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Asymmetry of Model Bin Wall Loads and Lateral Pressure Induced from Two- and Three-Dimensional Obstructions Attached to the Wall

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Abstract. *An obstruction attached to the wall of a bin produced by cohesive, moldy grain has been reported as a source of failure in steel bins. A study was conducted to estimate the effect of two-dimensional (plane) and three-dimensional (block) obstructions attached to the corrugated wall in a flat-floor model bin where the lateral wall pressure and vertical wall loads were measured. The model bin was 1.83 m in diameter, 5.75 m high, and filled with soft red winter wheat to a depth of 5.0 m (height-to-diameter ratio h/d of 2.75). The plane obstruction had the form of an annulus segment spanning 60° of the bin wall and a width of 0.154 m (surface area of 7.2% of the bin floor area). A three-dimensional obstruction was shaped as a block with two bases identical to the plane obstruction and a height of 0.5 m. The plane obstruction and the upper base of the block obstruction were attached to the wall at h/d ratios of 1.26, 0.81, and 0.38. Even in conditions of near symmetry during centric loading, wall overturning moments of approximately 1 kNm were observed. The highest wall moment measured was 2.7 kNm at the end of filling with the block attached at h/d of 0.38; the moment with a plane obstruction in the same position was 2.1 kNm. Without an obstruction attached to the wall, the maximum lateral pressure increased 2.5 times relative to the static pressuer compared to an increase of 4 times with an obstruction. The data collected indicated that there are considerable additional loads imposed on a bin due to obstructions that may form during storage that are not considered in the design codes and could approach levels observed during eccentric discharge.*

Keywords. *Granular flow, Horizontal pressure, Insert, Janssen's equation, Moments, Silo.*

During the design of bins, it is normally assumed that stresses are axially symmetric. This is difficult to ensure even in carefully controlled bin tests. Unsymmetrical pressure distributions can occur in bins because of many different factors, such as off-center filling or discharging, structural members located within the grain, bin flow devices, and even deteriorated grain forming a cohesive solid mass of material attached to the bin wall because of mold or insect problems. According to Rotter (1998), the most frequent cause of bin failure is high axial compressive membrane stress resulting from unsymmetrical normal wall pressures. Rotter stated that extensive work was needed to accurately quantify the effect of high local stresses. Areas of high localized stress have been addressed in Eurocode 1 (2003) by the use of a patch load acting on the bin wall. Gillie and Rotter (2002) conducted numerical experiments with various forms of patch loads acting on a bin wall. The results demonstrated that the stresses created are complex and could potentially lead to bin failure by elastic buckling or plastic collapse. The authors also concluded that additional information was needed related to the effects of size, position, and form of the patch loads on the stresses produced in bins.

Blight (2004) reported that serious structural problems occurred when bins of canola were discharged after 3 to 4 months of storage. After a large temperature increase in the stored canola, the stiffeners deflected inwards and the bin cylinder went out of round on initiation of discharge. Blight investigated the source of the structural failure and concluded that the inward deflection of the bin was most likely caused by development of a low-pressure channel or a void over a portion of the bin cross-section. The failure could have been due to the formation of cohesive obstructions on the bin wall due to time consolidation, moisture absorption, and insect development. All three were consistent with the high grain temperatures (maximum of 65°C) measured during storage. Initial investigations have shown considerable vertical load asymmetry in a bin wall with plane annular segments attached to the wall (Molenda et al., 2004). An annular segment in a 2.44 m model grain bin that was 8.6% of the bin floor area increased the resultant wall moments from 3 to 5 kNm.

The effective transition, that is, the point at which the flow channel boundary reaches the wall, is known to be associated with high local pressures. A minor change in symmetry of the flow pattern at the effective transition height can result in asymmetric wall pressures (Zhong et al., 2001). These load

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conditions produce a combination of tensile stress in one direction and compressive stress in another that can result in buckling of the shell. Non-uniform pressures along the height of the bin wall are not well understood and can result in buckling (Gillie and Rotter, 2002).

Controversy exists about the magnitude of the stress switch at the onset of discharge. Zhong et al. (2001) reported strong pressure fluctuations during discharge of plastic pellets from a cylindrical flat-floor bin up to a height-to-diameter ratio (h/d) of 2.5. Ostendorf et al. (2003), during tests with rectangular hopper-bottom bins, found that the change in the stress field was contained within the hopper volume, with the stress state in the bin cylinder remaining active.

The objective of this project was to examine the variation of lateral wall pressure and asymmetry of vertical wall loads in a flat bottomed, corrugated steel model grain bin with plane (two-dimensional) or block (three-dimensional) obstructions attached to the wall at three vertical locations. The asymmetry in the bin loads due to obstructions was compared to asymmetric loads created by eccentric discharge.

Equipment and Procedures

Tests were conducted in a cylindrical, flat-floor, corrugated-wall steel grain bin. The bin was 1.83 m in diameter and 5.75 m high. The wall corrugations were 13 mm high with a pitch of 68 mm. The cylindrical wall of the bin and the flat floor were supported independently from each other to isolate the wall and floor loads (fig. 1). The wall and floor of the model bin were each supported by three load cells spaced at an angle of 120° around the circumference of the bin. The load cells had an accuracy of ±50 N.

