hypodermis, peripheral bundle sheaths, and sclerified ground parenchyma. The relative importance of these tissues for stem strength varied from the base to the apex of the plant. Sclerified parenchyma was most important in lower internodes, hypodermal parenchyma (consisting of long fibers) was most important in middle and upper internodes while peripheral bundle sheaths (consisting of short fibers) increased in importance toward the stem apex.

Hunter and Dalbey (1937) contrasted the erect maize plants from lodged plants as having thick bundle sheaths surrounding the vascular bundles, thick subepidermal sclerenchyma, and angular cells with few intercellular spaces. Magee (1948) noted that a strong stalked maize plant had a low bundle number per square millimeter in the rind, a high percentage of sheath per bundle, a large stalk diameter, and a wide lignified zone.

Using diallel analysis, Chang and Loesch (1972) determined the nature of genetic variation among 66 F1 maize hybrids. General combining ability mean squares were small and not statistically significant for area of cross-section, area of rind, area of pith, and number of vascular bundles in pith. The latter was a poor indicator of strength.

Looking at anatomical variation in stalk internodes of 12

diverse lines of sorghum, Schertz and Rosenow (1977) observed most prominent differences in number of cells with lignified walls and wall thickness, and differences occurred in lignification in the epidermis, subepidermis and vascular bundles. In barley, oats, wheat and rye, thickness of cell walls was reported to be related to lodging resistance (Garber and Olson, 1919). They also found that the average number of vascular bundles in oats and barley was correlated with average number of culms. James and Smith (1970) observed that differences in distribution of fibrovascular bundles in sugarcane (Saccharum spp.) accounted for less than 1% of the variation in strength of single stalks while about 76% of the variation in stalk strength was attributed to differences in diameter and percent fiber of stalks.

Stiff and Powell (1974) compared the stem anatomy of turfgrass genera Cynodon, Zoysia, Agrostis, Poa, Stenotaphrum festuca, and Digitaria for wear-resistant turf, potential thatch problems and other traits. Three types of stems were distinguished: single ring - presence of a single ring of major vascular bundles embedded in the fiberond; multiple rings - a ring of minor bundles in the periphery of the fiberond, a ring of major bundles embedded in or connected to the fiberond, and a third ring of major bundles deeper in pith; and complex rings - minor bundles in the cortex, major bundles embedded in the fiberond and disposed throughout the pith.

METHODS FOR MEASURING LODGING / STALK STRENGTH:

1) FIELD EVALUATION - Natural lodging has been evaluated in the field qualitatively using any or a combination of any of the three procedures: counting the lodged and unlodged plants; expressing lodging in

percentage; or visual scale-rating.

The field counting procedure has normally been done at maturity of the crop, in maize (Thompson, 1963; Zuber and Grogan, 1961); in oats (Egorov, 1938 cited by Pendleton, 1954). This procedure is dependent on environmental forces and although it provides a measure of lodging, little information concerning the relative importance of component factors is provided. The procedure has served well in the past but it has become increasingly difficult to make additional progress (Thompson, 1963).

Expressing lodging in percentage has been done in oats (Hess and Shands, 1966; Murphy et al., 1958); in maize (Davis and Crane, 1976); in sorghum (Schertz et al., 1978). Berzonsky et al. (1986) expressed percent of lodged stalks per plot as [(number of lodged plants / total plants in a plot)] x 100. Visual scale-rating has been used in oats (Grafius, 1966). In sorghum, Ibrahim et al. (1985) used a scale from 1 (erect) to 10 (prostrate) while in barley, Leasure et al. (1948) used a 0 to 3 scale rating. Zero was taken as erect; 1, culms inclined from 0 to 30° from the vertical; 2, culms inclined from 30° to 60° and 3, culms inclined over 60°.

2) CRUSHING STRENGTH. Zuber and Grogan (1961) devised a mechanical method for testing the inherent strength of plant stalks by breaking an internode section laid horizontally and crushing another internode section placed vertically. They found that lines that had higher breaking and / or crushing strength were also lodging resistant, and vice versa. Many researchers have been able to successfully use the crushing strength method on lower stalk internode sections of mature

plants to identify stiff stalk lines in maize (Albrecht and Dudley, 1987; Berzonsky et al., 1986; Colbert et al., 1984; 1978; Thompson, 1982; 1972; 1964; 1963; Twumasi-Afriyie and Hunter, 1982; Zuber et al., 1980; Zuber and Loesch, 1966; Zuber and Grogan, 1961; Undersander et al., 1977; Chang et al., 1976; Arnold and Josephson, 1975; Arnold et al., 1974; Loesch et al., 1972; 1963; Singh et al., 1969; McRostie and McLachlan 1942; and in sorghum (Schertz et al., 1978).

Thompson (1964) and McRostie and McLachlan (1942) used crushing strength to compare the strength of successive internodes of maize below the ear. They found that strength decreased from lower to higher internodes. Schertz et al., (1978), Thompson (1963), Loesch et al., (1963), Zuber and Grogan, (1961), McRostie and McLachlan, (1942) reported significant association between crushing strength of lower internodes and stalk breakage in the field. Stem diameter of second internode above the soil was significantly correlated with crushing strength and rind thickness of the third internode (Zuber and Grogan, 1961). To enhance field stalk breakage, Schertz et al. (1978) left the sorghum plants in the field exposed to strong winds long after plant maturity.

Loesch et al. (1963) reported that in maize, lodging susceptible x resistant crosses gave higher crushing strength and rind thickness than susceptible x susceptible crosses. Zuber and Grogan, (1966) reported that data for crushing strength, rind thickness, and weight of a 5.1cm stalk section indicated good agreement between locations within years. Crushing strength and rind thickness varied more between years and variation in crushing strength was attributed in

part to pith destruction by stalk rots which were more prevalent in some seasons than in others.

3) BREAKING (BENDING) STRENGTH - is one of the oldest quantitative methods used to determine the inherent strength of plant stalks. Helmick (1916) described an apparatus that had been used at Cornell University for breaking strength of straw. Salmon (1931) used an instrument to determine the breaking strength of straw and found a relationship between breaking strength and lodging. Clark and Wilson (1933) used a special dynamometer to test the strength of wheat and barley culms and found a non-significant correlation between breaking strength and lodging.

In maize Durrell (1962) recorded the breaking strength of the first 5 nodes above the ground and noted that strength decreased successively from lower to higher nodes. The first node had approximately twice the strength of the fourth node and lower nodes had more lignification than upper nodes. Foley (1962) found that all stalks needed about the same breaking force in August but in October hybrids susceptible to stalk rots retained about one-fifth normal strength. Lower internodes were stronger than upper ones. Other researchers used the breaking strength method in maize (Twumasi-Afriyie and Hunter, 1982; McRostie and McLachlan, 1942); and in sorghum bending tests were significantly and negatively correlated with breakage of peduncles in the field (Schertz et al., 1978).

4) RIND PUNCTURE (PENETRATION). This method uses instruments to test the hardness of the rind. Twumasi-Afriyie and Hunter (1982) assessed several quantitative methods of stalk quality evaluation to determine which one

of them could be effective in predicting field stalk lodging performance in maize. Rind puncture was closest to meeting all the desired criteria for the best stalk lodging resistance indicator by being simple to determine, highly correlated with stalk lodging and consistent in distinguishing between lodging resistance levels under both high and low lodging conditions. Of the six methods Schertz et al. (1978) used to evaluate sorghum, penetration of non-dried or dried stalks was the least variable. Other researchers used the method in sugarcane (Khanna and Rao, 1939; Khanna, 1935); in maize (Albrecht and Dudley, 1987; McRostie and McLachlan, 1942).

5) PEDUNCLE SHEARING. Bright (1964) used mass shear strength to estimate the fibrousness of forages. Schertz et al. (1978) used the same instrument to determine the maximum force required to shear a dry sorghum peduncle and obtained a significant and negative correlation between shearing strength and peduncle breakage in the field.

6) SPECIFIC GRAVITY. Thompson (1972) used crosses between comparable cycles of two maize synthetics and obtained significant correlations for specific gravity with water content, grain yield, ear height, stalk rot and rind puncture. Chang and Loesch (1972) cited Nelson (1968) to have noted that genetic progress in specific gravity was not accompanied by change in the number of central stalk and rind bundles but by changes in rind thickness and stalk diameter.

7) OTHER METHODS, that have been used include the lodging resistance factor (cLr) method developed by Grafius (1958) and used on oats by Bhamonchant and Patterson (1964), Frey and Norden (1959), and Norden and Frey (1959); Snap test method described by Murphy et al. (1958) and

used extensively by Kaufmann (1956). They found that snap scores were highly correlated with lodging percentages and required considerably less time than obtaining cLr values.

GENE EFFECT, HERITABILITY AND HETEROSIS:

In pearl millet Rachie (1965a) and Murty et al. (1967b) noted that plant types vary widely in maturity, robustness, leafiness, tillering capacity, size and stiffness of stem and earhead. Burton and Powell (1968); and Burton (1951b) found dominance of low tillering over heavy tillering. Rachie and Majmudar (1980) cited Gillet al. (1968), Gupta and Nanda (1968) and Mahadevapa (1968e) to have showed the involvement of dominance, epistasis and additive gene effects in high tiller number, and complementary type of intra-allelic and inter-allelic interactions with epistasis in both length and diameter of peduncle. They cited Bilquez and Le Conte (1969) to have proposed at least four pairs of homologous genes to control stem size.

Variations in earliness were controlled by multiple genes each having two alleles one dominant over the other, and the dominant gene was associated with earliness (Bilquez and Clement, 1969, cited by Rachie and Majmudar, 1980). Gene effect for stem diameter and maturity were largely arithmetic while for plant height it was largely geometric. Transgressive segregation occurred in stem diameter, head length, plant height and leaf width (Burton, 1951b). In maize additive genetic effects were more important than non additive effects for percent senescent stalks, crushing strength and rind thickness (Arnold and Josephson, 1975). In 6 maize crosses heritability estimates ranged from 0.28 to 0.53 for crushing strength and from 0.33 to 0.62 for rind thickness

indicating that a selection procedure that takes advantage of additive genetic effects would be effective in improving these characters (Arnold et al., 1974). Albrecht and Dudley (1987) reported significant heritability estimates for percent stalk lodging and rind puncture resistance.

In pearl millet heritability values were high (0.98) for head length and (0.77) for maturity; moderately high (0.68) for plant height and (0.61) for internode length; intermediate (0.52) for stem diameter and leaf width; lowest (0.41) for number of leaves per stem; and (-0.56) for grain yield (Burton, 1951b). Observed midparent heterosis for yield increased from 14.9% for the C0 population cross involving Iowa Stiff Stalk Synthetic (BSSS) and Iowa Corn Borer No. 1 (BSCB1) to 41.7% for the C7 population cross (Martin and Hallauer, 1980). Selection-induced differences among strains of BSSS C0 resulted in 11.7% average midparent heterosis for yield (Oyervides-Garcia and Hallauer, 1986). Manifestation of hybrid vigor in forage yields of hybrid pearl millet ranged from 50% to 100% over their respective inbred parents (Burton, 1951b), and even higher (74 - 197%) in grain yield (Rachie et al., 1967).

BREEDING METHODS AND SUCCESSES:

1) RECURRENT SELECTION methods enable an increase in the frequency of desirable genes in breeding populations and the maintenance of genetic variability needed for continued improvement (Martin and Hallauer, 1980). There are various forms of recurrent selection methods (Singh et al., 1985). Genetic gain per year and not per cycle has been considered important. Berzonsky et al. (1986) recurrently selected MoSQA and MoSQB maize stalk-quality synthetics for low and high crushing strength taking

6 cycles. The percentage of soft stalks decreased by 2.8% and 3.5% per cycle for the two synthetics, respectively selected for high crushing strength. Using the same synthetics Undersander et al. (1977) and Colbert et al. (1984) carried out 5 cycles of recurrent selection for high and low crushing strength and found that lignin percentage of the pith and grain yield were not affected by selecting for high crushing strength but stalk lodging was significantly decreased, while selecting for low crushing strength reduced grain yield, increased stalk lodging in MoSQB and caused slightly earlier flowering and a decline in soluble stalk solids in MoSQA. Chang et al. (1976) discovered that the two synthetics were similar in stalk strength but derived their strength in different ways. MoSQA had greater number of vascular bundles and vascular bundle number was greater for the high than for the low sections. MoSQB had more lignification per bundle than MoSQA and the lignified area in the rind was correlated with crushing strength. Improvements resulting from recurrent selection for stalk quality in population crosses, population test crosses, and random S1 lines closely paralleled improvements in populations per se, indicating that stalk quality is controlled primarily by an additive type of gene action (Martin and Russell, 1984a). After two cycles of top cross selection Davis and Crane (1976) decreased lodging from 24.2 to 20.7%, and from 25.7 to 19.1% after three cycles of selection in the population per se. Other researchers used recurrent selection in improving stalk quality and grain yield (Zuber et al., 1980; Nyhus and Russell, 1987; Sibale et al., 1987; Tanner and Smith, 1987; Martin and Russell, 1984b; Martin and Hallauer, 1980; Thompson, 1982; Russell et al., 1973; Thomas and

Grissom, 1961).

2) MASS SELECTION. This method has been used as a quick means of pearl millet varietal improvement in situations where time, facilities and staff are limited, and hybrids are impractical due to production-distribution problems. Albrecht and Dudley (1987) reported that one cycle of divergent mass selection for rind puncture resistance in Illinois Stiff Stalk Synthetic Composite (RSSSC) and South African photoperiod Insensitive Composite II (PI C2) was as effective as S1 selection. Fraj and Compton (1986) compared mass selection and S1 family *per se* approach in improving Fusarium-related stalk-rot resistance using three maize populations (Nebraska B Synthetic, Nebraska Stiff Stalk Synthetic, and Nebraska version of the open-pollinated variety Krug). They found about 50% greater expected progress for mass selection than S1 family *per se* selection on gain per year basis.

3) BACKCROSSING. Singh et al. (1969) noted that means and ranges for weight of 5.1cm stalk sections, crushing strength, and rind thickness usually increased as with increases in the germplasm contributed by the stalk-lodging resistant parent. However, grain yields declined with additions of germplasm from the stalk-lodging resistant parent. The comparison of parents with advanced and backcross generations were all significant for crushing strength and rind thickness. Comparison between BC1 and BC2 was significant for rind thickness but not for crushing strength (Loesch et al., 1963).

In sorghum, Arnold and Josephson (1975) obtained highly significant differences among the F1, F2 and backcross genotype means for percent senescent stalks, crushing strength and rind thickness, and

noted that the influence of parents was apparent in the backcross populations in most crosses. Small correlation coefficients for many agronomic traits for backcross populations from six wild x cultivated sorghum led Cox et al. (1985) to conclude that limitations on recombination between wild and cultivated traits were weak.

Dujardin and Hanna (1987) showed that interspecific hybrid and derivatives between pearl millet and P. orientale with only one genome of both or either species gave male sterility regardless of whether plants had sterile or fertile pearl millet cytoplasm. Morphological characteristics of BC2 pearl millet plants indicated no evidence of gene transfer from P. orientale to pearl millet (Dujardin and Hanna, 1983; Hanna and Dujardin, 1982).

