

Effects of vibration on loads in a corrugated model grain bin

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Hao, D., Zhang, Q. and Britton, M.G. 1994. **Effects of vibration on loads in a corrugated model grain bin.** *Can. Agric. Eng.* 36:029-035. Experiments were conducted using a 1.5 m high by 1.0 m diameter corrugated steel bin to study the effects of vibration on loads acting on the bin wall. The bin was instrumented with force and pressure transducers to measure the vertical forces and lateral pressures. The bin was filled with wheat at 12% wb moisture content and then vibrated for 20 minutes at a frequency of 30 Hz and a vertical amplitude of 10 mm (peak to peak). Vibration increased the lateral pressure near the bin floor from 2.73 to 3.78 kPa, or 39%, and the resultant vertical force from 0.96 to 1.17 kN/m, or 22%. During discharge, no increase in lateral pressure was observed in the lower portion of the bin which was previously subject to vibration, whereas an increase of 31% was measured near the floor in the bin which had not been subject to vibration. The maximum load (static plus dynamic load) that was experienced by the vibrated bin was slightly higher than that by the non-vibrated bin.

Keywords: grain, bin, loads, vibration, discharge.

Des expériences on été effectuées avec un réservoir en acier ondulé de 1.5 m de hauteur et de 1.0 m de diamètre afin d'étudier les effets de vibration sur la charge agissant contre les murs du réservoir. Le réservoir a été équipé de transducteurs de force et de pression pour mesurer les forces verticales et les pressions latérales. Le réservoir a d'abord été rempli de blé ayant une teneur en humidité de 12% (base humide) et ensuite été vibré durant 20 minutes à une fréquence de 30 Hz et une amplitude verticale de 10 mm (crête à crête). La vibration a augmenté la pression latérale près du plancher du réservoir de 2.73 à 3.78 kPa (ou 39%), et la force verticale résultante a augmenté de 0.96 à 1.17 kN/m (ou 22%). Durant le déchargement, aucune augmentation de la pression latérale a été observée dans la partie inférieure du réservoir qui avait été auparavant soumis à la vibration, tandis qu'une augmentation de 31% a été mesurée près du plancher du réservoir lorsqu'il n'avait pas été soumis à la vibration. La charge maximum (statique et dynamique) observée sur le réservoir vibré a été légèrement supérieure à celle observée sur le réservoir non vibré.

INTRODUCTION

Grain storage bins may be subject to various vibratory conditions. Possible sources of vibration include running machinery (fans, conveyors, etc.), wind, earthquake, and vehicles travelling on nearby roads or railroads. Vibration imposes dynamic (inertial) forces on bin structures. These dynamic forces may lead to structural failures under severe vibratory conditions such as earthquakes. Under normal conditions, grain bins are more likely subject to low amplitude vibrations which do not produce dynamic loads severe enough to damage structures. However, low amplitude vibrations cause changes in grain properties, such as higher bulk density and reorientation of grain kernels. Changes in grain

properties may result in increased grain pressures on the bin structures. Increased pressures due to grain property changes are "static" and they continue acting on the bin even after vibration stops.

None of the existing grain pressure theories takes into account the effects of vibration on bin loads because "*there are insufficient data available to predict the magnitude or significance of vibration induced pressure*" (ASAE 1992a). Dynamic analysis of structures under vibratory conditions has received much attention in the area of seismic engineering (Newmark and Rosenblueth 1971). However, little can be found in the literature about load increases due to property changes in grain bins subject to low amplitude vibrations.

This study was aimed at exploring the significance of vibration induced loads in grain bins. The specific objectives were: (1) to compare loads before and after a bin had been subject to low amplitude vibrations; and (2) to determine the effects of previous vibration on dynamic loads during discharge.