Soft red winter wheat with a moisture content of 11.3% (wet basis) and an uncompacted bulk density of 772 kg m^{-3} was used for the tests. The bin was centrally filled at a flow rate of approximately 4.4 kg s^{-1} using a horizontal conveyor equipped with a discharge spout. After filling to a height of 5 m (h/d of 2.75), the grain was allowed to equilibrate during a detention period of 30 min. The bin was then discharged through a 7.2 cm diameter discharge orifice located in the center of the bin, which produced a sliding velocity of 3 m h^{-1} along the bin wall during plug flow. The wall and floor loads during loading, detention, and discharge were measured at 30 s intervals until discharge was completed. To observe the dynamic response of the loads at the start of grain discharge, loads were measured at a time interval of 0.1 s for 50 s. Tests were conducted using centric filling and centric discharge, except for two tests that were performed with centric filling and eccentric discharge through a 7.2 cm diameter discharge orifice located at an eccentricity ratio (er) of 0.67 in the $+y$ and $-y$ quadrants of the bin floor (fig. 1).

Tests were conducted using plane (two-dimensional) or block (three-dimensional) obstructions attached to the bin wall (fig. 1). The plane obstruction (two-dimensional) was an annular segment spanning 60° around the wall circumference. The plane obstruction had a width of 23 cm that resulted

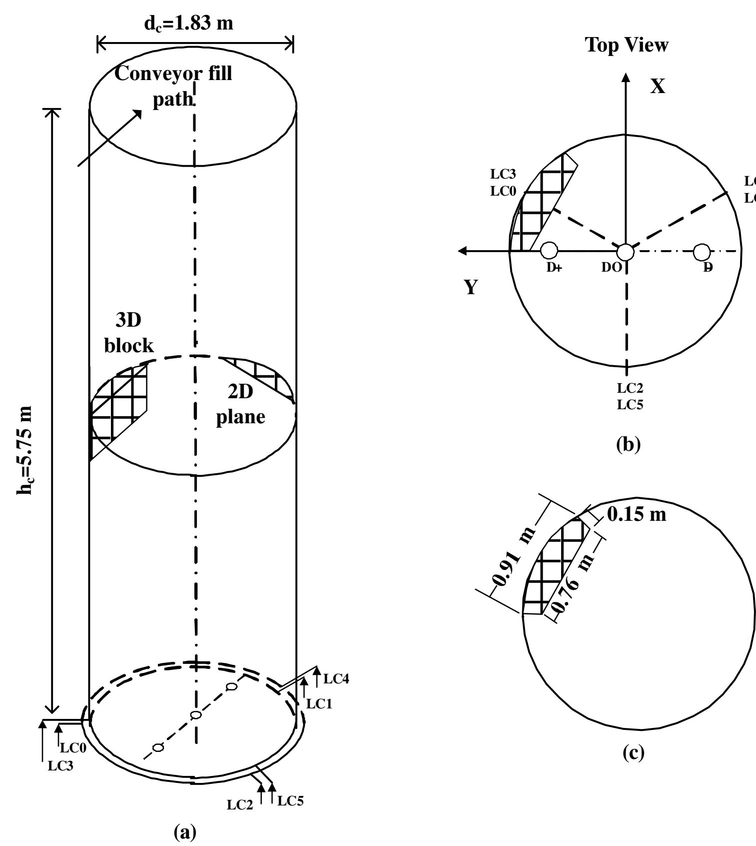


Figure 1. (a) Schematic diagram of the model bin showing an example location of the block obstruction placed at *h/d* of 1.26 in the (+*x*, +*y*) quadrant and an example location of the plane obstruction located at *h/d* of 1.26 in the (+*x*, –*y*) quadrant. Load cells LC0, LC1, and LC2 support the floor and LC3, LC4, and LC5 support the wall. (b) Reference system for the bin and location of discharge orifices on the +*y* axis (D+), centerline (D0), and –*y* axis (D–), and example location of the obstruction placed in the (+*x*, +*y*) quadrant (top view). (c) Top view of the bin with the obstruction located in the (+*x*, +*y*) quadrant.

in a surface area of 0.189 m^2, which was equivalent to 7.2% of the bin cross-sectional area. The block (three-dimensional) obstruction used the base of the plane obstruction but was 0.5 m high and had walls of smooth galvanized steel.

During earlier testing with wheat, the transition between the dead zone and grain flowing along the wall was observed to occur at a height of 1.2 m (h/d of 0.66). Obstructions were attached to the bin wall with their upper base at h/d ratios of 0.37, 0.81, and 1.26 (0.67, 1.49, and 2.31 m above the bin floor, respectively). These locations placed the obstructions within the stagnant zone (h/d = 0.37), within the transition zone between the stagnant zone and the flowing grain (h/d = 0.81), and in the plug flow zone (h/d = 1.26).The location of h/d of 0.81 is considered the region where the jump in lateral pressure, termed kick pressure by Eurocode 1 (2003), would be expected to occur. In both quadrants (+x, +y) and (+x, −y), the obstruction center of gravity was directly over wall load cell LC3 or LC4.

Earlier testing by the authors in a 2.44 m diameter bin (Molenda et al., 2004) showed that the presence of a plane obstruction prevented grain movement along the bin wall directly above the obstruction. The depth of stagnant grain measured above the midpoint of the 7.6, 15, and 23 cm wide annular obstruction that spanned 60° along the wall was 30, 70, and 100 cm, respectively. Based on this result, areas of high and low local lateral pressures would be expected within a distance of 1 m. The lateral pressure was measured using earth pressure cells. The earth pressure cells are designed to measure total pressure and are created from two stainless steel disks separated by de-aired oil. A vibrating wire pressure transducer is used to convert the change in fluid pressure to an electrical signal. Two Geokon 3500 earth pressure cells (Lebanon, New Hampshire) with a 100 kPa range and an accuracy of 0.25% of full scale (±250 Pa) were used for measuring grain pressure. The earth pressure cells were tested in a direct shear device and were found to be of acceptable accuracy under shear conditions that would be expected in a grain bin.