MATERIALS AND METHODS

Five field experiments, one in 1987 and four in 1988 were conducted on a Sharpsburg Silty Clay Loam (fine, montmorillonitic, mesic, Typic Argiudol) soil at the Agronomy Farm, Mead, Nebraska to investigate the type and range of lodging in pearl millet lines, derivatives of crosses between pearl millet and napier grass (PM X NG lines), test crosses of both types of lines, a millet hybrid and sorghum.

Experiment I in 1987 was exploratory in nature, designed to look at 21 tall and dwarf genotypes representing a range of genetic variability, to develop techniques of field evaluation for lodging to identify sampling methods and stem strength tests which could be used. It contained a range of pearl millet and PM X NG lines, and test crosses of these on two contrasting seed parents, 23DBE (weak stalk) and 68B (moderately stiff stalk), together with a millet hybrid and sorghum checks.

Experiment II in 1988 contained seven pearl millet lines retained from experiment I, test crosses on 68B with two of them and three new lines, all dwarf or semidwarf. These 12 treatments were selected to enable contrasts to be made between millets and sorghum, and between the seed parents per se for all the traits to be studied.

The 28 genotypes in experiment III were all new pearl millets comprising 14 male lines chosen from the breeding nursery on the basis of 1987 nursery lodging scores classified as 'stiff' or 'weak' stalk, and their 14 test crosses to either 23DAE or 68A A-lines. They

were chosen to provide a basis for contrasting stiff and weak stalk lines, lines and their test crosses, 23DAE and 68A test crosses, the best and worst lines (based on all mechanical strength tests) with their respective test crosses.

Twelve tall and semidwarf pearl millet and PM X NG male lines (7 retained from experiment I and 5 from Tifton, Georgia) and test crosses of all these to both 23DBE and 68B seed parents constituted the 36 treatments in experiment IV. The design for both experiments IV and V (below) was to enable contrasts to be made between male lines and their test crosses, between the two types of test crosses and to estimate male parent heterosis and effects of average and specific combining ability. The 27 entries in experiment V were comprised of a group of 9 dwarf advanced pearl millet lines selected from the breeding nursery on the basis of their 1987 nursery lodging scores, and a test cross of each to both 23DAE (weak stalk) and 68A (moderately stiff stalk) seed parents.

Seed was treated with a 2:1 by volume Captan/Graphite mixture as a fungicide/seed cone lubricant mixture after packing for planting.

The fields used are on a continuous pearl millet/soybeans rotation since 1985. Each strip was disced about one month prior to planting. On the day of or before planting a field cultivator and a spike-tooth harrow were run-through the strips to loosen the soil surface and to create a fine tilth, respectively.

Two experimental designs each with 3 replications were used: Randomised Complete Block Design (RCBD) for experiments I, II and III; and a Split Block Design for experiments IV and V. Tables I-1, II-1,

III-1, IV-1 and V-1 show the numbers and types of genotypes used in the study for each experiment. Each plot was a 5m and 8m long row for 1987 and 1988 experiments respectively, with an inter-row spacing of 0.76cm.

Planting was done on May 23 and May 27 in 1987 and 1988, respectively, using a White 5700 Seed Boss planter that had adjustments to operate with Kinkaid seed cone units. Plots were slightly over-seeded to allow for thinning and/or transplanting to one plant every 10cm within a row, after seedling establishment. The dry spell of 1988 at thinning/transplanting time necessitated bucket-watering of transplants for several days. Inter-row cultivating was done with a Lilliston rolling cultivator, and was followed by hand-hoe weeding within rows.

At physiological maturity of the crop a subset of the genotypes were identified in each experiment for structural and strength tests, based on the maturity and previous lodging observations in the breeding program. Reducing the number of genotypes was necessary due to the anticipated difficulty in collecting and processing the large amount of laboratory data. Five and ten plants in 1987 and 1988, respectively, were randomly selected in each plot and one tiller from each plant was cut at soil level with an anvil type scateur. Some of the PM X NG lines failed to reach physiological maturity due to the early onset of frost in the season of 1987 and due to drought in 1988. Sampling for structural and strength tests on such genotypes in experiments I and IV was done among those plants that reached physiological maturity. Sampled tillers from each plot were bundled and labeled. Stalk and peduncle measurements were taken before, in 1987, and after samples were oven-dried at 40°C for one week, in 1988. Hand-

harvesting for grain yield was done on a pre-measured portion of each plot.

The type of data (with abbreviations) collected for all genotypes in each experiment include:

1) Days to 50% Bloom [BLM]: the number of days from planting to date when approximately one-half of the plants in a plot had 50% of their main panicles in stigma emergence.

2) Plant Height [HT]: average height (cm) of plants in a plot measured by placing a graduated height stick from soil level to tips of the panicles, in the middle of the plot, at grain-hardening stage.

3) Stand count [PTP]: number of plants in the net harvest plot after marking for grain yield harvesting. 4) Grain yield (MGHA): amount (mg/ha) of grain after oven-drying at 40°C for 7 days, threshing and adjusting for 15% moisture by the formula:

$$MGHA = \left[\frac{YLD * (100 - PCM)}{85} \right] / 1000 * 10000 / \left[\frac{PTS * \text{plot width}}{1000} \right]$$

Where YLD = weight of grain (gm) per plot

plot width = 0.76m

PTS = length (m) of harvested portion of a plot

PCM as defined below

5) Percent moisture [PCM]: moisture content (%) of a 200gm sample of threshed grain per plot determined by a moisture tester.

6) Stalk lodged tillers [SL]: number of tillers in the unharvested portion of a plot that had broken stalks, excluding broken peduncles, at 4 weeks after harvesting. In experiment I, lodging (stalk + peduncle) is expressed in percentage.

7) Peduncle lodged tillers [PL]: number of tillers as described under

stalk lodged tillers, but that had broken peduncles (except in experiment I).

8) Lodging Scores [LG]: a visual 1-10 scale rating assessment (1=no lodging, 10=100%) of lodging (stalk + peduncle) 6 weeks after harvesting (except in experiment I).

9) Number of tillers [TT]: number of tillers on which lodging parameters SL and PL were determined (except in experiment I). 10) Head Number [HNO]: number of harvested heads used to determine grain yield and number of heads per square meter (HSM).

The data collected in the laboratory included:

1) Length (cm) of:

i) First extended internode [ALEN] above soil level of each tiller, hereafter designated Internode A.

ii) Second next extended internode [BLEN] above internode A of each tiller, hereafter designated Internode B.

iii) Peduncle [PLEN] of each tiller.

2) Diameter (cm) of:

i) Internode A [ADIM] taken as the average of the largest and smallest diameter measured in the middle of each internode A.

ii) Internode B [BDIM] taken as the average of the largest and smallest diameter measured in the middle of each internode B.

iii) Peduncle [PDIM] taken in the middle of each peduncle.

Only one measurement was taken since the peduncle is essentially round in cross section in the middle of its length.

3) Crushing strength (kg) of:

i) Internode A section [ACRS]: maximum load required to

vertically compress a 3cm long section of internode A.

- ii) Peduncle section [PCRS]: maximum load required to vertically compress a 3cm long section of peduncle.

4) Breaking strength (kg) by Three-point Bending of:

- i) Internode B section [BBRK]: maximum load required to horizontally break a 4cm long section of internode B.
- ii) Peduncle section [PBRK]: maximum load required to horizontally break a 4cm long section of peduncle.

Instron machines were used for crushing and breaking strength tests. Crushing strength of internode A was done at either 500 or 200kg full scale force, while the crushing strength of the peduncle, the breaking strengths of both internode B and peduncle were done at 100kg full scale force. Crushing strength was done at 1cm/minute and 10cm/minute crosshead and chart speeds, respectively while Breaking strength was done at 1cm/minute and 20cm/minute crosshead and chart speeds, respectively.

5) Rind thickness (mm) of internode A [ARND], internode B [BRND] and peduncle [PRND]: the thickness of the hard outer tissue of the stalk or peduncle excluding the pith, measured by a dial caliper to the nearest 0.01mm. Rind thickness was measured on a small and relatively flat portion of the internode and peduncle sections after the crushing and breaking strength tests. The soft pith tissue was scraped off the portions using a scalpel, before measuring.

Plot averages were used in the statistical analyses of different traits using the Statistical Analysis System (SAS) to perform the analysis of variance (ANOVA) and contrasts and the genotypic means to

obtain linear correlation coefficients.

The following modifications of Steel and Torrie's (1980) linear additive models were used:

Randomised Complete Block Design: Mixed effects model with B_j and E_{ij} as random variables and T_i as a fixed effect.

$$Y_{ij} = U + T_i + B_j + E_{ij}$$

Where Y_{ij} = response of the i^{th} treatment (genotype) in the j^{th} block (replication).

U = overall mean

T_i = mean effect of the i^{th} genotype.

B_j = mean effect of the j^{th} replication.

E_{ij} = random error of the ij^{th} observation.

Assumptions:

- i) random error is normally, independently and identically distributed with mean zero and variance σ_e^2 .
- ii) there is no replication x genotype interaction.
- iii) the sum of mean effects of genotypes is zero.

$$\sum T_i \text{'s} = 0$$

- iv) the sum of mean effects of replications is zero.

$$\sum B_j \text{'s} = 0$$

Split Block Design: Mixed effects model, with R_i , $(RA)_{ij}$, $(RB)_{ik}$ and E_{ijk} as random variables and A_j, B_k and $(AB)_{jk}$ as fixed effects.

$$Y_{ijk} = U + R_i + A_j + (RA)_{ij} + B_k + (RB)_{ik} + (AB)_{jk} + E_{ijk}$$

Where

Y_{ijk} = response of the k^{th} male mated to j^{th} tester in the i^{th} replication.

U = overall mean

R_i = mean effect of the i^{th} replication.

A_j = mean effect of the j^{th} tester,

$j = 0$ for males only

$j = 1$ for test crosses on either 23DBE or 23DAE.

$j = 2$ for test crosses on either 68B or 68A.

$(RA)_{ij}$ = Error a = replication x tester interaction.

The error term used to test mean effects of testers.

B_k = mean effect of the k^{th} male.

$(RB)_{ik}$ = Error b = replication x male interaction.

$(AB)_{jk}$ = tester x male interaction.

E_{ijk} = Error c = residual error.

Assumptions:

- 1) Error a is normally, independently and identically distributed with mean zero and variance σ_{ra}^2 .
- 2) Error b is normally, independently and identically distributed with mean zero and variance σ_{rb}^2 .
- 3) Error c is normally, independently and identically distributed with mean zero and variance σ_e^2 .

Table 1 shows the list of traits used for the analyses. The forms of analyses of variance for the RCBD and Split Block Designs are shown in Tables 2 and 3. Table 4 shows the climatological data for Mead in 1987 and 1988.

Estimates of male parent heterosis was obtained as the difference between the mean of the F1 and mean of the male parent expressed as a percent of the mean of the male parent. The following

linear additive model as suggested by C.O. Gardner (personal communications) was used to estimate the average and specific combining ability (aca and sca, respectively) effects:

$$Y_{ijk} = U + F_i + M_j + (FM)_{ij} + E_{ijk}$$

Where Y_{ijk} = the value of the k^{th} experimental unit of the progeny from mating the i^{th} tester and j^{th} male.

U = overall mean

F_i = an effect common to progeny of the i^{th} tester.

M_j = an effect common to all progeny of the j^{th} male.

$(FM)_{ij}$ = an effect specific to the progeny of mating the i^{th} tester and the j^{th} male.

E_{ijk} = random error

with the following restrictions:

$$\sum F_i = 0$$

$$\sum M_j = 0$$

$$\sum_i (FM)_{ij} = \sum_j (FM)_{ij} = 0$$

Calculations of aca and sca effects were done using the following modifications of Beil and Atkins' (1967) formulae:

$$F_i = (Y_{i.} - Y_{..})$$

$$M_j = (Y_{.j} - Y_{..})$$

$$(FM)_{ij} = (Y_{ij} - Y_{i.} - Y_{.j} + Y_{..})$$

Possible simple correlation coefficients between any two variables were obtained. The data were grouped into the following four categories:

- i) Lodging parameters: stalk lodging, peduncle lodging, and lodging score or percent lodging (PLG).

- ii) Mechanical strength tests: crushing and breaking strength of the basal stalk internodes and peduncle.
- iii) General agronomic traits: grain yield, days to 50% bloom, height and number of heads per square meter.
- iv) Critical traits: rind thickness, diameter and length of basal internodes and peduncle. These traits were called 'critical' because rind thickness and diameter have been proved in maize and sorghum to be important in imparting strength to the stalk.

Table 1: List of traits used for analyses.

A: LODGING PARAMETERS:

1. PLG lodging (%)
2. SL stalk lodging (count)
3. PL peduncle lodging (count)
4. LG lodging score (1=0% lodging, 10=100% lodging)

B: MECHANICAL STRENGTH TESTS:

1. ACRS stalk crushing strength (kg)
2. BBRK stalk breaking strength (kg)
3. PCRS peduncle crushing strength (kg)
4. PBRK peduncle breaking strength (kg)

C: GENERAL AGRONOMIC TRAITS:

1. MGHA grain yield (mg/ha)
2. BLM days to 50% bloom
3. HT plant height (cm)
4. HSM no. of heads per square meter

D: CRITICAL TRAITS:

1. ARND basal stalk rind thickness (mm)
2. ADIM basal stalk diameter (cm)
3. ALEN basal stalk internode length (cm)
4. PRND peduncle rind thickness (mm)
5. PDIM peduncle diameter (cm)
6. PLEN peduncle length (cm)

Table 2: Form of analysis of variance of RCBD for experiments I, II and III.

Source	df	Mean square		F-test
		Observed	Expected	
Replications	r-1	M1		
Treatments	t-1	M2	$\sigma_e^2 + r \sum T_i^2 / (t-1)$	M2/M3
Contrast #	1	M#		M#/M3
Error	(r-1)(t-1)	M3	σ_e^2	
Total	rt-1			

r = number of replications

t = number of treatments (genotypes)

= contrast number, see Tables I-3, II-3, III-3, IV-3 and V-3.

T_i = fixed effect of i^{th} genotype

σ_e^2 = error variance among genotypes within replications.

M1, M2, M3 = respective mean squares

Table 3: Form of analysis of variance of Split Block Design for experiments IV and V.

Source	df	Mean squares		F-test
		Observed	Expected	
R	r-1	M1		
A	a-1	M2	$\sigma_e^2 + b\sigma_{ra}^2 + rb\phi_a^2$	M2/M5
Contrast 1	1	M3		M3/M5
Contrast 2	1	M4		M4/M5
Error a	(r-1)(a-1)	M5	$\sigma_e^2 + b\sigma_{ra}^2$	
B	b-1	M6	$\sigma_e^2 + a\sigma_{rb}^2 + ra\phi_b^2$	M6/M7
Error b	(r-1)(b-1)	M7	$\sigma_e^2 + a\sigma_{rb}^2$	
AB	(a-1)(b-1)	M8	$\sigma_e^2 + r\phi_{ab}^2$	M8/M9
Error c	(a-1)(b-1)(r-1)	M9	σ_e^2	
Total	rab-1			

r = number of replications

a = number of testers

b = number of males

ϕ_a^2 = fixed effects of testers

ϕ_b^2 = fixed effects of males

ϕ_{ab}^2 = fixed effects of tester x male interaction

σ_{ra}^2 = tester x replication interaction + random variation among tester whole plots within replications.