EXPERIMENTAL METHODOLOGY

A model bin 1.5 m high and 1.0 m diameter, constructed from 0.97 mm thick corrugated galvanized sheet steel, was used for all tests. Wall corrugations were 64 mm pitch and 13 mm deep. The bin wall (an open-end cylinder) was supported approximately 5 mm above a flat floor by three load transducers placed 120° apart (Fig. 1). The sum of forces measured by these three transducers was the total vertical load carried by the bin wall. A flexible plastic skirt was taped to the bottom of the wall to prevent grain kernels from leaking through the clearance between the wall and floor. The bin floor was suspended by three steel rods, each fitted with a integral load transducer to measure rod tension (Fig. 1). These three transducers provided a measurement of the total in-bin grain mass, which was equivalent to the total vertical wall load plus floor load because the bin wall rested on the floor through the three wall-load transducers (Fig. 1). All six load transducers were calibrated using dead weights up to 3.9 kN ($R^2 > 0.99$ for all calibrations).

Lateral pressures on the bin wall were measured using diaphragm sensors mounted on the inside surface of the bin wall at six elevations of 192, 384, 576, 768, 960, and 1152 mm from the bin floor (the base of the bin wall) (Fig. 1). Two additional pressure sensors were placed on the bin wall 120° apart around the bin circumference for measuring circumferential pressure distribution at an elevation of 384 mm above the floor.

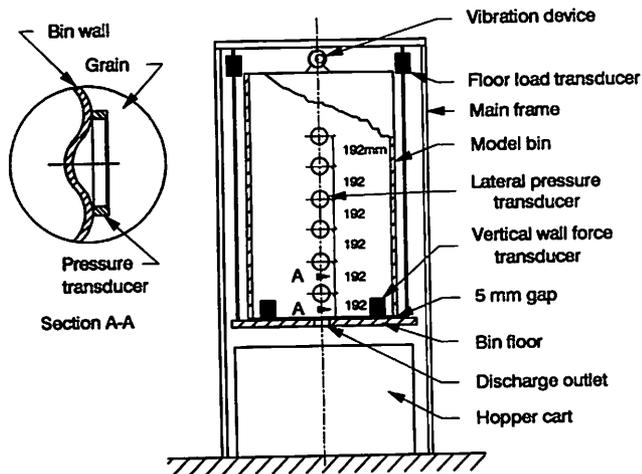


Fig. 1. Schematic of model bin testing system.

Each diaphragm pressure sensor had an aluminum diaphragm 0.52 mm thick and 60 mm diameter. This relatively large size of diaphragm and small aspect ratio (8.7×10^{-3}) was used to maximize the accuracy of grain pressure measurements (Atewologun et al. 1992). Under the maximum design pressure of 5 kPa, the deflection at the centre of the diaphragm was calculated to be 0.074 mm. This small deflection ensured a linear output (Atewologun et al. 1992), and minimized the strain relieve (bridging) in the grain mass immediately next to the diaphragm (Dale and Robinson 1954). Four strain gauges were mounted on the inside surface of the diaphragm. The gauges were temperature compensated for aluminum and connected as a full-bridge. All diaphragm sensors were calibrated using a water column up to 4.9 kPa ($R^2 > 0.99$ for all calibrations). The resolution of the water column was 10 Pa.

The manner in which grain produces pressure on a diaphragm sensor might be different from that of water. Tests were conducted to compare the response of the sensors to grain pressure and water pressure. The sensor was placed in a plastic container of 200 mm diameter and the container was then filled with wheat to a depth of 50 mm. Dead weights were added on the grain surface incrementally. Chi-square test showed that the pressure-strain curve measured from the dead load test had no significant difference ($\alpha=0.05$) from that obtained from the water column calibration.

Zhang et al. (1991) reported that the peak lateral pressure near the bottom of a model bin occurred within 0.4 to 0.7 s after the discharge gate was opened. To capture the peak dynamic loads of discharge, a high-speed data acquisition system, HP 8532A data acquisition unit controlled by a microcomputer, was used to record outputs from all load transducers and pressure sensors. The data acquisition unit was capable of taking 20 readings per second for each of the 14 channels.