Each experimental condition was performed without replication. Previous experiments using this model bin allowed for the estimation of the run-to-run variability as well as its sources. The runs were randomized, and samples of grain were collected for tracking any potential changes in material properties. The coefficient of friction, bulk density, and moisture content were measured to verify that the material properties did not significantly vary during testing.

A measure of vertical load asymmetry (observed as unequal measurements on the wall load cells) can be determined by calculating the wall overturning moment (Horabik et al., 1993). This value is calculated using the forces measured by the wall load cells. Total vertical floor loads (F_{vl}) and total vertical wall loads (W_{vl}) were calculated using the following equations:

$$F_{vl} = F_o + F_1 + F_2 \quad (1)$$

$$W_{vl} = F_3 + F_4 + F_5 \quad (2)$$

where

F_{vl} = vertical forces carried by the floor (floor load cells 0, 1, and 2) (N)

W_{vl} = vertical forces carried by the wall (wall load cells 3, 4, and 5) (N).

The longitudinal bending wall moments in the bin about each of the major axes were calculated using the following equations:

$$M_x = R(F_3 \sin\alpha_3 + F_4 \sin\alpha_4 + F_5 \sin\alpha_5) \quad (3)$$

$$M_y = -R(F_3 \cos\alpha_3 + F_4 \cos\alpha_4 + F_5 \cos\alpha_5) \quad (4)$$

where

M_x = moment about the x axis of the bin (N m)

M_y = moment about the y axis of the bin (N m)

α_i = angular coordinates of load cell i with respect to the x axis (°)

R = distance of the load cell from the axis of the bin (m)

Values of the resultant moment M were calculated using:

$$[M] = [M^2 x + M^2 y]^{1/2} \quad (5)$$

Results and Discussion

Symmetric Load Conditions

The average vertical floor pressure was estimated using the summation of the forces measured by the three load cells that supported the floor divided by the floor area. The average floor pressure, the floor pressure predicted by Janssen's equation (with k = 0.42 and μ = 0.4), and the vertical floor pressures measured by the earth pressure cells at two locations (er = 0.5 and angular location of 60° and 180°) are shown in figure 2. The floor pressure measured during filling using the average floor pressure (load cells) and predicted using Janssen's equation were very similar, less than 0.35 kPa difference. The floor pressure measured using the earth pressure cell located at 180° (pv_2) was approximately 1.1 times greater (~2 kPa) than the pressure determined using the load cells. However, the floor pressure at 60° (pv_1) was 1.34 times greater (~6 kPa) than the pressure measured using the load cells. The difference measured between the earth pressure cell located at 60° and the average pressure determined by the load cells was due to imperfect centric filling. Although the experiment was conducted to simulate centric filling, the grain entered the bin with a velocity in the +y direction (fig. 1), with the wheat impacting the floor along the +y axis at an er of approximately 0.5. The imperfect centric filling generated a pressure distribution with a maximum at the location where the grain stream reached the grain surface during filling.

At the initiation of discharge (fig. 2b), the floor pressure measured using the load cells immediately decreased to a value of 14.3 kPa. The pressure measured by the earth pressure cells decreased by approximately 7 kPa immediately after the initiation of discharge, which resulted in closer agreement with the value measured using the floor load cells. This was due to the change in the stress state within the bin, which increased the state of symmetry due to centric discharge. Changes in the flow pattern from plug flow to enveloping flow at h/d of 1.8 resulted in the floor pressure measured using the earth pressure cells to converge to a similar value. After the bin was discharged to h/d of 0.5, the floor pressure decreased linearly to zero.

Asymmetry of Vertical Wall Loads Generated by the Obstruction

In the model bin, even in conditions of near symmetry during centric loading, wall overturning moments at the end of

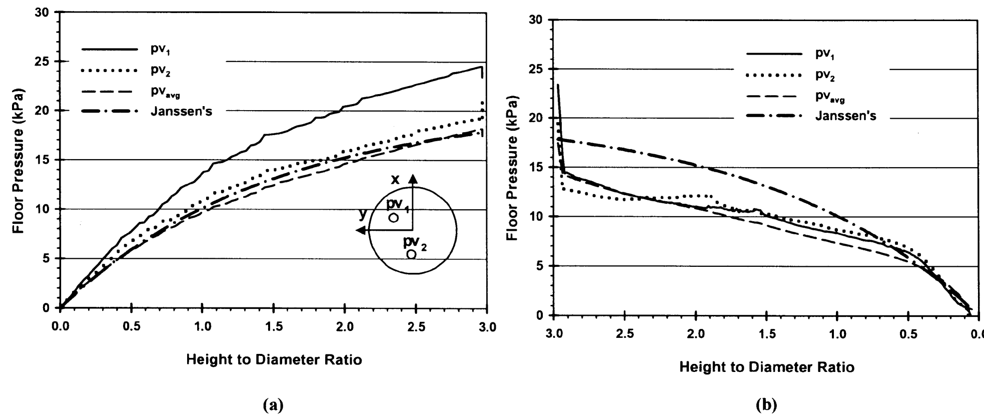


Figure 2. Vertical floor pressure (a) during filling and detention and (b) during discharge estimated using the load cells supporting the floor (pv_{avg}), Janssen's equation, and the earth pressure cells located at an *er* of 0.5 and an angular position of 60° (pv_1) and 180° (pv_2).