σ_{rb}^2 = male x replication interaction + random variation among male whole plots within replications.

σ_e^2 = residual error.

M1, M2, M3, M4, M5, M6 M7 M8 M9 = respective mean squares.

Contrast 1 = males V test crosses

Contrast 2 = 23DAE or DBE test crosses V 68A or B test crosses.

Table 4. Climatological data for Mead, Nebraska in 1987 and 1988.

Year	Pre-season ⁺	May	June	July	Aug.	Sept.	Total
----- precipitation (mm) -----							
1987	355	158	42	97	220	47	919
1988	169	83	26	91	18	122	509
---Mean minimum/maximum temperatures (°C) -----							
1987	13.0/25.7	16.5/31.3	18.6/31.8	15.3/27.5	10.9/25.0		
1988	13.3/27.1	18.1/33.2	17.5/31.2	16.2/33.4	12.1/27.5		

+ Pre-season rainfall from October of previous year through April of current year.

RESULTS AND DISCUSSION

EXPERIMENT I (1987)

Experiment number I was conducted to survey for potential sources of contrasting lodging resistance among pearl millets, PM X NG lines, their test crosses, and sorghum; and to develop methodology for evaluating lodging among 21 genotypes (Table I-1). Early onset of frost in 1987 and drought in 1988 prevented most of the PM X NG lines from reaching maturity although they had matured in 1986. The stem internodes of the sorghum hybrid proved to be too short and could not meet the required length for strength tests. These genotypes were thus excluded from the analyses in experiment I.

Highly significant differences were detected for all 15 traits studied which were grouped into four categories (Table I-2). Lodging (PLG) ranged from 0 to 98%. Table I-3 shows the pre-planned genotypic groups between which contrasts were examined for percent lodging. The PM X NG test crosses were significantly poorer with regards to lodging than the pearl millets and the sorghum line. However, it was observed that most of the lodging on the PM X NG test crosses was due to peduncle breakage whereas the stalks were very strong. This field observation was reaffirmed by both stalk strength tests when the pearl millets and PM X NG test crosses were contrasted.

This discovery led us into differentiating stalk lodging due to breaking of stalks between ground level and the flag-leaf node from peduncle lodging due to breaking of peduncles between the flag-leaf node

and the base of the inflorescence, in the 1988 experiments. The pearl millets as a group as well as the best pearl millet line, based on all the 4 strength tests, had significantly higher percent lodging values than the sorghum line, the millet hybrid check had equal percent lodging value to that of the sorghum line (Table I-3). Stalk strength tests (Table I-4) show that whenever significant differences occurred, the sorghum line was superior in strength to all pearl millet genotypes. Strength tests of the peduncle show consistent superiority of the sorghum line in peduncle strength to all three pearl millet genotypic groups.

Test crosses on 23DBE seed parent with PM X NG lines showed significantly higher percent lodging values than those on 68B seed parent with different PM X NG lines. This was evident in both peduncle strength tests, but only in the crushing strength of the stalk, suggesting that lodging, especially peduncle lodging could be reduced in crosses with PM X NG lines by using unrelated seed parents with stiff or moderately stiff peduncles. Both percent lodging and peduncle strength tests show superiority of 68B over 23DBE indicating good agreement with our expected classification (Table I-1). Whereas percent lodging failed to detect significant differences between pearl millet lines and the hybrid check, all the four strength tests indicate the significant superiority of the hybrid check over the lines.

The PM X NG test crosses had significantly higher values for all the general agronomic traits (Table I-5) than the pearl millets as a group. Although the former had significantly larger values for the critical traits ARND, ALEN and PLEN (Table I-6), they had significantly

lower values for the critical traits PRND, and PDIM than the latter. The smaller PRND, PDIM and larger PLEN values coupled with increased yield, height and number of heads per square meter suggest the reasons for increased peduncle lodging of PM X NG test crosses, although their male parents appear to be good potential sources for improving the rind thickness of the stalk. The significant superiority of pearl millet lines over the hybrid check in PRND suggest existence of potential sources among the lines for improving rind thickness of the peduncle. Significant superiority of 68B over 23DBE in all the critical traits except ARND and PLEN suggest that 68B would be the better of the two seed parents in crosses for improving structural strength and for use with lodging resistant males to produce lodging resistant hybrids.

Simple correlation coefficients between the critical traits and percent lodging, strength tests and general agronomic traits are shown in Table I-7. Significant and positive correlations were found for ARND with percent lodging, ACRS, BBRK, BLM and HT; for ADIM with PCRS and PBRK; for ALEN with PLG, ACRS, BBRK, BLM, HT and HSM; and for all critical traits of the peduncle with both PCRS and PBRK. Significant and negative correlations were observed for ADIM with HSM; PRND with PLG, ACRS, BLM and HSM; and for PDIM with HSM. These correlations suggest that ARND is more important than ADIM in imparting strength to the stalk and that lateness in maturity as well as increased plant height are important for increased ARND, but PRND, PDIM and HSM have an important effect on peduncle strength. Increased tillering seems detrimental to ADIM, PRND and PDIM and could be a major factor in increasing lodging, especially peduncle lodging.

Correlations among the critical traits are shown in Table I-8 in which significant and positive associations were detected for ARND with ALEN; ADIM with PDIM and PLEN; PRND with PDIM; and PDIM with PLEN, suggesting that selection for larger ARND would be accompanied with longer ALEN. ADIM and PDIM could be selected for simultaneously but this could also be associated with selection for PLEN. This type of association would be desirable in simultaneous improvement in stalk strength, peduncle strength and exertion, but if exertion was not a problem any additional increase in the length of the peduncle might increase peduncle lodging. This situation could arise if selection was based on PRND rather than PDIM.

Significant and positive correlations were found (not shown in tables) for ACRS with BBRK (0.80**), and PCRS with PBRK (0.93***) suggesting that either crushing or breaking strength could be used effectively in determining the inherent strength of the stalk or peduncle. However, correlations of this nature should be used cautiously because genotypes could be separated into three distinct groups: pearl millets, PM X NG test crosses and the sorghum line.

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Table I-1. Genotypes studied in experiment I (1987).

Code	genotype	description
1	59110-2 G86	p.p. (ss)
2	59110-9 G86	p.p. (ss)
3*	58030-1 G85	p.m. (ss)
4	PPI-1 G87	p.p. (ss)
5	PPI-2 G87	p.p. (ss)
6*	23DBE	p.m. (ws)
7*	68B	p.m. (moderately ss)
8*	23BDE X PPI-1 G87	p.m. x p.p. test cross
9*	68B X PPI-1 G87	p.m. x p.p. test cross
10*	23DBE X PPI-2 G87	p.m. x p.p. test cross
11	68B X PPI-2 G87	p.m. x p.p. test cross
12*	68B X 56112-1	p.m. x p.p. test cross
13*	23DBE X 59110	p.m. x p.p. test cross
14	68B X 78110tr	p.m. x p.p. test cross
15	56112	p.p. (ss)
16*	80025-1	p.m.
17*	80026-1	p.m.
18*	80026-2	p.m.
19	F2233	sorghum hybrid
20*	KS57B	sorghum line
21*	KS HYB	p.m. hybrid

* structural and strength tests conducted on these genotypes

p.m. pearl millet

p.p. derivative of crosses between pearl millet and napier grass (PM X NG) line.

ss stiff stalk, based on 1986 observations.

ws weak stalk, based on previous observations.

Table I-2. Means of lodging(+), strength tests(@), critical traits (#) and general agronomic traits (\$).

Trait	units	mean	range	cv(%)	s.e.(±)
PLG ⁺	%	47***	0 - 98	38.3	10.5
ACRS [@]	kg	77.8***	25.3 - 213.8	31.0	13.9
BBRK [@]	kg	32.9***	8.9 - 59.6	17.1	3.2
PCRS [@]	kg	19.2***	10.3 - 53.3	20.9	2.3
PBRK [@]	kg	10.6***	4.4 - 22.5	18.5	1.1
ARND [#]	mm	0.96***	0.66 - 1.48	11.2	0.06
ADIM [#]	cm	1.21**	0.73 - 1.62	17.2	0.12
ALEN [#]	cm	6.7***	3.0 - 12.4	13.0	0.5
PRND [#]	mm	0.42***	0.30 - 0.65	10.4	0.02
PDIM [#]	cm	0.67***	0.42 - 1.14	6.9	0.03
PLEN [#]	cm	32.5***	21.6 - 45.7	5.5	1.0
MGHA ^{\$}	mg/ha	3.1***	1.0 - 5.5	22.5	0.4
BLM ^{\$}	days	69***	56 - 101	2.6	1.0
HT ^{\$}	cm	134***	65 - 270	11.4	8.8
HSM ^{\$}	m-2	29***	13 - 55	28.0	4.6

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.
s.e. of genotypic mean.

Table I-3 . Results of tests of contrasts for lodging.

Contrast	PLG (%)
1# 3 6 7 16 17 18 21 V 8 9 10 12 13 [@]	33 78***
2 3 6 7 16 17 18 21 V 20	33 0**
3 8 9 10 12 13 V 20	78 0***
4 3 16 17 18 V 21	32 15
5 20 V 21	0 15
6 16 V 20	61 0***
7 6 V 7	63 21***
8 8 10 13 V 9 12	98 51***

* ** *** significant differences among
genotypic means at 5%, 1% and
0.1% levels, respectively.

s.e. of genotypic mean.

@ see Table I-1 for genotypes.

1# pearl millets V PM X NG test crosses
2 pearl millets V sorghum line
3 PM X NG test crosses V sorghum line
4 pearl millet lines V millet hybrid
5 sorghum line V millet hybrid
6 best⁺ millet line V sorghum line
7 23DBE V 68B
8 23DBE test crosses V 68B test crosses

+ based on all the strength tests

Table I-4 . Results of tests of contrasts for strength tests

Con#	----- stalk -----				----- peduncle -----			
	ACRS (kg)		BBRK (kg)		PCRS (kg)		PBRK (kg)	
1	39.5	138.3**	19.7	51.3**	16.6	19.9	9.7	9.5
2	39.5	43.3	19.7	32.7**	16.6	53.3**	9.7	22.5**
3	138.3	43.3**	51.3	32.7**	15.9	53.3**	9.5	22.5**
4	32.9	84.0**	19.9	32.2**	15.2	24.4**	9.5	13.7**
5	43.3	84.0*	32.7	32.2	53.3	24.4**	22.5	13.7**
6	35.1	43.3	19.4	32.7**	18.7	53.3**	12.3	22.5**
7	25.3	35.4	8.9	17.4	10.3	20.9**	4.4	12.1**
8	123.2	161.1**	50.1	53.1	13.6	19.2*	7.3	12.9**

* ** significant differences among genotypic means at 5%,
and 1% levels, respectively.

see Table I-3 for genotypes contrasted.

- 1 pearl millets V PM X NG test crosses
 2 pearl millets V sorghum line
 3 PM X NG test crosses V sorghum line
 4 pearl millet lines V millet hybrid
 5 sorghum line V millet hybrid
 6 best⁺ millet line V sorghum line
 7 23DBE V 68B
 8 23DBE test crosses V 68B test crosses

+ based on all the strength tests

Table I-5. Results of tests of contrasts for general agronomic traits.

Con#	MGHA		BLM		HT		HSM	
	(mg/ha)		(days)		(cm)		(m ⁻²)	
1	2.8	3.5**	61	81***	98	197***	26	34**
2	2.8	2.9	61	64*	98	83	26	17
3	3.5	2.9	81	64***	197	83***	34	17**
4	2.0	6.1***	61	62	93	128**	19	27
5	2.9	6.1***	64	62	83	128**	17	27
6	2.4	2.9	59	64**	102	83	22	17
7	2.8	2.9	56	64***	90	96	55	26***
8	4.4	2.3***	77	86***	185	214***	43	22***

* ** *** significant among genotypic means at 5%, 1% and 0.1% levels, respectively.

see Table I-3 for genotypes contrasted

- 1 PM X NG test crosses
 2 pearl millets V sorghum line
 3 PM X NG test crosses V sorghum line
 4 pearl millet lines V millet hybrid
 5 sorghum line V millet hybrid
 6 best⁺ millet line V sorghum line
 7 23DBE V 68B
 8 23DBE test crosses V 68B test crosses

+ based on all the strength tests

Table I-6. Results of tests of contrasts for critical traits.

Con#	stalk				peduncle							
	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)						
1	0.77	1.22**	1.15	1.23	5	9**	0.45	0.33**	0.66	0.60**	31	32*
2	0.77	0.95*	1.15	1.62**	5	3**	0.45	0.65**	0.66	1.14**	31	45*
3	1.22	0.95**	1.23	1.62**	9	3**	0.33	0.65**	0.60	1.14**	32	45**
4	0.77	1.01**	1.15	1.47*	5	6	0.47	0.42*	0.71	0.80**	31	36**
5	0.95	1.01	1.62	1.47	3	6**	0.65	0.42**	1.14	0.80**	45	36**
6	0.80	0.95	1.08	1.62**	6	3**	0.52	0.65**	0.70	1.14**	34	45**
7	0.66	0.67	0.73	1.23**	7	5**	0.34	0.49**	0.42	0.60**	27	30*
8	1.17	1.29*	1.13	1.36*	9	8**	0.33	0.31	0.54	0.71**	31	34**

* ** significant differences among genotypic means at 5%, and 1% levels, respectively.

see Table I-3 for genotypes contrasted.

- 1 pearl millets V PM X NG test crosses
- 2 pearl millets V sorghum line
- 3 PM X NG test crosses V sorghum line
- 4 pearl millet lines V millet hybrid
- 5 sorghum line V millet hybrid
- 6 best+ millet line V sorghum line
- 7 23DBE V 68B
- 8 23DBE test crosses V 68B test crosses

+ based on all the strength tests

Table I-7. Correlation coefficients for critical traits with lodging(+), strength tests(@) and general agronomic traits(\$).

		----- critical traits -----					
		----- stalk -----			----- peduncle -----		
		ARND	ADIM	ALEN	PRND	PDIM	PLEN
Trait	units	(mm)	(cm)	(cm)	(mm)	(cm)	(cm)
PLG ⁺	%	0.76**	-0.21	0.95**	-0.66*	-0.49	-0.26
ACRS [@]	kg	0.93**	0.21	0.79**	-0.58*	-0.17	-0.01
BBRK [@]	kg	0.84**	0.38	0.57*	-0.43	0.01	0.28
PCRS [@]	kg	0.04	0.72**	-0.50	0.71**	0.85**	0.83**
PBRK [@]	kg	0.12	0.85**	-0.53	0.71**	0.90**	0.80**
MGHA ^{\$}	mg/ha	0.24	0.09	0.26	-0.35	-0.16	0.28
BLM ^{\$}	days	0.90**	0.21	0.73**	-0.43	-0.12	-0.13
HT ^{\$}	cm	0.88**	0.07	0.83**	-0.64*	-0.31	-0.03
HSM ^{\$}	m ⁻²	0.09	-0.66*	0.61*	-0.68*	-0.75**	-0.32

* ** significant differences among genotypic means at 5%, and 1% levels, respectively.

Table I-8. Correlation coefficients among critical traits.