Each test was carried out in six steps: (1) the bin was filled using a surge hopper centrally located 0.8 m above the bin top, (2) the grain surface was levelled, (3) the bin was allowed to settle for 10 min, (4) the bin was vibrated until the grain surface stopped moving (about 20 min), (5) the bin was

allowed to settle until static pressures and forces became stabilized (about 2 h), and (6) grain was discharged through a centrally located circular orifice, 60 mm in diameter. Lateral pressures and the total vertical forces on the bin wall were recorded from the beginning of filling to the end of discharge, except that data recording was paused before and after vibration for changing computer diskettes (Fig. 2). Sensor outputs were recorded every two seconds during the filling, settling, and vibrating phases. The recording rate was increased to 20 readings per second per channel for the first 87 s of discharge, and then decreased to 0.5 readings per second until the end of discharge. Tests were also carried out on the same bin without being vibrated. For both vibrated and non-vibrated conditions, tests were repeated four times.

All tests were performed using Hard Red Spring wheat (cv. Katepwa) at 12% wb moisture content. Physical properties of the wheat are summarized in Table I. Moisture content was measured by the air-oven method (ASAE 1992b). In-bin bulk densities were determined as the total in-bin grain mass divided by the grain volume. Particle density was measured by using an air comparison pycnometer (Mohsenin 1986). Both the angle of internal friction and the friction coefficient of grain on the corrugated wall were measured by using a direct shear device (ASTM 1981). Normal pressures used in the direct shear tests ranged from 9.73 to 94.85 kPa.

Bin vibration was induced using an off-centre weight vibrator which generated a vibration frequency of 30 Hz and a vertical amplitude of 10 mm (peak to peak). This frequency was chosen based on the observations reported by Duncan (1980) that ground vibration at distances 5 to 80 m from

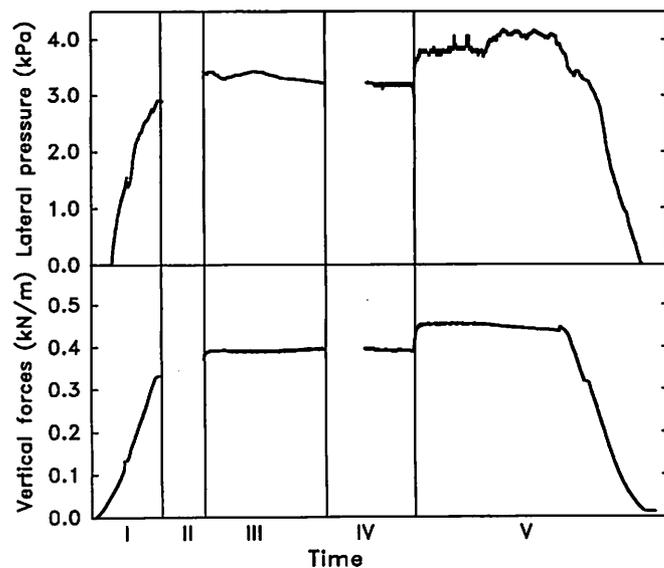


Fig. 2. Typical measured lateral pressure and vertical force on the bin wall from one test (I: filling; II: 10 min settling; III: 20 min vibrating; IV: 2 h settling; and V: discharge). Lateral pressure was measured at the lowest measuring level (192 mm from the floor) and the vertical force was from one of the three wall-load transducers which was approximately one third of the total vertical force acting on the bin wall.

Table I. Physical properties of wheat used in experiments

Moisture content (% wb)*	12
Bulk density (kg/m ³)	797 ⁺ , 836 [‡]
Particle density (kg/m ³)	1432
Angle of internal friction	25.5°
Grain-corrugated steel friction coefficient	0.43

* Wet basis

+ Bulk density before vibration

‡ Bulk density after vibration

railways had frequencies ranging from 5 to 100 Hz. A low amplitude of 10 mm was used so that the inertial force would not cause damage to the bin during vibration and yet the bulk density of grain stabilized in a relatively short time period (within 20 min). Vibration frequency and amplitude may affect bulk density and kernel re-orientation. However, no attempt was made to investigate different frequencies or amplitudes in this study because the vibrator was capable of generating only one frequency and one amplitude.