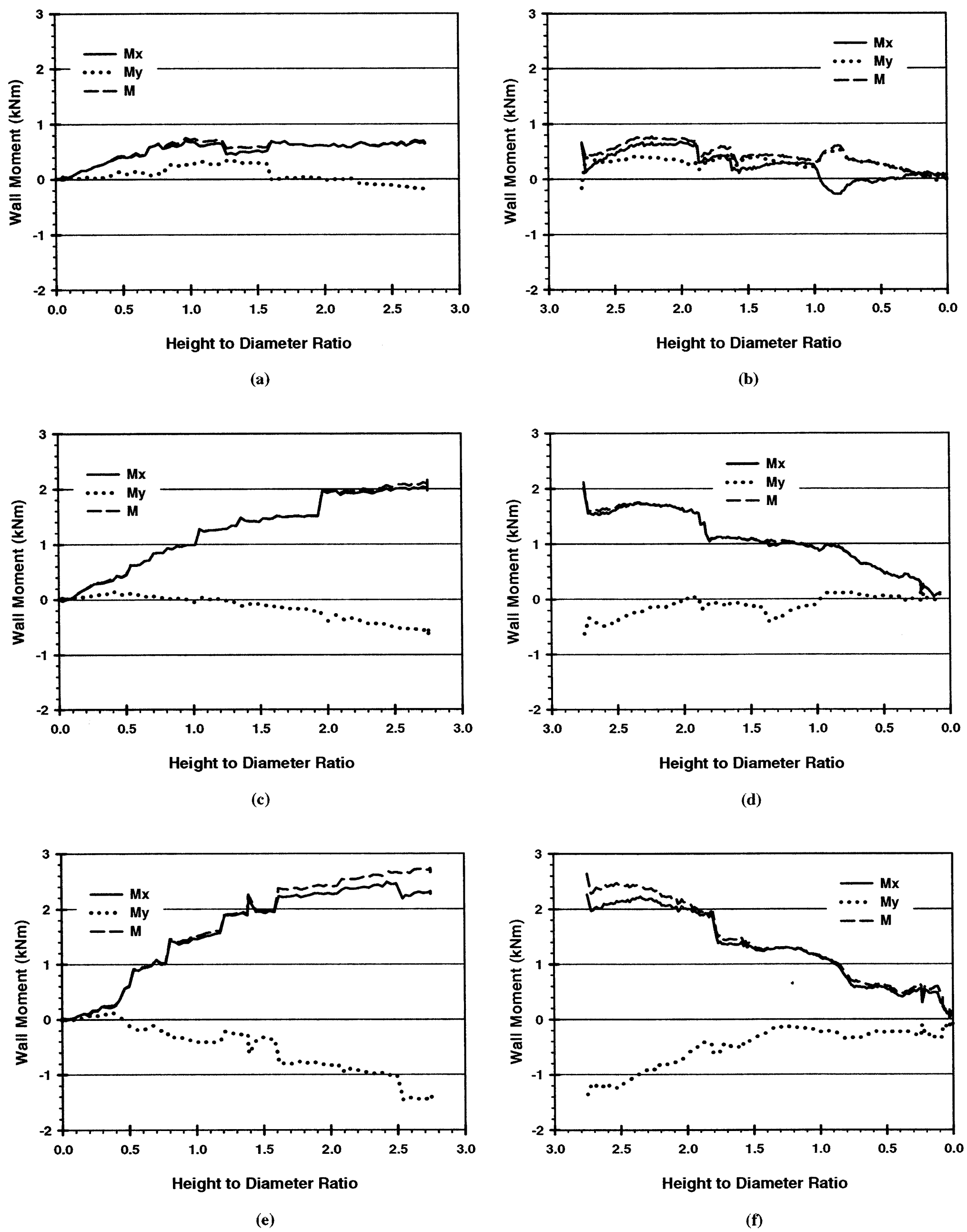


Figure 3. Wall moments produced (a) during filling and detention and (b) during discharge with no obstruction; (c) during filling and detention and (d) during discharge with a plane obstruction located at *h*/*d* of 0.38 in the (+*x*, +*y*) quadrant; and (e) during filling and detention and (f) during discharge with a block obstruction located at *h*/*d* of 0.38 in the (+*x*, +*y*) quadrant.

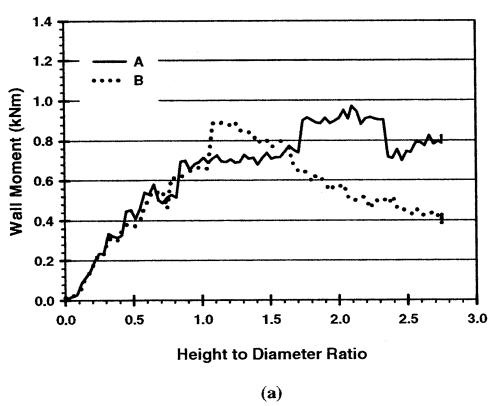
filling of approximately 0.7 kNm were observed due to the imperfect centric filling (fig. 3a). The bin was filled using a conveyor and a centrally located spout. However, the stream of wheat fell along a parabolic path and impacted the floor at an eccentric location (along the +*y* axis between the center discharge orifice and the D– orifice; fig. 1). In addition, variation in bin wall friction contributed to additional asymmetry in lateral pressure and vertical load. At the initiation of centric discharge (fig. 3b) the wall moments exhibited a decrease to 0.4 kNm, followed by an increase to 0.75 kNm. The wall moments then stayed approximately constant at this level to *h*/*d* of 1.8. Between a grain height of *h*/*d* of 1.8 and *h*/*d* of 1.0, the wall moments exhibited a series of fluctuations between 0.4 and 0.6 kNm. After the bin was discharged to *h*/*d* of 1.0, the wall moment decreased continuously without fluctuation. During discharge, the moments were fairly stable in each region of flow (plug flow, transition flow, and funnel flow) with very few rapid fluctuations in the moments. This can be observed by the smooth changes in loads throughout discharge, which indicated a stable stress field.