	ARND	ADIM	ALEN	PRND	PDIM	PLEN
ARND	.	0.37	0.69**	-0.45	0.03	0.09
ADIM		.	-0.35	0.47	0.84***	0.65*
ALEN			.	-0.80***	-0.64**	-0.40
PRND				.	0.79**	0.44
PDIM					.	0.69**
PLEN						.

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

EXPERIMENT II (1988)

This experiment aimed at evaluating 12 dwarf or semidwarf genotypes (Table II-1) for the 17 traits studied (Table II-2). Seven of the twelve genotypes were retained from experiment I while three new observed stiff stalk pearl millet lines and two test crosses on 68B involving two stiff stalk pearl millet lines from experiment I were included. Although data on lodging parameters and general agronomic traits were collected for all the 12 genotypes, a subset of 6 were selected (Table II-1) for the strength tests and evaluation of critical traits. For consistence in the analyses and interpretation among all 17 traits, only results from the 6 selected genotypes are presented.

Significant differences were detected among the genotypes for all the 17 traits (Table II-2). Peduncle lodging was again greater than stalk lodging. Evaluation of lodging parameters (Table II-3) shows superiority of the sorghum line over the pearl millets as a group, over the millet hybrid check and over the best pearl millet line, for both peduncle lodging and lodging score, but the best millet line and sorghum check were similar in stalk lodging. Duncan's multiple range test showed that the best millet line in experiment II had significantly larger values for all traits except HT, PRND, ALEN and HSM than the best line in experiment I. Peduncle strength tests (Table II-4) similarly indicated that the sorghum line had stronger peduncles compared with any of the millet genotypic groups. However, the stalk strength tests show that both the millet hybrid and the best line were similar in stalk strength with the sorghum check, whereas BBRK

shows superiority of the sorghum check to the millets as a group. When tested for critical traits (Table II-6) sorghum had significantly thicker peduncle rind and diameter, and shorter ALEN than any of the millet genotypic groups. Sorghum had significantly larger ARND and PLEN values than the millets as a group, but had significantly smaller ADIM than both the millet hybrid and the best line.

Table II-5 shows results of tests of general agronomic traits. All the millet genotypic groups were significantly taller than the sorghum. Although both millets as a group and the millet hybrid were significantly higher tillering than sorghum, only the millet hybrid was similar in yield to sorghum. The best millet line was later in maturity than sorghum. The sorghum line exhibited delayed senescence (stay green), a field condition that was reported in sorghum by Bashford et al. (1976) to be an important component of lodging resistance. During preparation of samples for strength tests, it was observed that the sorghum line had shorter ALEN than all millet genotypes and this was confirmed statistically (Table II-6). As a result of shorter ALEN, there were more multiple overlappings of the basal portions of leaf sheaths on the sorghum stalks than the millet stalks which possibly contributed to the strength of sorghum stalks in the field.

Because no significant differences were detected between the best pearl millet line and the sorghum check for SL, ACRS, BBRK, and ARND, and the fact that the best millet line had significantly larger ADIM than the sorghum, and because ADIM and ARND are closely correlated (Table II-8) suggests that this millet line could be potentially good in improving these traits, provided ALEN was not increased, because ALEN

is significantly and positively correlated with SL and negatively correlated with both PCRS and PBRK (Table II- 7). Evaluation of the two B-line seed parents per se shows that 68B was better than 23DBE for both types of lodging and lodging score (Table II-3). Peduncle lodging was more serious than stalk lodging for both seed parents. There was agreement between field evaluation for both types of lodging (Table II-3) and both types of strength tests (Table II-4) for both stalk and peduncle portions of these seed parents. The seed parent 68B was statistically better than 23DBE for the critical traits ARND, ADIM, PRND and PDIM suggesting that it could be the better of the two in improving these traits. However, if the general agronomic traits of shorter days to 50% bloom, reduced height and increased tillering were important in selection of a seed parent, 23DBE would be preferred (Table II-5).

Table II-7 shows the correlations for the critical traits with lodging parameters, strength tests and general agronomic traits. Significant and negative correlations were found for SL with ARND and PDIM; ARND with PL; ALEN with PCRS, and PBRK; HSM with all critical traits except ARND and ALEN. Significant and positive correlations were detected for ALEN with SL and LG; ACRS with ARND and ADIM; BBRK with ARND, ADIM and PDIM; PCRS with PDIM; PBRK with ARND, PRND and PDIM; PDIM with MGHA; ADIM with BLM.

Correlations among the critical traits are shown in Table II-8. Significant and positive associations were found for ARND with ADIM; PDIM with PLEN; ADIM with PDIM and PLEN; PRND with PDIM; and PDIM with PLEN while significant and negative correlations were observed for ALEN with PRND; and ALEN with PDIM.

The significant and positive associations involving ARND, ADIM, PRND and PDIM suggest that both rind thickness and diameter could be improved simultaneously. However, whereas selection for large PDIM could be associated with simultaneous selection for thicker PRND, thicker ARND and larger ADIM, selection based on PRND would not be effective in simultaneous improvement of the critical traits of the stalk.

Significant and positive associations (not shown in tables) were found between ACRS and BBRK (0.96**) and between PCRS and PBRK (0.96**) indicating that any of the two strength test methods, crushing or breaking strength, could be used on both the stalk and peduncle portions of the plant. However, no significant associations were found between any of the strength tests methods of the stalk (ACRS or BBRK) and any of the strength tests of the peduncle (PCRS or PBRK) suggesting the need to test both portions of the plants for strength.

In considering any of the correlations in this experiment involving sorghum, it is important to note that genotypes were from two unrelated genera, Pennisetum and Sorghum in which the relative contribution of a trait or traits to reducing lodging might have differing effects in the two genera.

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Table II-1. Genotypes studied in experiment II (1988).

Code	genotype	description
1*	80025-1	pearl millet
2	68B X 80025-1	p.m. test cross
3	80026-2	pearl millet
4	68B X 80026-2	p.m. test cross
5	68B X 78110tr	p.m. x p.p. test cross
6	84-5480	pearl millet (ss)
7*	84-5481	pearl millet (ss)
8	85-58029-1	pearl millet (ss)
9*	68B	pearl millet (mss)
10*	23DBE	pearl millet (ws)
11*	KS HYB	millet hybrid
12*	KS57B	sorghum line

* structural and strength tests conducted on these genotypes

ss stiff stalk

mss moderately stiff stalk

ws weak stalk

Table II-2. Means of lodging parameters(+), strength tests(@) critical traits(#) and general agronomic traits(\$).

Trait	units	mean	range	cv(%)	s.e. (\pm)
SL ⁺	count	5*	0 - 10	58.6	1.8
PL ⁺	count	9***	0 - 17	31.8	1.6
LG ⁺	score	8***	1 - 10	13.9	0.6
ACRS [@]	kg	45.7***	17.8 - 69.4	24.6	6.5
BBRK [@]	kg	8.2***	2.9 - 11.2	12.8	0.6
PCRS [@]	kg	25.1***	12.8 - 46.9	12.5	1.8
PBRK [@]	kg	5.0***	2.3 - 8.4	8.9	0.3
ARND [#]	mm	0.72***	0.52 - 0.85	7.4	0.03
ADIM [#]	cm	0.89***	0.60 - 1.05	5.4	0.03
ALEN [#]	cm	6.4*	4.5 - 9.0	12.4	0.5
PRND [#]	mm	0.34***	0.24 - 0.44	7.8	0.02
PDIM [#]	cm	0.63***	0.44 - 0.78	4.6	0.02
PLEN [#]	cm	27.7***	19.7 - 33.9	5.8	0.9
MGHA ^{\$}	mg/ha	3.7***	2.4 - 5.3	16.8	0.4
BLM ^{\$}	days	65***	60 - 68	2.5	0.9
HT ^{\$}	cm	95***	78 - 122	4.1	2.2
HSM ^{\$}	m-2	23***	13 - 46	18.9	2.5

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.
s.e. of genotypic mean.

Table II-3. Results of tests of contrasts for lodging parameters.

Contrast	SL (count)	PL (count)	LG (count)
1 [#] 1 7 9 10 11 V 12 [@]	6 0*	11 0****	9 1****
2 11 V 12	6 0*	11 0****	8 1****
3 7 V 12	3 0	5 0*	9 1****
4 10 V 9	10 3*	14 7*	10 7*

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

@ see Table II-1 for genotypes.

#1 pearl millets V sorghum line
 2 millet hybrid V sorghum line
 3 best⁺ millet line V sorghum line
 4 23DBE V 68B

+ based on all the strength tests

Table II-4. Results of tests of contrasts for strength tests.

Con#	----- stalk -----		----- peduncle -----	
	ACRS (kg)	BBRK (kg)	PCRS (kg)	PBRK (kg)
1	50.7 54.9	7.6 11.2***	20.8 46.9***	4.3 8.4***
2	65.0 54.9	10.1 11.2	25.8 46.9***	5.2 8.4***
3	69.4 54.9	11.2 10.3	23.2 46.9***	5.3 8.4***
4	17.8 50.5**	2.9 10.3***	13.9 28.2***	2.3 5.4***

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.
see Table II-3 for genotypes contrasted.

1 pearl millets V sorghum line
2 millet hybrid V sorghum line
3 best⁺ millet line V sorghum line
4 23DBE V 68B

+ based on all the strength tests

Table II-5. Results of tests of contrasts for general agronomic traits.

Con#	MGHA (mg/ha)	BLM (days)	HT (cm)	HSM (m ⁻²)
1	3.4 5.3***	65 65	97 81***	25 13**
2	5.2 5.3	65 65	121 81***	22 13*
3	3.0 5.3***	69 65*	95 81**	13 13
4	2.4 3.7*	60 68***	78 103***	46 20***

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

see Table II-3 for genotypes contrasted.

1 pearl millets V sorghum line
 2 millet hybrid V sorghum line
 3 best⁺ millet line V sorghum line
 4 23DBE V 68B

+ based on all the strength tests

Table II-6. Results of tests of contrasts for critical traits.

Con#	----- stalk -----				----- peduncle -----							
	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)						
1	0.70	0.83**	0.88	0.93	7	5**	0.32	0.44**	0.60	0.78**	27	32**
2	0.79	0.83	1.05	0.93*	6	5*	0.32	0.44**	0.69	0.78**	32	32
3	0.85	0.83	1.03	0.93*	7	5*	0.35	0.44**	0.64	0.78**	30	32
4	0.53	0.74**	0.60	0.92**	8	7	0.24	0.33**	0.44	0.66**	20	26**

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.
see Table II-3 for genotypes contrasted.

1 pearl millets V sorghum line
2 millet hybrid V sorghum line
3 best⁺ millet line V sorghum line
4 23DBE V 68B

+ based on all the strength tests

Table II-7. Correlation coefficients for critical traits with lodging parameters(+), strength tests(@) and general agronomic traits(\$).

		----- critical traits -----					
		----- stalk -----			----- peduncle -----		
Trait	units	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
SL ⁺	count	-0.87*	-0.68	0.82*	-0.79	-0.89*	-0.72
PL ⁺	count	-0.82*	-0.52	0.75	-0.66	-0.78	-0.58
LG ⁺	score	-0.51	-0.25	0.90*	-0.77	-0.76	-0.49
ACRS [@]	kg	0.97**	0.91*	-0.52	0.40	0.75	0.80
BBRK [@]	kg	0.98***	0.87*	-0.67	0.56	0.87*	0.80
PCRS [@]	kg	0.73	0.50	-0.91*	0.76	0.88*	0.65
PBRK [@]	kg	0.82*	0.66	-0.96**	0.87*	0.96**	0.80
MGHA ^{\$}	mg/ha	0.69	0.64	-0.80	0.55	0.85*	0.77
BLM ^{\$}	days	0.77	0.82*	-0.41	0.51	0.66	0.64
HT ^{\$}	cm	0.44	0.71	-0.04	-0.09	0.36	0.50
HSM ^{\$}	m ⁻²	-0.81	-0.85*	0.75	-0.85*	-0.86*	-0.87*

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

Table II-8. Correlation coefficients among critical traits.

	ARND	ADIM	ALEN	PRND	PDIM	PLEN
ARND	.	0.91*	-0.70	0.61	0.86*	0.87*
ADIM		.	-0.58	0.55	0.81*	0.92**
ALEN			.	-0.93**	-0.93**	-0.81
PRND				.	0.84*	0.75
PDIM					.	0.90*
PLEN						.

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

EXPERIMENT III (1988)

Fourteen new pearl millet lines chosen from the breeding nursery on the basis of 1987 nursery lodging scores, and their 14 test crosses to either 23DAE or 68A A-lines (Table III-1) were evaluated for 17 traits grouped in four categories (Table III-2). Data was collected on lodging parameters and general agronomic traits for all 28 genotypes, but only a subset of 6 male lines and their test crosses were selected for strength tests and evaluation of critical traits. Analyses for all the 17 traits were done on these 12 genotypes. Significant differences were obtained for all the traits except PCRS (Table III-2). A high lodging score of 8 suggests that on average lodging was high among these genotypes, and most of the lodging resulted from peduncle breakage.

Seven pre-planned contrasts between genotypic groups were considered (Table III-3). Male lines classified in 1987 as stiff stalk were significantly lower than the weak stalk lines in all three lodging parameters but none of the strength tests indicated any significant differences (Table III-4). In this experiment therefore, there was no agreement between field evaluation of lodging and mechanical strength tests. The 1987 classification of the lines into stiff or weak stalk could not be validated by mechanical strength tests. The inherent strength among these lines were similar but the significantly higher yields and extra height of the 'weak' lines (Table III-5) might have caused them to lodge more although they had significantly larger ADIM and shorter PLEN than the 'stiff' stalk group (Table III-6).

Lodging scores are based on phenotypic response to the effect of the environmental factors that tend to promote lodging and to how well the genetic makeup of the plants can withstand the factors causing lodging. Selection for lodging resistance using lodging scores are therefore based on phenotype. How well the genetic makeup for lodging resistance represents the phenotype can indirectly be estimated by obtaining the inherent strength using mechanical strength tests which have been reported in maize to be independent of the environment (Chang et al., 1976; Cloninger et al., 1970; Thompson, 1963; Zuber et al., 1961). When no differences are detected in the inherent strength between lines classified as 'stiff' or 'weak' stalk, such a classification, as is for the lines in this experiment could be misleading.

The general agronomic traits strongly suggest that the 'weak' stalk lines only lodged more because they were higher yielding and taller than the 'stiff' stalk lines. For purposes of classifying lines into stiff or weak stalks, both the mechanical strength tests and field evaluation should be done. However, a truly stiff stalk genotype would only be so if it had such strength in both stalk and peduncle that it can withstand the effects of high yield, tillering, and all types of combinations and degrees of severity of environmental effects, until the optimal time of harvesting.

No significant differences were shown between the groups of male lines and their test crosses for all lodging parameters despite test crosses being significantly higher yielding, earlier in maturity, taller and more tillering and having significantly smaller ADIM than the lines. This suggests that a lot of heterosis was manifested for improved

inherent strength of both the stalk and peduncle. The test crosses had larger strength tests values than male lines although they differed statistically only in ACRS.