The vibrator was placed on the top of the bin wall. A vibration analyzer (Model 4660'VIBRA/VIEW', VITEC Inc., Cleveland, OH) was used to measure vibration frequencies and amplitudes at 12 random locations on the bin wall and floor to check for uniformity of bin vibration. The measurements showed that vibration was relatively uniform over the entire bin with no noticeable difference in frequency among these 12 locations. The lowest amplitude of 8 mm was observed on the bin floor.

RESULTS AND DISCUSSION

Preliminary tests

Mounting diaphragm sensors on the inside surface of the wall might disturb the grain flow during discharge, thus affecting bin loads. Preliminary tests were performed to measure static and dynamic vertical forces on the bin wall when all pressure sensors were removed from the bin. The measured static and dynamic vertical forces were 0.98 and 1.24 kN/m (force per unit length of bin circumference), respectively, whereas the corresponding forces measured in the presence of all eight sensors were 0.99 and 1.24 kN/m. Static and dynamic resultant vertical forces measured in the presence of sensors were not significantly different ($\alpha = 0.05$) from the corresponding forces measured in the absence of sensors. This suggested that mounting sensors on the wall did not significantly affect the total loads on the bin wall. However, the stress field in the vicinity of each sensor might have been altered by the sensor. This study did not investigate interactions between diaphragm sensors and grain.

Effect of vibration on static loads

Figure 2 shows typical measured lateral pressure and vertical force from one test. The shown lateral pressure was from the diaphragm sensor at the lowest measuring level (192 mm from the floor) and the vertical force was from one of the three wall-load transducers, which was approximately one third of the total vertical force acting on the bin wall. To

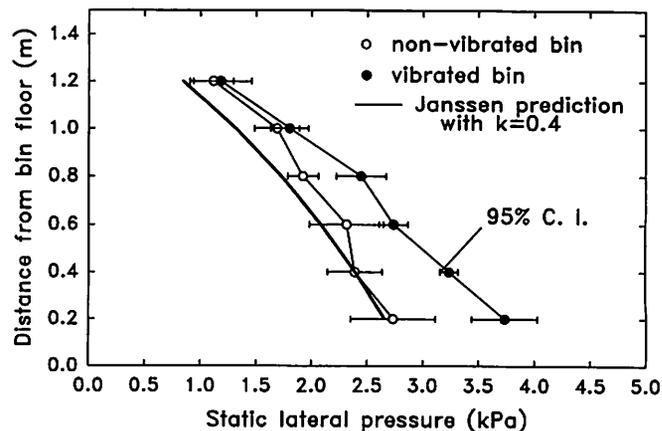


Fig. 3. Measured static lateral pressures on the bin wall at six depths in a corrugated bin 1.5 m high and 1.0 m in diameter.

facilitate discussion, the pressures or forces measured after the bin was fully filled but before discharge were referred to as the static pressures or forces, whereas the loads measured during discharge were defined as dynamic loads.

Vibration caused increases in static lateral pressures at all six measuring levels (Fig. 3). Lateral pressure increased more in the lower portion of the bin than in the upper portion. For instance, the lateral pressure at the bottom level increased from 2.73 to 3.78 kPa, or 39%, whereas the pressure at the top layer increased from 1.11 to 1.18 kPa, or 6%. Further statistical analysis showed that increases in lateral pressure at the two upper measuring levels were not significant ($\alpha = 0.05$), whereas increases at the two lower levels were significant. It was noticed that lateral pressure predicted by Janssen's equation (Ketchum 1919) was in good agreement with pressure in the non-vibrated bin and was lower than that in the vibrated bin (Fig. 3). A k -value of 0.4, determined from the measured angle of internal friction, was used in Janssen's prediction.