The wall moment for a plane obstruction mounted on the wall in the (+*x*, +*y*) quadrant at *h*/*d* of 0.38 is shown in figure 3c during loading and figure 3d during discharge. This condition resulted in a resultant wall moment reaching a maximum of 2.1 kNm at the end of filling (fig. 3c). This was approximately triple the wall moment that was observed in the bin with no obstruction. After discharge initiation, the resultant wall moment rapidly decreased to 1.6 kNm and remained relatively constant until *h*/*d* of 1.8, when the moment decreased rapidly down to 1.0 kNm. Between *h*/*d* of 1.8 and *h*/*d* of 1.0, the moment remained approximately constant. At grain depths below *h*/*d* of 1.0, the moment decreased to zero.

Overturning moments acting on the bin wall with a block obstruction attached to the wall in the (+*x*, +*y*) quadrant at *h*/*d* of 0.38 during filling and detention are shown in figure 3e. Under these conditions, the wall moment reached a maximum of 2.7 kNm at the end of filling and detention, approximately four times the wall moment observed in the bin with no obstruction. Initiation of discharge (fig. 3f) resulted in an immediate decrease to 2.4 kNm, followed by a continuous decrease with some minor fluctuations during plug flow. The overturning moments then ramped down from 1.9 to 1.4 kNm at *h*/*d* of approximately 1.8, coincident with the change in the flow pattern from plug flow to funnel flow. During discharge, with the plane and block obstruction in place, the resultant overturning moments did not decrease below those observed in the bin with no obstruction until the bin was nearly empty.

Tests were also conducted in which both types of obstructions were located in the (+*x*, +*y*) quadrant at *h*/*d* of 0.81 and 1.26. Locating the plane obstruction in the bin at *h*/*d* of 0.81 and 1.26 created wall moments at the end of filling of 0.9 and 0.8 kNm, respectively. Maximum wall moments were observed during plug flow and were approximately 1.3 times higher than the maximum static values. Locating the block obstruction at *h*/*d* of 0.81 and 1.26 resulted in moments at the end of filling of 1.3 and 0.75 kNm, respectively. The resultant moment from the block obstruction during discharge did not exceed the static value when positioned at *h*/*d* of 0.81. When the obstruction was positioned at *h*/*d* of 1.26, the maximum moment at the end of plug flow was 1.1 kNm. For both obstructions, the maximum moment was observed when the obstructions were located at *h*/*d* of 0.38. For all tests, a sharp decrease in the wall moment occurred during the transition from plug to funnel flow at a grain height of approximately *h*/*d* of 1.8.

Obstruction orientation had a significant effect on the wall overturning moments (fig. 4), which can be seen in the three times greater resultant wall moment when the obstruction was moved from the (+*x*, –*y*) quadrant to the (+*x*, +*y*) quadrant. Tests were conducted in which the obstructions were mounted in both the (+*x*, +*y*) and (+*x*, –*y*) quadrants at *h*/*d* of 0.81. The resultant wall moment with the plane obstruction positioned at *h*/*d* of 0.81 in the (+*x*, +*y*) quadrant (A in fig. 4) and the (+*x*, –*y*) quadrant (B in fig. 4) resulted in similar moments during filling until the wheat reached the obstruction (fig 4a). After further filling, the obstruction had a significant effect on the resultant wall moment. For the test condition in which the obstruction was located on the –*y* axis (B), the resultant overturning moment decreased during further filling and reached 0.4 kNm at the end of filling. The moment with an obstruction located on the +*y* axis (A) fluctuated considerably during further filling and reached a value of 0.85 kNm after filling. After discharge initiation, the moments in all tests exhibited distinctly different behaviors. The obstruction located in the +*y* quadrant (A) resulted in a sharp increase in the moment to 1.2 kNm after discharge initiation. At *h*/*d* of 1.8, the moment decreased rapidly and remained lower than 0.4 kNm. During transition from plug to funnel flow, the moment remained below 0.45 kNm throughout the remainder of discharge. The wall moment when the obstruction was located on the –*y* axis (B) remained below 0.45 kNm during the



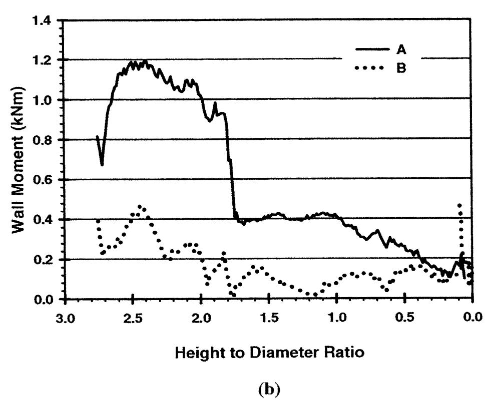


Figure 4. Wall moments produced (a) during filling and detention and (b) during discharge with the plane obstruction located (A) at *h*/*d* of 0.81 in the (+*x*, +*y*) quadrant of the bin and (B) at *h*/*d* of 0.81 in the (+*x*, –*y*) quadrant of the bin.

entire discharge period. Although both obstructions were mounted near the stagnant zone where grain flow would have been expected to act on the obstruction, only the obstruction on the +*y* axis significantly influenced the wall moments.