There was significantly more peduncle lodging among the 68A test crosses than among the 23DAE test crosses, although their inherent peduncle strengths were similar and despite the 68A test crosses having significantly larger ADIM and PDIM. On the other hand, although no significant differences existed between the two groups of test crosses for stalk lodging, both strength tests of the stalk indicated that stalks of 23DAE test crosses were significantly stronger.

These results were unexplained, since in other experiments 68A or 68B and their test crosses exhibit more or equal strength and less or equal lodging, particularly peduncle lodging, than 23A or 23B and their test crosses.

The contrast involving the best male line and its 23DAE test cross shows superiority of the line over the test cross in stalk lodging but not in either peduncle lodging or lodging score. However, strength tests ACRS and PBRK indicate that the line had stronger stalks and peduncles. Significant differences for the critical traits ADIM, PDIM and PLEN suggest that they were responsible for the higher inherent strength of the line. The test cross on the other hand was significantly higher yielding, earlier, taller and higher tillering than the line. The worst line had significantly more peduncle lodging than its 23DAE test cross. Strength tests however show that the test cross had similar inherent peduncle strength to the line although it had significantly higher mechanical stalk strength. The test cross was significantly higher

yielding, earlier, taller and had larger ADIM and longer PLEN than the line.

Of the two male lines and their 68A test crosses, the better line was better than its test cross only in lodging scores. Strength tests show that the line and its test cross were similar in both stalk and peduncle strengths. The test cross was significantly higher yielding, taller and had shorter PLEN than the line. The poor male line had significantly more stalk lodging but less peduncle lodging than its 68A test cross. Only ACRS shows that the line had higher stalk strength than the test cross. The line was significantly better than the test cross in all the critical traits except ADIM and PDIM, and was taller than the test cross.

Table III-7 shows the correlations of the critical traits with lodging parameters, strength tests and general agronomic traits. Significant and positive correlations existed for ARND with ACRS and BBRK indicating that ARND was more important than ADIM in imparting strength to the stalks whereas the significant and positive association for PDIM with PBRK indicates that PDIM was more important than PRND in imparting strength to the peduncles. ALEN was significantly and positively associated with SL and LG suggesting that increased ALEN could aggravate lodging. Significant and negative associations for both ADIM and PDIM with HSM suggests that increased tillering would tend to decrease the size of diameters of both stalk and peduncle and thus increase lodging.

Correlations among the critical traits are shown in Table III-8. Significant and positive associations for PDIM with ARND, ADIM and PRND

suggests that selection for high PDIM would simultaneously select for improved ARND, ADIM and PRND. ARND however was significantly and negatively associated with ALEN. Significant and positive correlations were found (not shown in tables) between ACRS and BBRK (0.86***), PCRS and PBRK (0.84***), ACRS and PCRS (0.63*) suggesting that either of the crushing strength methods or either of the breaking strength methods could be used to evaluate the strength of both the stalks and peduncles. These findings were consistent in all the experiments. The significant and positive correlation (0.63*) between ACRS and PCRS suggests that selection based on peduncle strength determined by PCRS would be associated with simultaneous selection for stalk strength. This is supported by the significant positive associations for ACRS with PCRS (0.84***) in experiment IV; ACRS with PCRS (0.53*), BBRK with PCRS (0.65**), and BBRK with PBRK (0.49*) in experiment V.

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Table III-1. Genotypes studied in experiment III (1988).

Male code	male	test cross code	test cross	description of male
1*	88049	2*	23DAE X 88049	p.m.(ss)
3	88084	4	23DAE X 88084	p.m.(ss)
5	88092	6	23DAE X 88092	p.m.(ss)
7*	88093	8*	23DAE X 88093	p.m.(ss)
9	88106	10	23DAE X 88106	p.m.(ss)
11*	88114	12*	23DAE X 88114	p.m.(ss)
13*	88116	14*	23DAE X 88116	p.m.(ws)
15	88117	16	23DAE X 88117	p.m.(ss)
17*	88062	18*	68A X 88062	p.m.(ss)
19	88138	20	68A X 88138	p.m.(ss)
21	88143	22	68A X 88143	p.m.(ws)
23	54116	24	68A X 54116	p.m.(ss)
25*	54151	26*	68A X 54151	p.m.(ws)
27	55662-1	28	68A X 55662-1	p.m.(ss)

* structural and strength tests conducted on these genotypes.

p.m. pearl millet

ss stiff stalk

ws weak stalk

Table III-2. Means of lodging parameters(+), strength tests critical traits(#) and general agronomic traits(\$).

Trait	units	mean	range	cv(%)	s.e.(±)
SL ⁺	count	9***	0 - 26	40.6	2.1
PL ⁺	count	14***	4 - 36	50.8	4.0
LG ⁺	score	8***	4 - 10	19.7	0.9
ACRS [@]	kg	61.5***	33.9 - 93.6	18.9	6.7
BBRK [@]	kg	9.4**	6.4 - 12.3	16.9	0.9
PCRS [@]	kg	26.1NS	22.4 - 30.1	14.5	2.2
PBRK [@]	kg	4.9**	3.9 - 5.7	11.4	0.3
ARND [#]	mm	0.71***	0.49 - 0.86	10.2	0.04
ADIM [#]	cm	0.79***	0.71 - 0.91	6.7	0.03
ALEN [#]	cm	6.3*	2.8 - 10.6	17.0	0.6
PRND [#]	mm	0.28**	0.24 - 0.33	9.8	0.02
PDIM [#]	cm	0.62***	0.53 - 0.70	6.7	0.02
PLEN [#]	cm	30.6**	21.5 - 41.1	5.5	1.0
MGHA ^{\$}	mg/ha	3.9***	2.3 - 5.2	20.1	0.4
BLM ^{\$}	days	68***	65 - 77	2.1	0.8
HT ^{\$}	cm	93***	67 - 120	4.4	2.4
HSM ^{\$}	m ⁻²	23***	16 - 26	18.7	2.4

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.
s.e. of genotypic mean.

Table III-3. Results of tests of contrasts for lodging parameters.

Contrast	SL (count)	PL (count)	LG (score)
1# 1 7 11 17 V 13 25 [@]	6 17***	6 25***	7 9***
2 1 7 11 13 17 25 V 2 8 12 14 18 26	10 8	12 15	8 8
3 2 8 12 14 V 18 26	7 9	11 25***	8 9
4 11 V 12	4 15**	4 11	7 9
5 13 V 14	10 8	34 14**	9 9
6 17 V 18	3 5	8 14	6 9*
7 25 V 26	25 14**	15 36**	10 10

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

@ see Table III-1 for genotypes.

#1 Stiff stalk male lines V Weak stalk male lines
 2 Male lines V their test crosses
 3 23DAE test crosses V 68A test crosses
 4 Best⁺ male line V its 23DAE test cross
 5 Worst⁺ male line V its 23DAE test cross
 6 Good⁺ male line V its 68A test cross
 7 Poor⁺ male line V its 68A test cross

+ based on all the strength tests

Table III-4. Results of tests of contrasts for strength tests.

Con#	----- stalk -----				----- peduncle -----			
	ACRS (kg)		BBRK (kg)		PCRS ^{NS} (kg)		PBRK (kg)	
1	52.7	52.2	8.8	9.1	25.7	24.2	4.7	4.7
2	52.5	70.6***	8.9	9.9	25.2	26.9	4.7	5.0
3	76.7	58.4**	10.5	8.7*	27.3	26.2	4.9	5.1
4	61.4	84.9*	8.8	10.7	30.1	26.4	5.7	4.3**
5	33.9	85.1***	8.1	11.2*	22.7	27.9	4.5	5.2
6	55.0	67.6	10.6	9.7	25.7	29.9	4.8	5.7
7	70.4	49.2*	10.1	7.8	25.6	22.4	4.9	4.5

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant

see Table III-3 for genotypes contrasted.

1 Stiff stalk male lines V Weak stalk male lines
 2 Male lines V their test crosses
 3 23DAE test crosses V 68A test crosses
 4 Best⁺ male line V its 23DAE test cross
 5 Worst⁺ male line V its 23DAE test cross
 6 Good⁺ male line V its 68A test cross
 7 Poor⁺ male line V its 68A test cross

+ based on all the strength tests

Table III-5. Results of tests of contrasts for general agronomic traits.

Con#	MGHA (mg/ha)	BLM (days)	HT (cm)	HSM (m ⁻²)
1	2.6 3.7*	69 68	87 94***	19 22
2	3.0 4.5***	69 68*	86 101***	20 24*
3	4.5 4.4	68 67*	101 100	24 24
4	2.6 5.0***	69 65**	75 120***	16 24**
5	3.2 5.2**	70 66**	78 105***	22 26
6	2.9 4.6*	66 67	82 103***	18 24
7	4.2 4.4	67 67	110 97***	22 24

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

see Table III-3 for genotypes contrasted.

- 1 Stiff stalk male lines V Weak stalk male lines
 2 Male lines V their test crosses
 3 23DAE test crosses V 68A test crosses
 4 Best⁺ male line V its 23DAE test cross
 5 Worst⁺ male line V its 23DAE test cross
 6 Good⁺ male line V its 68A test cross
 7 Poor⁺ male line V its 68A testcross

+ based on all the strength tests

Table III-6. Results of tests of contrasts for critical traits.

Con#	----- stalk -----				----- peduncle -----		
	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)	
1	0.46 0.75	0.81 0.83*	7 7	0.28 0.31	0.63 0.62	34 27**	
2	0.71 0.72	0.82 0.76**	6 6	0.29 0.28	0.63 0.61	30 31	
3	0.73 0.71	0.74 0.82**	6 7	0.28 0.27	0.59 0.64*	31 30	
4	0.63 0.75	0.91 0.74**	7 6	0.28 0.27	0.68 0.57**	28 33**	
5	0.67 0.78	0.88 0.72**	7 7	0.28 0.28	0.59 0.63	23 32**	
6	0.86 0.79	0.84 0.87	4 5	0.33 0.30	0.70 0.69	40 32**	
7	0.82 0.62**	0.83 0.77	7 9*	0.33 0.24**	0.65 0.59	32 28**	

* ** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

see Table III-3 for genotypes contrasted.

-
- 1 Stiff stalk male lines V Weak stalk male lines
 - 2 Male lines V their test crosses
 - 3 23DAE test crosses V 68A test crosses
 - 4 Best⁺ male line V its 23DAE test cross
 - 5 Worst⁺ male V its 23DAE test cross
 - 6 Good⁺ male line V its 68A test cross
 - 7 Poor⁺ male line V its 68A test cross
-

+ based on all the strength tests

Table III-7. Correlation coefficients for critical traits with lodging parameters(+), strength tests(@) and general agronomic traits(\$).

		----- critical traits -----					
		----- stalk -----			----- peduncle -----		
Trait	units	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
SL ⁺	count	-0.23	-0.15	0.68*	-0.01	-0.30	0.15
PL ⁺	count	-0.20	0.16	0.41	-0.23	-0.18	-0.36
LG ⁺	score	-0.23	-0.01	0.76***	-0.04	-0.22	0.04
ACRS [@]	kg	0.59*	-0.09	-0.13	0.32	0.30	0.13
BBRK [@]	kg	0.88***	0.09	-0.53	0.55	0.52	0.11
PCRS [@]	kg	0.33	0.33	-0.26	0.42	0.53	0.19
PBRK [@]	kg	0.43	0.57	-0.35	0.40	0.72**	-0.14
MGHA ^{\$}	mg/ha	0.34	-0.23	0.22	0.14	-0.04	0.13
BLM ^{\$}	days	0.27	0.06	-0.46	-0.16	0.10	-0.66*
HT ^{\$}	cm	0.12	-0.30	0.47	0.13	-0.15	0.37
HSM ^{\$}	m ⁻²	-0.26	-0.61*	0.57	-0.22	-0.59*	0.25

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

Table III-8. Correlation coefficients among critical traits.

	ARND	ADIM	ALEN	PRND	PDIM	PLEN
ARND	.	0.28	-0.71*	0.68	0.69*	0.16
ADIM		.	-0.24	0.43	0.74**	-0.18
ALEN			.	-0.48	-0.51	-0.07
PRND				.	0.63*	0.48
PDIM					.	0.18
PLEN						.

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

EXPERIMENT IV (1988)

Twelve lines involving 6 pearl millets and 6 PM X NG lines each test crossed to both 23DBE (weak stalk) and 68B (moderately stiff stalk) constituted the 36 entries in this experiment (Table IV-1). Because of drought some of the pearl millet and late PM X NG lines did not mature and could not provide any data. A subset of 6 male lines including 3 pearl millets and 3 PM X NG lines and test crosses of these on both 23DBE and 68B (Table IV-1) were selected for collecting data on strength tests and critical traits. Plant samples from late PM X NG lines were taken only from 10 randomly selected plants that had reached maturity within each plot. Data analyses for all traits studied were done on these 18 genotypes.

Significant differences were found between male lines and their test crosses for all lodging parameters (Table IV-2). Test crosses were worse than male lines in both types of lodging. The 23DBE test crosses had significantly more peduncle lodging and higher lodging scores than 68B test crosses but they were similar in stalk lodging. Peduncle lodging was more serious than stalk lodging in all the three groups of genotypes. There were significant differences for ACRS, PCRS and PBRK between the male lines and test crosses. In contrast to the observation on lodging parameters, test crosses had both stronger stalks and peduncles than the male lines (Table IV-3) suggesting that high inherent strength does not necessarily imply more lodging resistance. There was agreement between peduncle lodging and both PCRS and PBRK between the types of test crosses further confirming that 68B test crosses had

stronger peduncles than 23DBE test crosses.

Tests on general agronomic traits indicate that test crosses were significantly earlier and taller than their male parents (Table IV-4) while critical traits show that test crosses had significantly larger ARND and PDIM than their male parents suggesting that among the test crosses higher stalk strength was derived more from thicker ARND than from ADIM whereas higher peduncle strength was due more to larger PDIM than PRND. However, test crosses had significantly longer ALEN and PLEN than male lines. Although no significant differences could be found for SL, ACRS and BBRK among the test crosses, 68B test crosses were significantly taller and had significantly thicker ARND, larger ADIM, PDIM and longer ALEN than 23DBE test crosses.

The only significant correlation between critical traits and lodging parameters involved ALEN and LG (Table IV-6). Both ARND and PRND were significantly and positively correlated with their respective strength tests. ADIM was significantly and positively correlated with ACRS while PDIM was significantly and negatively correlated with BBRK. ALEN was significantly and positively correlated with crushing strength of both stalk and peduncle while PLEN was positively correlated with PCRS and PBRK. Both PDIM and PLEN had significant and negative correlations with BLM while all critical traits of the stalk were positively correlated with HT. Significant and positive associations among critical traits (Table IV-7) were those for ARND with ADIM, and PRND with PDIM suggesting that diameter and rind thickness in either the stalk or the peduncle could be selected for simultaneously. Selection of these traits based in one of the two portions of the plant

(stalk or peduncle) would not result in simultaneous selection in the other portion. Significant and positive correlations were detected for ALEN with ARND and ADIM and for PDIM with PLEN.

Strong significant positive correlations were found (not shown in tables) for ACRS with BBRK (0.84***) and PCRS with PBRK (0.90***) as was the case in all other experiments. However, only the significant positive association between ACRS and PCRS (0.67**) suggests that joint selection based on either ACRS or PCRS could improve both the stalk and the peduncle strengths.

Average estimates of male parent heterosis for lodging parameters (Table IV-8) shows a range of -7 to 850% for PL and 7 to 332% for LG. Line 86-59110-9 had the least heterotic effect for both PL and LG. Ranges for male parent heterosis among the strength tests were 5 to 327% for ACRS, -28 to 291% for BBRK, 48 to 145% for PCRS and 14 to 88% for PBRK (Table IV-9). The line that had the highest heterotic effect for strength tests of the stalk was not the same one that had highest heterotic effect for strength tests of the peduncle. Line 86-59110-9 which showed least heterotic effect for both PL and LG also had the highest heterotic effect for both PCRS and PBRK. Among general agronomic traits, male parent heterosis ranged from 6 to 93% for HT and -49 to -6% for BLM (Table IV-10). Line 86-59110-9 had the least heterotic effect for both HT and BLM. Ranges for male parent heterosis among the critical traits were -3 to 51% for ARND, -4 to 17% for ADIM, 13 to 102% for ALEN, -4 to 24% for PRND, 1 to 53% for PDIM and 32 to 68% for PLEN (Table IV-11). Line 86-5110-9 had the least heterotic effect for both ARND and ALEN but had highest heterotic effect for PRND.

Tables IV-12 through IV-15 show estimates of average and specific combining ability for lodging parameters, strength tests, general agronomic and critical traits. Line 86-59110-9 had the highest aca for the traits SL, ACRS, BBRK, PCRS, HT, ARND, ADIM and ALEN but had the least gca for PDIM and PLEN. The aca superiority in SL, ACRS BBRK and PCRS of this PM X NG line 86-59110-9 over the other lines suggest that it could be the best potential source of genes for improving stalk strength and stalk lodging. However, although it could also be a potential source of genes for improving peduncle strength, its tremendously high (54.02) estimate of aca for HT shows that increased height would impose serious limitations in improving both peduncle strength and peduncle lodging unless it was converted into a dwarf phenotype.

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Table IV-1. Genotypes studied in experiment IV (1988).

Male code	male	23DBE test cross	68B test cross	description of male
1	86-7406-1	23DBEX86-7406-1	68BX86-7406-1	p.p.
2	86-7411-2	23DBEX86-7411-2	68BX86-7411-2	p.p.
3*	86-7517-1	23DBEX86-7517-1	68BX86-7517-1	p.p.
4	86-7728-1	23DBEX86-7728-1	68BX86-7728-1	p.p.
5*	86-7821-2	23DBEX86-7821-2	68BX86-7821-2	p.p.
6*	86-59110-9	23DBEX86-59110-9	68BX86-59110-9	p.p.(ss)
7*	56112	23DBEX56112	68BX56112	p.p.(ss)
8	56113	23DBEX56113	68BX56113	p.p.(ss)
9*	56114	23DBEX56114	68BX56114	p.p.(ss)
10*	85-58030-1	23DBEX85-58030-1	68BX85-58030-1	p.m.(ss)
11	PPI-1 G87	23DBEXPPI-1 G87	68BXPPI-1 G87	p.p.(ss)
12	PPI-2 G87	23DBEXPPI-2 G87	68BXPPI-2 G87	p.p.(ss)

* structural and strength tests conducted on these male lines and their test crosses.

p.m. pearl millet

p.p. derivative of a cross between pearl millet and napier grass (PM X NG) line.

ss stiff stalk

Table IV-2. Results of tests of contrasts for lodging parameters.

	SL (count)	PL (count)	LG (score)
CONTR			
-AST# 1	*	*	*
# 2	NS	*	*
MEAN			
males	1	4	6
TX1	4	10	9
TX2	3	6	8
RANGE			
males	0 - 5	1 - 9	2 - 9
TX1	1 - 6	4 - 17	9 - 10
TX2	0 - 5	3 - 10	7 - 10
CV (%)	94.5	44.5	14.0
s.e. (\pm)	1.4	1.7	0.6

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant
s.e. of genotypic mean.

1 males V test crosses

2 23DBE test crosses V 68B test crosses

TX1 23DBE test crosses

TX2 68B test crosses

Table IV-3. Results of tests of contrasts for strength tests.

	----- stalk -----		----- peduncle -----	
	ACRS (kg)	BBRK (kg)	PCRS (kg)	PBRK (kg)
CONTR				
-AST# 1	**	NS	***	**
# 2	NS	NS	*	*
MEAN				
males	58.5	11.7	14.2	3.5
TX1	88.7	12.0	23.8	4.7
TX2	111.3	14.4	29.3	6.0
RANGE				
males	16.7 - 91.7	3.4 - 17.2	12.3 - 19.0	2.9 - 4.1
TX1	68.1 - 109.8	9.4 - 14.4	20.1 - 28.4	4.3 - 6.0
TX2	55.4 - 191.3	9.1 - 20.6	27.3 - 34.4	5.1 - 6.6
CV (%)	33.0	21.6	16.2	12.7
s.e. (±)	16.4	1.6	2.1	0.3

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively

NS non-significant
s.e. of genotypic mean.

1 males V test crosses

2 23DBE test crosses V 68B test crosses

TX1 23DBE test crosses

TX2 68B test crosses

Table IV-4. Results of tests of contrasts for general agronomic traits.

	MGHA (mg/ha)	BLM (days)	HT (cm)
	-----	-----	-----
CONTR			
-AST# 1	&	**	**
# 2	NS	NS	*
MEAN			
males	&	97	102
TX1	3.8	76	122
TX2	3.6	70	140
RANGE			
males	&	71 - 147	58 - 175
TX1	2.7 - 4.8	67 - 85	98 - 182
TX2	2.8 - 4.4	66 - 79	88 - 192
CV (%)	&	14.3	5.6
s.e. (\pm)	&	6.7	3.9

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant
s.e. of genotypic mean.

1 males V test crosses

2 23DBE test crosses V 68B test crosses

TX1 23DBE test crosses

TX2 68B test crosses

& data not obtained

Table IV-5. Results of tests of contrasts for critical traits.

	----- stalk -----			----- peduncle -----		
	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
CONTR						
-AST# 1	*	NS	***	NS	**	***
# 2	*	*	*	NS	**	NS
MEAN						
males	0.81	0.88	5.9	0.27	0.54	19.5
TX1	0.85	0.88	7.8	0.28	0.62	29.5
TX2	0.95	0.99	8.8	0.30	0.69	30.8
RANGE						
males	0.53-1.17	0.80-1.02	5-10	0.24-0.29	0.43-0.70	15-23
TX1	0.65-1.03	0.76-1.02	6-10	0.25-0.29	0.53-0.72	24-36
TX2	0.66-1.24	0.91-1.08	6-13	0.26-0.32	0.61-0.81	25-36
CV (%)	9.6	6.2	12.8	8.7	5.9	10.5
s.e. (\pm)	0.05	0.03	0.5	0.01	0.02	1.6

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant
s.e. of genotypic mean.

1 males V test crosses

2 23DBE test crosses V 68B test crosses

TX1 23DBE test crosses

TX2 68B test crosses

Table IV-6. Correlation coefficients for critical traits with lodging parameters(+), strength tests(®) and general agronomic traits(\$).

		----- critical traits -----					
		----- stalk -----			----- peduncle -----		
Trait	units	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
SL ⁺	count	-0.06	-0.03	-0.17	0.13	-0.25	-0.19
PL ⁺	count	0.18	0.24	0.24	-0.08	0.16	0.32
LG ⁺	score	0.42	0.41	0.50*	0.08	0.14	0.43
ACRS [®]	kg	0.85***	0.53*	0.48*	0.29	-0.21	0.09
BBRK [®]	kg	0.80***	0.45	0.25	0.04	-0.51*	-0.21
PCRS [®]	kg	0.42	0.53*	0.51*	0.63**	0.51*	0.69**
PBRK [®]	kg	0.21	0.44	0.34	0.66**	0.74***	0.75***
BLM ^{\$}	days	0.38	0.10	-0.04	-0.55*	-0.75***	-0.74***
HT ^{\$}	cm	0.81***	0.76***	0.81***	-0.09	-0.19	0.01

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

Table IV-7. Correlation coefficients among critical traits.

	ARND	ADIM	ALEN	PRND	PDIM	PLEN
ARND	.	0.67**	0.56*	-0.03	-0.36	-0.18
ADIM		.	0.56*	0.23	0.10	-0.05
ALEN			.	0.06	0.04	0.22
PRND				.	0.49*	0.46
PDIM					.	0.77***
PLEN						.

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

Table IV-8. Estimates of male parent heterosis (%) for lodging parameters.

Trait	units	----- male code -----					
		3	5	6	7	9	10
PL	count						
TX1		82	26	31	1325	257	491
TX2		4	74	-45	375	414	109
\bar{X}		43	50	-7	850	335	300
LG	score						
TX1		20	28	10	129	196	382
TX2		20	35	4	83	160	282
\bar{X}		20	32	7	106	178	332

TX1 23DBE test crosses
 TX2 68B test crosses

Table IV-9. Estimates of male parent heterosis (%) for strength tests.

Trait	units	----- male code -----					
		3	5	6	7	9	10
ACRS	kg						
TX1		4	284	20	48	33	308
TX2		6	370	108	95	56	233
\bar{X}		5	327	64	72	45	271
BBRK	kg						
TX1		-15	254	-25	-20	-6	179
TX2		-22	328	19	5	4	171
\bar{X}		-18	291	-3	-7	-1	175
PCRS	kg						
TX1		49	60	111	63	52	82
TX2		48	126	180	116	99	164
\bar{X}		48	93	145	89	75	123
PBRK	kg						
TX1		59	4	51	36	35	33
TX2		65	24	125	82	85	65
\bar{X}		62	14	88	59	60	49

TX1 23DBE test crosses
TX2 68B test crosses

Table IV-10. Estimates of male parent heterosis (%) for general agronomic traits.

Trait	units	----- male code -----					
		3	5	6	7	9	10
HT	cm						
TX1		16	35	4	2	18	97
TX2		23	150	8	15	38	51
\bar{X}		19	93	6	8	28	74
BLM	days						
TX1		-17	-4	-52	-12	-13	-5
TX2		-36	-8	-47	-25	-26	-7
\bar{X}		-26	-6	-49	-18	-19	-6

TX1 23DBE test crosses
 TX2 68B test crosses

Table IV-11. Estimates of male parent heterosis (%) for critical traits.

Trait	units	----- male code -----					
		3	5	6	7	9	10
ARND	mm						
TX1		2	23	-12	6	7	3
TX2		10	78	6	24	12	-5
\bar{X}		6	51	-3	15	9	-1
ADIM	cm						
TX1		11	0	0	-12	9	-12
TX2		8	29	31	6	26	5
\bar{X}		9	15	15	-3	17	-4
ALEN	cm						
TX1		18	42	2	35	57	76
TX2		16	161	23	39	29	61
\bar{X}		17	102	13	37	43	68
PRND	mm						
TX1		-3	-2	21	0	7	1
TX2		-4	-5	26	24	17	11
\bar{X}		-4	-4	24	12	12	6
PDIM	cm						
TX1		47	-1	25	22	21	-9
TX2		59	3	42	33	40	15
\bar{X}		53	1	34	27	31	3
PLEN	cm						
TX1		45	32	62	42	67	65
TX2		72	32	72	49	69	64
\bar{X}		58	32	67	45	68	65

TX1 23DBE test crosses
TX2 68B test crosses

Table IV-12. Estimates of average and specific combining ability effects for lodging parameters.

		----- male code -----					
Trait	units	3	5	6	7	9	10
		-----	-----	-----	-----	-----	-----
SL	count						
sca1		-2.01	0.07	0.49	-0.01	0.31	1.15
sca2		2.02	-0.07	-0.48	0.02	-0.32	-1.15
aca		-0.13	1.96	2.37	-2.63	-1.95	0.38
PL	count						
sca1		1.72	-3.19	1.31	1.22	-2.85	1.81
sca2		1.72	3.20	-1.30	-1.22	2.87	-1.80
aca		5.33	-0.26	-0.09	-1.67	-2.93	-0.43
LG	score						
sca1		-0.40	-0.65	-0.15	0.52	0.19	0.51
sca2		0.40	0.65	0.15	-0.52	-0.18	-0.52
aca		0.93	0.35	0.68	-0.82	0.01	-1.15

sca1 specific combining ability on 23DBE
sca2 specific combining ability on 68B
aca average combining ability of males

Table IV-13. Estimates of average and specific combining ability effects for strength tests.

		----- male code -----					
Trait	units	3	5	6	7	9	10
ACRS	kg						
sca1		10.17	3.67	-29.47	-4.98	2.97	17.64
sca2		-10.16	-3.66	29.46	4.98	-2.97	-17.63
aca		-13.60	-24.00	50.58	20.39	4.84	-38.20
BBRK	kg						
sca1		1.66	0.16	-2.64	-0.86	0.37	1.31
sca2		-1.65	-0.17	2.63	0.87	-0.38	-1.31
aca		-0.41	-2.78	3.62	1.49	2.04	-3.95
PCRS	kg						
sca1		2.85	-1.42	-1.51	-0.79	-0.65	1.54
sca2		-2.85	1.44	1.51	0.80	0.67	-1.54
aca		1.72	-2.27	3.60	-1.51	-1.14	-0.42
PBRK	kg						
sca1		0.51	0.22	-0.47	-0.10	-0.17	0.04
sca2		-0.50	-0.21	0.48	0.11	0.18	-0.03
aca		0.74	-0.67	0.19	-0.27	-0.22	0.22

sca1 specific combining ability on 23DBE

sca2 specific combining ability on 68B

aca average combining ability of males

Table IV-14. Estimates of average and specific combining ability effects for general agronomic traits.

		----- male code -----					
Trait	units	3	5	6	7	9	10
BLM	days						
sca1		6.41	-2.09	-7.09	2.58	2.91	-2.76
sca2		-6.42	2.07	7.08	-2.59	-2.92	2.74
aca		2.42	-5.74	1.92	2.25	5.92	-6.74
HT	cm						
sca1		4.81	-35.19	5.98	1.48	0.65	22.32
sca2		-4.80	35.20	-5.97	-1.47	-0.63	-22.30
aca		-3.81	16.19	54.02	-12.14	-24.65	-29.65

sca1 specific combining ability on 23DBE
sca2 specific combining ability on 68B
aca average combining ability of males

Table IV-15. Estimates of average and specific combining ability effects for critical traits.