Lateral Pressures Above and Below the Obstruction

The distribution of lateral pressures within the bin was significantly influenced by the presence of the obstruction on the bin wall (fig. 5). Without the obstruction during filling, the pressure cells recorded only small variations in lateral pressure at the two different locations. At the end of filling, both pressure cells measured a value of approximately 5 kPa. However, during discharge there was a significant difference in lateral pressure measured by the load cells located at different points on the bin wall (fig. 5). At the onset of discharge (fig. 5b), the lateral pressure measured at *h*/*d* of 0.66 increased almost immediately from 5 to 13 kPa. Between a grain height of *h*/*d* of 2.6 and *h*/*d* of 1.8, the lateral pressure fluctuated, much like pressure curves previously observed during slip-stick movement of grain along a bin wall (Bucklin et al., 1996). During slip-stick movement, it is thought that the grain friction fluctuates from a higher to low value, causing the grain to move in a stop-start fashion. This movement causes the lateral pressure values to rapidly ramp up and down between maximum and minimum pressure values, much like those observed in figure 5b. The pressure fluctuations were observed until the grain reached *h*/*d* of 1.8, when the flow pattern in the model bin changed from plug to funnel flow. The lateral pressure for the load cell located at *h*/*d* of 1.09 initially ramped up to 7.5 kPa but decreased to less than 4 kPa during further discharge. At a grain depth of *h*/*d* of 1.8, the pressure momentarily ramped up to 5 kPa and decreased to 1 kPa at *h*/*d* of 1.6. Transition from plug to funnel flow probably created the sharp increase in pressure observed at *h*/*d* of 1.8. The resultant wall moment with the plane obstruction located at *h*/*d* of 0.81 in the (+*x*, +*y*) quadrant is shown in figure 4b and with no obstruction in figure 3b. The obstruction definitely increased the resultant wall moment and lateral pressure relative to the case with no obstruction.

Previous theoretical studies support the observed lateral pressures (Walters, 1973; Drescher, 1991), as well as experimental studies (Walters, 1973; Benink, 1989; Molenda et al., 1995). It has been suggested that, due to the change in state of stress upon discharge, initiation areas of high pressure are created, referred to as a "switch." Flat-floor bins experience peak wall pressures where the angle of the stagnant grain zone intersects the bin wall. In experiments performed using wheat (Ooms et al., 1985), the angle of the stagnant grain was at an angle of 45° and the lateral pressure at this point was three times the static pressure after filling. Tests with wheat in the same 1.83 m diameter bin indicated that the angle of stagnant wheat was not constant but increased during discharge from 40° to 50° (Day, 2005). This would place the transition in a 1.83 m diameter bin at a level between 0.7 and 1.1 m, which corresponds to *h*/*d* of 0.4 to 0.6. The pressure measured at *h*/*d* of 0.66 confirmed this as a region of high pressure.

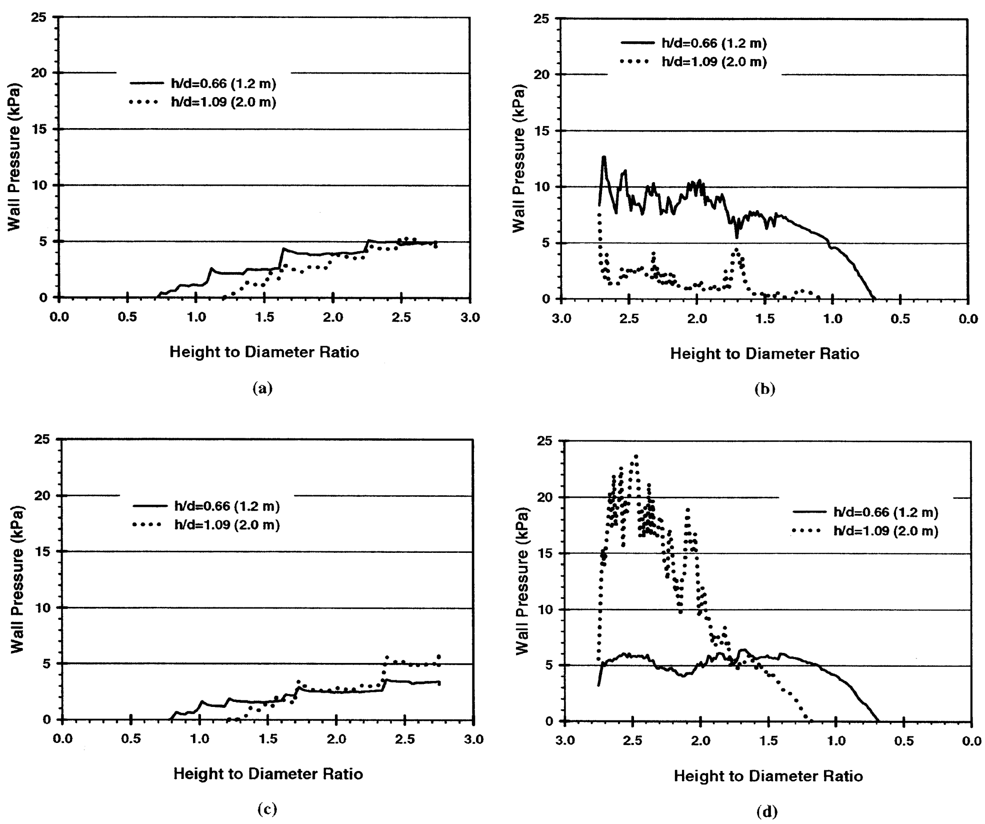


Figure 5. Lateral pressure with no obstruction measured using the earth pressure cells at *h*/d of 0.66 and 1.09 (height of 1.2 and 2.0 m) (a) during filling and detention and (b) during discharge, and with the plane obstruction attached to the wall at *h*/*d* of 0.81 (1.5 m) above the floor (c) during filling and detention and (d) during discharge in the (+*x*, +*y*) quadrant.

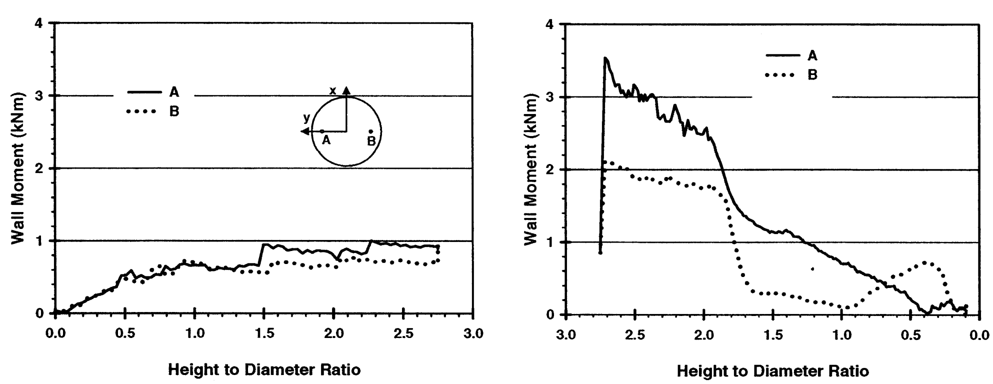
Measured lateral pressures with the plane obstruction mounted at *h*/*d* of 0.81 resulted in a similar behavior during filling (fig. 5c), with a value of approximately 5 kPa at the end of detention. Initiation of discharge (fig. 5d) resulted in the lateral pressure increasing by a factor of 4.4 (to 24 kPa) above the obstruction and remaining above 10 kPa with considerable fluctuations until *h*/*d* of 1.8, when the pressure decreased rapidly to zero. Below the obstruction, the lateral pressure remained less than 6.5 kPa during discharge. The lateral pressure above the obstruction was up to 3.7 times the magnitude of the lateral pressure below the obstruction. Large disturbances in the lateral pressure distribution result in bending moments acting on the wall shell, both in the circumferential direction and along the height of the bin wall, which can lead to serious damage to the bin, as reported by Blight (2004). A four- to five-fold change in local lateral pressures recorded by the pressure cells at the initiation of discharge was associated with an increased total vertical wall load of 1.1 times the static wall load. The increase in the vertical wall load due to discharge initiation has been well documented, and a factor of 1.4 is recommended in ASAE Standard EP 433 (*ASAE Standards*, 1991). Bin failures are frequently caused by local regions of instability, and conditions that create local high-pressure areas need to be determined. The lateral pressure with the block obstruction was very similar to the two-dimensional obstruction and is not shown.

Wall Moments and Lateral Pressure During Eccentric Discharge

Eccentric discharge results in dangerous loads and moments that can lead to bin failure. Previous tests have been conducted in which the model bin used in this experiment was discharged eccentrically (Horabik et al., 1993). The highest wall moments observed during eccentric discharge were found through the orifice located at an eccentricity ratio (*er*) of 0.7. Two tests were performed to compare the wall moments and horizontal pressure measured during eccentric discharge to the tests with obstructions.

Wall overturning moments during centric filling and eccentric discharge through orifices located at *er* = 0.7 on the +*y* (A) and –*y* (B) side are shown in figure 6. During filling, the wall moments followed a similar path as those previously observed and after detention reached a value of 0.9 kNm. Initiation of eccentric discharge resulted in a sharp increase in the wall moment to 3.5 and 2.1 kNm from orifice A and B, respectively. The increase in the wall moment was 2.9 and 1.3 times greater, respectively, than the static wall moment at the two eccentric discharge locations. Differences in the observed moments from the two locations are likely due the imperfect centric filling. The wall moment at the initiation of discharge with an obstruction placed at *h*/*d* of 0.38 reached a value of 2.8 kNm, which falls within the range of 2.1 and 3.5 kNm that was observed during eccentric discharge. As a result, it could be concluded that an obstruction located on the wall of a bin could potentially create significant loads equal to or greater than those observed during eccentric discharge, and these loads could lead to bin failure.