Trait	units	----- male code -----					
		3	5	6	7	9	10
ARND	mm						
sca1		0.02	-0.10	-0.06	-0.02	0.03	0.08
sca2		-0.02	0.09	0.04	0.01	-0.04	-0.09
aca		0	-0.08	0.26	0.03	0.01	-0.19
ADIM	cm						
sca1		0.08	-0.06	0.03	-0.02	-0.01	-0.01
sca2		-0.06	0.06	-0.02	0.03	0.01	0.02
aca		0.04	0.01	0.11	-0.10	0.01	0.01
ALEN	cm						
sca		0.54	-2.42	-0.57	0.42	1.14	0.91
sca2		-0.54	2.43	0.59	-0.41	-1.13	-0.90
aca		-2.41	1.56	3.12	-1.52	-1.67	0.87
PRND	mm						
sca1		0	0.01	0	-0.03	-0.01	-0.01
sca2		-0.01	-0.01	0	0.02	0.01	0
aca		0	-0.02	0.01	0	0.01	0.02
PDIM	cm						
sca1		0.01	0.03	0	0.01	-0.01	-0.05
sca2		-0.01	-0.02	0	-0.02	0	0.04
aca		0.09	0.01	-0.09	-0.05	-0.04	0.07
PLEN	cm						
sca1		-2.09	0.70	-0.03	-0.04	0.47	0.99
sca2		2.09	-0.71	0.04	0.04	-0.47	-1.00
aca		1.97	-0.12	-5.31	0.16	-2.78	6.07

sca1 specific combining ability on 23DBE
sca2 specific combining ability on 68B
aca average combining ability of males

EXPERIMENT V (1988)

Nine new pearl millet male lines from the breeding nursery classified into three lodging classes (moderately stiff, moderately weak and weak stalk) on the basis of 1987 nursery lodging scores, were evaluated for performance both per se and each in two test crosses involving 23DAE (weak stalk) and 68A (moderately stiff stalk) A-lines (Table V-1) as seed parents. Data were collected on lodging parameters and general agronomic traits in all the 27 genotypes but data on strength tests and critical traits were collected only on a subset of 6 male lines and their test crosses (Table V-6). For consistency in the analyses and interpretation, only these 18 genotypes were considered.

Significant differences were detected between the male lines and their test crosses for all lodging parameters and between 23DAE and 68A test crosses for PL (Table V-2). The means indicate that the test crosses lodged more than male lines and 23DAE test crosses had more peduncle lodging than 68A test crosses. The means for SL and PL show that peduncle lodging was more serious than stalk lodging in all the three genotypic groups. However, strength tests show that test crosses had significantly higher stalk strength than their male parents (Table V-3). There was agreement between peduncle lodging and peduncle breaking strength for the two types of test crosses indicating that 68A test crosses were more peduncle lodging tolerant than 23DAE test crosses. However, peduncle crushing strength failed to show superiority of 68A test crosses in peduncle strength over 23DAE test crosses.

The general agronomic (Table V-4) and critical (Table V-5) traits

suggest that test crosses lodged more because they were significantly higher yielding, earlier, taller, tillered more and had significantly smaller PRND and longer PLEN than their male parents. On the other hand, 23DAE test crosses had lower peduncle strength and more peduncle lodging possibly because they tillered significantly more, had smaller PRND, PDIM and longer PLEN than 68A test crosses.

Significant and positive correlations were found between ALEN and HT, as well as between ALEN and each of the three lodging parameters suggesting that longer basal internodes could be associated with increased height and that increased height could be associated with lodging. ARND was significantly and positively correlated with each of the four strength tests where as PRND was significantly and positively correlated only with each of the two peduncle strength tests. Both ADIM and PDIM were significantly and positively correlated with 50% bloom where as ALEN and 50% bloom were negatively correlated. The significant positive and negative correlations for PRND and PLEN, respectively with HSM suggest that increased tillering could be associated in both reducing rind thickness and increasing the length of the peduncle which would tend to promote peduncle lodging. Significant and negative correlations for ALEN with ADIM and ALEN with PDIM (Table V-7) indicate that longer basal internodes could promote both stalk and peduncle lodging. The significant positive correlation between ADIM and PDIM suggest that the two traits could be selected for simultaneously.

Strong significant and positive correlations (not shown in tables) existed for ACRS with BBRK (0.77**) and PCRS with PBRK (0.89***), which is in agreement with results in all other experiments, suggest that

either the crushing or the breaking strength tests would give a good estimate of the strength of either the stalk or the peduncle. Whereas PCRS was significantly and positively correlated with ACRS (0.53*) and BBRK (0.65**), PBRK was correlated only with BBRK (0.49*).

Tables V-8 through V-11 show estimates of male parent heterosis for lodging parameters, strength tests, general agronomic and critical traits. Although there were considerable differences in mean heterotic effect of the male lines for all traits studied, no consistent pattern was evident in the manifestation of male parent heterosis for all traits with respect to the previous classification of male lines into three lodging classes. Generally, manifestation of male parent heterosis was highest among lodging parameters followed by strength tests, general agronomic traits and critical traits.

Among the lodging parameters ranges for mean male parent heterosis were 126 to 8048% for SL, 10 to 1240% for PL and 15 to 156% for LG; among the strength tests 49 to 211% for ACRS, 11 to 238% for BBRK, -4 to 40% for PCRS and -3 to 23% for PBRK; among the general agronomic traits 53 to 154% for MGHA, -14 to 1% for BLM and 25 to 50% for HT; and among the critical traits -4 to 32% for ARND, -13 to 19% for ADIM, -1 to 22% for ALEN, -17 to 1% for PRND, -12 to 12% for PDIM and 12 to 33% for PLEN.

Tables V-12 through V-15 show estimates of average and specific combining ability effects for all traits. For SL the best average combiner was a moderately stiff stalk line 88016 while for PL the best average combiner was a weak stalk line 88139, and the best specific combiners were moderately stiff stalk lines 88134 on 23DAE and 88016 on

68A. However, for LG the best average combiner was line 88069, a moderately stiff stalk and different line from that for PL.

Among the strength tests the best average combiners were 88061 for ACRS, 88134 for both BBRK and PBRK. Line 88134 has also the best aca for PRND. This suggests that among the 6 male lines, line 88134 could be the best candidate line for improving the inherent strength of both the stalk and peduncle, and that if selection was based on crushing strength alone, the best line might not have been selected. However, the best average combiner to improve both yield and maturity would be line 88139 which is classified as weak stalk. In test cross combinations lines 88139 and 88134 were the top yielders.

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Table V-1. Genotypes studied in experiment V (1988).

Male code	male	23A test cross	68A test cross	description of male
1	88003	23DAE X 88003	68A X 88003	p.m.(ms)
2*	88009	23DAE X 88009	68A X 88009	p.m.(mw)
3	88014	23DAE X 88014	68A X 88014	p.m.(ms)
4*	88016	23DAE X 88016	68A X 88016	p.m.(ms)
5*	88061	23DAE X 88061	68A X 88061	p.m.(ms)
6*	88069	23DAE X 88069	68A X 88069	p.m.(ms)
7*	88134	23DAE X 88134	68A X 88134	p.m.(ms)
8	88137	23DAE X 88137	68A X 88137	p.m.(ms)
9*	88139	23DAE X 88139	68A X 88139	p.m.(ws)

* structural and strength tests conducted on these male lines and their test crosses.

p.m. pearl millet
ms moderately stiff stalk
mw moderately weak stalk
ws weak stalk

Table V-2. Results of tests of contrast for lodging parameters.

Trait	SL (count)	PL (count)	LG (score)
CONTR			
-AST# 1	**	**	**
# 2	NS	**	NS
MEAN			
males	2	5	7
TX1	8	15	10
TX2	8	10	9
RANGE			
males	0 - 4	1 - 9	4 - 8
TX1	4 - 14	10 - 25	9 - 10
TX2	4 - 16	5 - 14	7 - 10
CV (%)	53.1	40.7	17.6
s.e. (\pm)	1.8	2.4	0.8

* ** *** significant differences among genotypic means at %5, 1% and 0.1% levels, respectively.

NS non-significant

s.e. of genotypic mean.

1 males V test crosses

2 23DAE test crosses V 68A test crosses

TX1 23DAE test crosses

TX2 68A test crosses

Table V-3. Results of tests of contrasts for strength tests.

	----- stalk -----		----- peduncle -----	
	ACRS (kg)	BBRK (kg)	PCRS (kg)	PBRK (kg)
CONTR				
-AST# 1	*	*	NS	NS
# 2	NS	NS	NS	**
MEAN				
males	33.1	7.0	25.9	5.4
TX1	61.6	9.4	27.6	5.1
TX2	54.3	10.8	29.8	6.2
RANGE				
males	16.9 - 43.7	3.5 - 9.8	20.8 - 36.1	4.2 - 6.8
TX1	50.7 - 72.6	7.9 - 11.2	21.9 - 32.4	4.1 - 6.2
TX2	37.1 - 66.6	9.6 - 11.8	24.0 - 34.4	5.1 - 6.9
CV (%)	24.6	16.4	12.4	9.3
s.e. (\pm)	7.0	0.9	2.0	0.3

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant

s.e. of genotypic mean.

#1 males V test crosses

2 23DAE test crosses V 68A test crosses

TX1 23DAE test crosses

TX2 68A test crosses

Table V-4. Results of tests of contrasts for general agronomic traits.

	MGHA (mg/ha)	BLM (days)	HT (cm)	HSM (m ⁻²)
CONTR				
-AST# 1	***	**	**	***
# 2	NS	NS	NS	**
MEAN				
males	2.6	70	80	16
TX1	4.9	65	114	25
TX2	4.8	66	103	21
RANGE				
males	1.9 - 3.4	63 - 76	70 - 90	12 - 22
TX1	4.4 - 5.6	64 - 66	107 - 120	20 - 32
TX2	4.3 - 6.1	63 - 69	92 - 115	17 - 22
CV (%)	12.4	2.1	3.7	12.6
s.e.(±)	0.3	0.8	2.1	1.4

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant

s.e. of genotypic mean.

1 males V test crosses

2 23DAE test crosses V 68A test crosses

TX1 23DAE test crosses

TX2 68A test crosses

Table V-5. Results of tests of contrasts for critical traits

	----- stalk -----			----- peduncle -----		
	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
CONTR						
-AST# 1	NS	NS	NS	*	NS	**
# 2	NS	NS	NS	*	*	*
MEAN						
males	0.70	0.84	4.6	0.33	0.68	28.1
TX1	0.73	0.84	5.3	0.28	0.66	34.8
TX2	0.75	0.84	4.8	0.32	0.69	32.3
RANGE						
males	0.60-0.78	0.67-0.95	4-5	0.25-0.37	0.57-0.75	24-30
TX1	0.67-0.78	0.77-0.98	5-6	0.25-0.32	0.58-0.76	31-39
TX2	0.67-0.82	0.75-0.89	4-5	0.27-0.35	0.60-0.75	27-37
CV (%)	7.3	6.8	11.8	8.3	5.6	5.3
s.e. (\pm)	0.03	0.03	0.3	0.01	0.02	1.0

* ** *** significant differences among genotypic means at 5%, 1% and 0.1% levels, respectively.

NS non-significant

s.e. of genotypic mean.

1 males V test crosses

2 23DAE test crosses V 68A test crosses

TX1 23DAE test crosses

TX2 68A test crosses

Table V-6. Correlation coefficients for critical traits with lodging parameters(+), strength tests(@) and general agronomic traits(\$).

		----- critical traits -----					
		----- stalk -----			----- peduncle -----		
Trait	units	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
SL ⁺	count	0.31	-0.19	0.50*	-0.13	-0.13	-0.28
PL ⁺	count	0.07	-0.28	0.47*	-0.45	-0.23	0.32
LG ⁺	score	0.10	-0.28	0.56*	-0.26	-0.18	0.16
ACRS [@]	kg	0.59**	-0.18	0.66**	0.09	-0.31	0.08
BBRK [@]	kg	0.70**	-0.16	0.37	0.25	-0.22	-0.03
PCRS [@]	kg	0.74***	-0.03	0.13	0.57*	-0.17	-0.17
PBRK [@]	kg	0.55*	0.11	-0.12	0.63**	0.06	-0.34
MGHA ^{\$}	mg/ha	0.21	-0.18	0.44	-0.31	-0.16	0.32
BLM ^{\$}	days	-0.11	0.69**	-0.63**	0.16	0.64**	-0.34
HT ^{\$}	cm	0.38	-0.28	0.59**	-0.19	-0.36	0.32
HSM ^{\$}	m ⁻²	-0.19	-0.34	0.39	-0.62**	-0.40	0.51*

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

Table V-7. Correlation coefficients among critical traits.

	ARND (mm)	ADIM (cm)	ALEN (cm)	PRND (mm)	PDIM (cm)	PLEN (cm)
ARND	.	0.07	0.11	0.39	-0.07	-0.29
ADIM		.	-0.59*	-0.24	0.86***	-0.27
ALEN			.	0.08	-0.56*	0.23
PRND				.	-0.24	-0.33
PDIM					.	-0.47
PLEN						.

* ** *** significant at 5%, 1% and 0.1% levels, respectively.

Table V-8. Estimates of heterosis for lodging parameters.

Trait	units	----- male code -----					
		2	4	5	6	7	9
SL	count						
TX1		73	271	6699	204	106	242
TX2		180	271	9398	35	159	258
\bar{X}		126	271	8048	119	133	250
PL	count						
TX1		502	322	1140	230	61	25
TX2		310	-8	1340	57	139	-5
\bar{X}		406	157	1240	144	100	10
LG	count						
TX1		18	76	156	27	47	12
TX2		12	32	156	5	37	22
\bar{X}		15	54	156	16	42	17

23DAE test crosses
68A test crosses

Table V-9. Estimates of male parent heterosis (%) for strength tests.

Trait	units	----- male code -----					
		2	4	5	6	7	9
ACRS	kg						
TX1		261	68	75	47	45	98
TX2		160	39	65	77	53	37
\bar{X}		211	54	70	62	49	67
BBRK	kg						
TX1		167	42	1	19	6	53
TX2		309	73	21	59	21	38
\bar{X}		238	57	11	39	14	45
PCRS	kg						
TX1		29	5	25	-19	-1	27
TX2		28	75	37	11	-5	5
\bar{X}		28	40	31	-4	-3	16
PBRK	kg						
TX1		3	-9	3	35	-8	23
TX2		13	30	43	0	2	20
\bar{X}		8	11	23	17	-3	22

TX1 23DAE test crosses

TX2 68A test crosses

Table V-10. Estimates of male parent heterosis (%) for general agronomic traits.

Traits	units	----- male code -----							
		2	4	5	6	7	9		
MGHA	mg/ha								
TX1		139	64	158	84	80	46		
TX2		73	41	150	85	74	77		
\bar{X}		106	53	154	85	77	62		
BLM	days								
TX1		-7	-10	-15	-13	1	1		
TX2		-4	-5	-12	-6	-3	1		
\bar{X}		-5	-7	-14	-9	-1	1		
HT	cm								
TX1		67	46	56	36	32	22		
TX2		33	19	41	19	30	28		
\bar{X}		50	33	48	27	31	25		
TX1	23DAE t aca	sca2		-0.66	-0.23	0.05	0.15	0.04	0.67
		-0.02	-0.25	-0.12	-0.47	0.16			

Table V-11. Estimates of male parent heterosis (%) for critical traits.

Trait	units	----- male code -----					
		2	4	5	6	7	9
ARND	mm						
TX1		30	5	3	-8	-3	5
TX2		33	15	8	0	-2	-3
\bar{X}		32	10	6	-4	-3	1
ADIM	cm						
TX1		6	-16	-19	-9	24	24
TX2		-4	-5	-7	-1	2	15
\bar{X}		1	-11	-13	-5	13	19
ALEN	cm						
TX1		5	28	33	13	9	8
TX2		12	-2	10	6	15	-9
\bar{X}		8	13	22	9	12	-1
PRND	mm						
TX1		-8	-3	-9	-32	-13	-16
TX2		-3	5	-2	-3	-3	-11
\bar{X}		-6	1	-6	-17	-8	-14
PDIM	cm						
TX1		4	-16	-18	-11	19	6
TX2		0	-8	6	-2	5	6
\bar{X}		2	-12	-6	-6	12	6
PLEN	cm						
TX1		28	29	39	40	5	7
TX2		-5	2	27	19	23	25
\bar{X}		12	15	33	29	14	16

TX1 23DAE test crosses
TX2 68A test crosses

Table V-12. Estimates of average and specific combining ability effects for lodging parameters.

		----- male code -----					
Trait	units	2	4	5	6	7	9
-----	-----	-----	-----	-----	-----	-----	-----
SL	count						
sca1		-1.29	0.04	-2.21	4.29	-0.71	-0.13
sca2		1.29	-0.05	2.20	-4.30	0.70	0.12
aca		-2.21	-3.54	5.71	2.21	-1.29	-0.87
PL	count						
sca1		0.14	7.38	-3.36	1.81	-4.86	-1.12
sca2		-0.19	-7.44	3.32	-1.85	4.81	1.06
aca		1.52	2.94	-1.32	-0.32	-0.48	-2.06
LG	score						
sca1		-0.13	0.87	-0.38	0.45	-0.05	-0.79
sca2		0.12	-0.88	0.37	-0.46	0.04	0.79
aca		0.16	-0.51	0.57	-0.76	0.24	0.32

sca1 specific combining ability on 23DAE
sca2 specific combining ability on 68A
aca average combining ability of males

Table V-13. Estimates of average and specific combining ability effects for strength tests.

		----- male code -----					
Trait	units	2	4	5	6	7	9
ACRS	kg						
sca1		4.95	3.17	-1.58	-8.78	-5.29	7.55
sca2		-4.95	-3.17	1.59	8.79	5.28	-7.55
aca		-5.34	-13.96	10.42	-1.78	7.06	3.59
BBRK	kg						
sca1		-0.22	-0.13	-0.15	-0.73	0.02	1.24
sca2		0.23	0.13	0.16	0.75	-0.01	-1.24
aca		0.23	-1.41	-0.48	0.14	0.98	0.50
PCRS	kg						
sca1		1.18	-1.23	-0.29	-3.26	0.03	3.56
sca2		1.19	1.23	0.30	3.25	-0.03	-3.56
aca		2.23	-4.62	1.35	-1.28	4.57	-2.26
PBRK	kg						
sca1		0.27	-0.31	-0.15	-0.61	0.20	0.59
sca2		-0.28	0.31	0.15	0.60	-0.20	-0.59
aca		0.30	-0.72	0.13	-0.12	0.95	-0.51

sca1	specific combining ability on 23DAE						
sca2	specific combining ability on 68A						
aca	average combining ability of males						

Table V-14. Estimates of average and specific combining ability effects for general agronomic traits.

Trait	units	----- male code -----					
		2	4	5	6	7	9
MGHA	mg/ha						
sca1		0.67	0.24	-0.04	-0.14	-0.03	-0.66
sca2		-0.66	-0.23	0.05	0.15	0.04	0.67
aca		-0.02	-0.25	-0.12	-0.47	0.16	0.68
BLM	days						
sca1		-0.36	-0.87	-0.19	-1.59	2.14	0.97
sca2		0.37	0.86	0.20	1.70	-2.14	-0.97
aca		2.08	0.26	-0.42	1.08	-1.08	-1.91
HT	cm						
sca1		6.25	4.58	0.42	1.25	-4.59	-7.92
sca2		-6.26	-4.59	-0.42	-1.26	4.57	7.91
aca		-3.19	-6.52	5.97	-8.19	7.65	4.31

sca1 specific combining ability on 23DAE
sca2 specific combining ability on 68B
aca average combining ability of males

Table V-15. Estimates of average and specific combining ability effects for critical traits.

Trait	units	----- male code -----					
		2	4	5	6	7	9
ARND	mm						
sca1		0.01	-0.02	-0.01	-0.01	0.01	0.04
sca2		0	0.02	0.01	0.02	0	-0.04
aca		0.04	-0.03	0.06	-0.05	0.02	-0.04
ADIM	cm						
sca1		0.04	-0.05	-0.06	-0.04	0.08	0.03
sca2		-0.05	0.04	0.05	0.03	-0.08	-0.03
aca		0.10	0.01	0.01	0.02	0.01	0.04
ALEN	cm						
sca1		-0.38	0.35	0.26	-0.09	-0.37	0.22
sca2		0.38	-0.35	-0.27	0.08	0.38	-0.23
aca		-0.33	-0.53	0.25	0.25	0.02	0.36
PRND	mm						
sca1		0.01	0.01	0	-0.03	0	0.01
sca2		-0.01	-0.01	-0.01	0.03	-0.01	-0.01
aca		-0.02	-0.04	0.02	0	0.04	-0.01
PDIM	cm						
sca1		-0.01	-0.05	-0.10	-0.05	0.01	-0.02
sca2		0.01	0.04	0.11	0.05	-0.02	0.02
aca		0.08	-0.01	-0.01	-0.01	-0.03	-0.01
PLEN	cm						
sca1		3.46	2.79	0.44	1.20	-3.94	-3.97
sca2		-3.46	-2.80	-0.45	-1.20	3.93	3.95
aca		-1.72	1.11	2.83	-2.41	0.36	-0.16

sca1 specific combining ability on 23DAE
sca2 specific combining ability on 68A
aca average combining ability of males

SUMMARY OF CONCLUSIONS

Differences were found in lodging and mechanical strength tests among pearl millets, PM X NG lines, test crosses and sorghum genotypes with contrasting yield levels, heights, maturity and tillering in each of the 5 experiments.

Field lodging (PLG) in 1987 ranged from 0 to 98% and showed that the PM X NG test crosses were worse than the group of millets and sorghum. On the contrary, the PM X NG test crosses had stronger stalks than the millets and sorghum. It was observed in the field that most of the lodging in the PM X NG test crosses was due to peduncle breakage. This required distinguishing peduncle lodging from stalk lodging in all the 1988 experiments. Peduncle lodging was more severe than stalk lodging in all experiments. This indicated that any effort to improve lodging in pearl millet should first be directed at improving peduncle strength.

The PM X NG test crosses were superior to the millets and sorghum in ARND, which is correlated with ACRS (0.59* to 0.97**) and BBRK (0.70** to 0.98***) in all experiments. Their longer ALEN and PLEN; smaller PRND and PDIM accompanied with higher yield, increased height and tillering, and because ARND had undesirable positive association (0.76**) with PLG, suggest the reasons for observed severe peduncle lodging, and the anticipated difficulty in improving lodging although the PM X NG lines could be valuable sources of genes for rind thickness of basal internodes.

The sorghum check was later in maturity and superior to the millets in PLG, SL, PL, LG, PCRS, PBRK, BBRK, ARND, ADIM, ALEN, PRND and PDIM.

Unlike millets its increased PLEN had no effect on both types of lodging. Superiority in PRND of the group of millet lines to, and lack of significant differences in PLG of these lines with the millet hybrid, and because PRND is negatively correlated (-0.66^*) with PLG indicates existence of useful germplasm to improve the rind thickness of the peduncle, which in turn would reduce peduncle lodging.

Useful correlations were found for PRND with PDIM (0.49^* to 0.84^*) in experiments I, II, III and IV; and PDIM with ADIM (0.74^{**} to 0.86^{***}) in experiments I, II, III and V. PDIM was also correlated with PLEN (0.69^{**} to 0.90^*) in experiments I, II and IV. To improve the inherent mechanical strength of the peduncle and the stalk, selection should be based on both thicker rinds and larger diameters of the peduncle. However, this would simultaneously select for PLEN which would be desirable if exertion was a problem, but unfavourable if additional increase in the lengths of peduncles led to increased peduncle lodging.

Inconsistencies existed for associations between field lodging and mechanical strength tests, implying need to do both. Strong correlations were found in all experiments for crushing strength with breaking strength tests on both the stalks and peduncles. However, correlations between the stalk strength tests and the peduncle strength tests were inconsistent.

Both the rind thickness and diameter of either stalk or peduncle were important in imparting strength to the respective plant portions. However their relative individual contributions were influenced by yield, height and tillering which also had major negative effects, more on peduncle than stalk lodging in different genotypes. In test cross

combinations, genotypes could still lodge, especially by their peduncles despite manifestation of male parent heterosis for lodging parameters and increased mechanical strength if yield, height and tillering increased. Height and tillering must be considered in efforts to improve lodging resistance in pearl millet and yield level must be taken into account when estimating lodging.

Seed parent, 68A (or B) was better per se or in test cross combinations than 23DAE (or DBE) in lodging, breaking strength and diameter of the peduncle and in diameter of the stalk, except in experiment III for unexplained reasons. Selection for resistance to peduncle lodging in seed parents is therefore especially important.

Appendix Table A: Genotypic means for traits studied in Experiment IV.

Trait	Units	male code					
		3	5	6	7	9	10
SL	count						
male		0	5	0	0	0	1
tx1		2	6	6	1	2	5
tx2		5	5	5	0	1	2
PL	count						
male		9	5	8	1	1	2
tx1		17	6	11	9	4	11
tx2		10	9	5	3	6	4
LG	score						
male		8	7	9	4	3	2
tx1		10	9	10	9	10	9
tx2		10	10	9	7	8	7
ACRS	kg						
male		82.2	17.8	91.7	70.2	72.6	16.7
tx1		85.2	68.3	109.8	104.1	96.5	68.1
tx2		87.5	83.6	191.3	136.6	113.1	55.4
BBRK	kg						
male		15.7	2.3	17.2	15.8	15.4	3.4
tx1		13.3	9.4	13.0	12.7	14.4	9.4
tx2		12.3	11.4	20.6	16.7	16.0	9.1
PCRS	kg						
male		19.0	12.5	12.3	13.2	14.5	13.7
tx1		28.4	20.1	25.9	21.5	22.0	24.9
tx2		28.1	28.4	34.4	28.5	28.8	27.3
PBRK	kg						
male		3.7	4.1	2.9	3.2	3.2	3.7
tx1		6.0	4.3	4.4	4.4	4.3	5.0
tx2		6.2	5.1	6.6	5.8	5.9	6.2
BLM	days						
male		103	72	147	92	98	71
tx1		85	69	71	81	85	67
tx2		66	66	79	69	73	66
HT	cm						
male		107	77	175	110	83	58
tx1		123	103	182	112	98	115
tx2		132	192	188	127	115	88
ARND	mm						
male		0.83	0.53	1.17	0.79	0.81	0.70
tx1		0.85	0.65	1.03	0.96	0.87	0.72
tx2		0.92	0.95	1.24	0.98	0.93	0.66
ADIM	cm						
male		0.90	0.83	1.02	0.87	0.80	0.87
tx1		1.00	0.83	1.02	0.76	0.88	0.77
tx2		0.97	1.06	1.08	0.92	1.01	0.91

ALEN	cm						
male		5.1	4.9	10.2	5.0	4.6	5.5
tx1		6.0	7.0	10.4	6.7	7.3	9.6
tx2		5.9	12.8	12.5	6.9	6.0	8.8
PRND	mm						
male		0.29	0.28	0.24	0.25	0.26	0.28
tx1		0.28	0.27	0.29	0.25	0.28	0.29
tx2		0.28	0.26	0.30	0.31	0.31	0.32
PDIM	cm						
male		0.49	0.67	0.43	0.48	0.47	0.70
tx1		0.72	0.66	0.53	0.58	0.57	0.64
tx2		0.78	0.69	0.61	0.63	0.66	0.81
PLEN	cm						
male		20.3	22.7	14.8	20.8	16.3	21.9
tx1		29.3	30.0	24.1	29.6	27.2	36.5
tx2		34.9	30.0	25.6	31.1	27.6	35.9

tx1 test cross on 23DBE
tx2 test cross on 68B

Appendix Table B: Genotypic means for traits studied in experiment V.

Trait	Units	male code					
		2	4	5	6	7	9
SL	count						
male		3	1	0	4	3	2
tx1		4	4	11	14	6	7
tx2		7	4	16	6	7	7
PL	count						
male		3	6	1	5	6	9
tx1		17	25	10	16	10	12
tx2		11	6	12	8	14	9
LG	score						
male		8	6	4	7	7	8
tx1		10	10	10	9	10	9
tx2		9	7	10	8	9	10
ACRS	kg						
male		16.9	26.7	40.1	34.6	43.7	36.6
tx1		61.1	50.7	71.0	50.9	63.2	72.6
tx2		44.0	37.1	66.3	61.3	66.6	50.3
BBRK	kg						
male		3.5	5.5	8.7	7.4	9.8	7.3
tx1		9.4	7.9	8.8	8.8	10.4	11.2
tx2		11.3	9.6	10.5	11.7	11.8	10.1
PCRS	kg						
male		24.1	20.8	23.0	28.6	36.1	22.9
tx1		31.2	21.9	28.8	23.3	32.4	28.1
tx2		30.8	26.4	31.5	31.8	34.4	24.0
PBRK	kg						
male		5.5	4.4	4.5	6.7	6.8	4.2
tx1		5.7	4.1	5.1	4.4	6.2	5.2
tx2		6.2	5.8	6.5	6.6	6.9	5.1
MGHA	mg/ha						
male		2.4	3.0	1.9	2.4	2.8	3.4
tx1		5.6	5.0	4.8	4.4	4.9	5.0
tx2		4.7	4.3	4.7	4.4	4.9	6.1
BLM	days						
male		72	71	76	74	65	63
tx1		66	64	64	64	66	64
tx2		69	68	66	69	63	64
HT	cm						
male		70	77	77	78	88	90
tx1		117	112	120	107	117	110
tx2		93	92	108	93	115	115
HSM	m ⁻²						
male		14	22	12	13	19	17
tx1		20	28	23	32	21	23
tx2		21	22	17	22	20	22

ARND	mm						
male		0.60	0.65	0.76	0.73	0.78	0.69
tx1		0.78	0.68	0.78	0.67	0.76	0.73
tx2		0.79	0.74	0.82	0.72	0.77	0.67
ADIM	cm						
male		0.93	0.93	0.95	0.86	0.73	0.67
tx1		0.98	0.78	0.77	0.78	0.91	0.83
tx2		0.89	0.87	0.88	0.85	0.75	0.77
ALEN	cm						
male		4.4	4.0	4.4	4.8	4.5	5.5
tx1		4.6	5.1	5.8	5.5	4.9	5.9
tx2		4.9	3.9	4.8	5.2	5.2	4.9
PRND	mm						
male		0.30	0.25	0.33	0.36	0.37	0.34
tx1		0.27	0.25	0.30	0.25	0.32	0.28
tx2		0.29	0.27	0.33	0.35	0.35	0.30
PDIM	cm						
male		0.74	0.75	0.71	0.71	0.57	0.62
tx1		0.76	0.63	0.58	0.63	0.67	0.66
tx2		0.74	0.69	0.75	0.69	0.60	0.66
PLEN	cm						
male		28.5	30.0	27.4	24.1	29.7	28.8
tx1		36.6	38.7	38.1	33.6	31.2	30.7
tx2		27.2	30.6	34.7	28.7	36.6	36.1

tx1 test cross on 23DAE

tx2 test cross on 68A

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