The lateral pressure recorded during eccentric discharge by the two pressure cells located at a height of 1.2 m (*h*/*d* of 0.66) on both sides of the *y* axis is shown in figure 7. During this test, the discharge orifice was located on the +*y* axis of the bin. During filling, the lateral pressure on both sides of the bin followed a similar pattern and had a value of 6.2 and 5.3 kPa on the +*y* and –*y* axes (A and B in fig. 7), respectively, at the end of filling. Initiation of discharge resulted in a sharp increase in the lateral pressure on the –*y* axis (B) side of the bin to a value of 11 kPa. During discharge, the lateral pressure on the –*y* axis (B) side of the bin decreased in the plug flow region of the bin down to *h*/*d* >1.8 with only minor up and down stress cycling. The lateral pressure at the end of the plug flow region on the –*y* axis (B) side of the bin was approximately 7.5 kPa. The lateral pressure on the +*y* axis (A) side of the bin decreased initially and then fluctuated in larger, more rapid up and down stress cycling between 0.4 and 4.4 kPa until *h*/*d* of 1.5. The lateral pressure on the +*y* axis (A) side then ramped up to 6 kPa at *h*/*d* of 1.5 and decreased with smaller cyclic fluctuations during further discharge. Fluctuations in lateral pressure during discharge were much more pronounced on the +*y* axis (A), although the pressure magnitude on the –*y* axis (B) remained considerably higher until *h*/*d* of 1.5. Lateral pressure differences on opposite sides of a bin are known to produce ovalization of the bin wall. This is most dangerous in the case of partial discharge and refilling of a bin. Decreases in wall pressure near the floor of a bin adjacent to eccentric discharge orifices have been reported during forensic investigations to be a factor in wall buckling of failed grain bins.



(a) (b)

Figure 6. Wall moments produced (a) during centric filling and detention and (b) during eccentric discharge (A) through the orifice located at *er* = 0.7 on the +*y* axis side and (B) through the orifice located at *er* = 0.7 on the –*y* axis side.

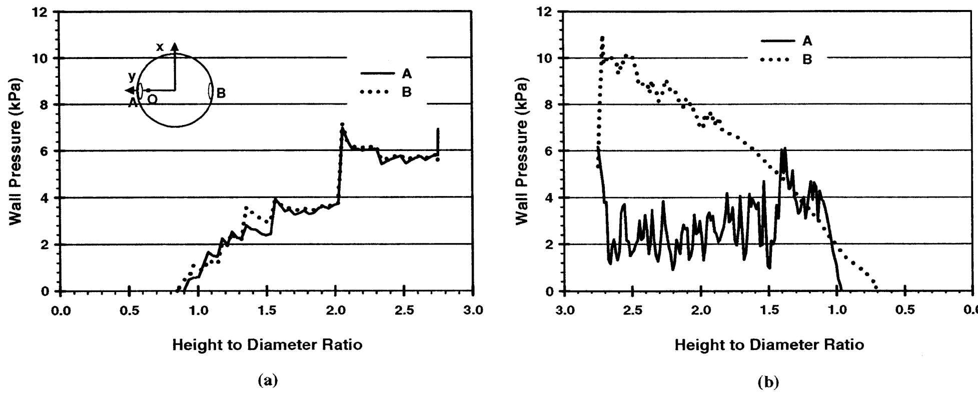


Figure 7. Lateral pressure p_h at 1.2 m height (a) during centric filling and detention and (b) during eccentric discharge through the orifice (O) located at *er* = 0.7 on the +*y* axis side. Curve A shows readings of the earth pressure cell located closest to the discharge orifice, and curve B shows readings of the earth pressure cell located farthest from the orifice.

Summary and Conclusions

In formulation of bin design codes, the basic structural model assumes a uniformly, symmetrically stressed cylinder, while in reality serious discrepancies from symmetry occur. Considerable unevenness of normal floor pressure after filling was observed in the radial as well as in the circumferential direction. Non-perfect centric filling generated a pressure distribution with a maximum at the location where the stream of grain reached the static surface of the grain.

Even in conditions of near symmetry during centric filing, wall overturning moments of approximately 1 kNm were observed. Without the obstruction attached to the wall, load asymmetry as a result of filling decreased after onset of centric discharge and remained stable during plug flow discharge. Changes in flow pattern from plug to funnel flow led to further decrease in load asymmetry. Attachment of an obstruction resulted in an increased wall moment. The highest moment (2.7 kNm) was found at the end of centric filling of the bin with the block obstruction attached at *h*/*d* of 0.38; the wall moment with the plane obstruction in the same location was measured as 2.1 kNm. Eccentric discharge of the bin is considered very dangerous, and most design standards recommend avoiding it. The maximum moment measured in this bin for eccentric discharge (without an obstruction on the wall) was 3.5 kNm. Thus, an obstruction with a horizontal surface area of 7.2% of the bin floor area and a vertical surface area of 3% of the total bin wall area created a wall overturning moment that was 0.77 times the overturning moment observed in the worst case of eccentric discharge.

Initiation of centric discharge with an obstruction attached to the bin wall resulted in an increase in wall pressure above it. Such loading conditions generated high discontinuity in lateral pressure in the circumferential direction and along the height of the bin wall. Asymmetry in circumferential distribution of lateral pressure produces lateral bending moments that cause distortion of the bin wall shape. This is particularly dangerous in conditions of partial discharge and refilling because grain stored in the bin maintains the distorted shape during further storage and subsequent discharge results in further shape distortion. Sharp increases in lateral pressure above the obstruction produce local vertical bending moments. These moments combined with compressive stress due to frictional tractions may result in buckling of the wall and bending of vertical wall stiffeners, as reported by Blight (2004). The dynamic wall pressure above the obstruction reached a maximum of approximately 24 kPa, which was approximately 4.4 times higher than the static pressure.

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