The commonly accepted explanation of increasing pressure is the higher bulk density caused by vibration (ASAE 1992a). The measured in-bin density was 797 kg/m³ with a standard deviation (SD) of 14 kg/m³ before vibration, and 836 kg/m³ with a SD of 7 kg/m³ after vibration. This indicated that the average bulk density increased 5% after vibration. Because of grain compaction caused by vibration, the grain surface was lowered by 50 mm, therefore, the total depth of grain decreased 3%. According to Janssen's equation (Ketchum 1919), a 5% increase in bulk density would result in a 5% increase in lateral pressure at all depths, whereas a 3% decrease in grain depth would cause a 19% decrease in lateral pressure at the top measuring level and 3% at the bottom. Therefore, the net change in lateral pressure would be -14% (decrease) at the top level and +2% (increase) at the bottom level. The measured results did not support the above calculations. This suggests that the bulk density increase does not fully explain the increased lateral pressure after vibration.

One possible cause of increasing lateral pressure was the grain kernel re-orientation induced by vibration. For a non-spherical particle such as a wheat kernel in the gravitational field, the preferred orientation is achieved when the longest

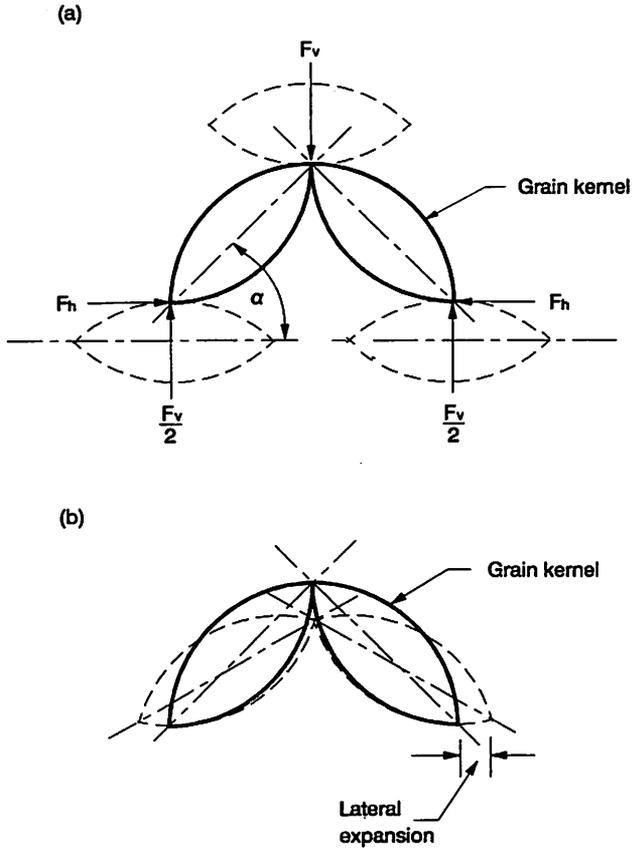


Fig. 4. A hypothetical spacial arrangement of grain kernels: (a) force relationship; and (b) tendency of lateral expansion during vibration.

axis coincides with the horizontal direction. When wheat is placed into a bin, not all kernels are in the preferred orientation. Vibration tends to re-orient grain kernels to their preferred orientation. This kernel re-orientation induces a tendency for lateral expansion within the grain mass, as illustrated in Fig. 4b for a hypothetical situation. Any lateral expansion is resisted by the bin wall, thus lateral pressure on the wall increases. Consider the hypothetical situation shown in Fig. 4a. A two-kernel aggregate is subject to a vertical force (F_v) from a kernel above it and is supported by two kernels underneath it. From the force equilibrium equation, the relationship between the vertical force, F_v , and the lateral force, F_h , can be written as:

$$F_h = \frac{F_v}{2 \tan \alpha} \quad (1)$$

where α is the angle between the longest axis of a kernel and a horizontal plane. The lateral force, F_h , increases with decreasing angle α as vibration re-orientes the kernels to their preferred position even if the vertical force, F_v , remains constant. Many two-kernel aggregates may exist in a grain bulk. The overall effect of increased horizontal forces, F_h , from all aggregates in the grain bulk is an increase in lateral pressure on the bin wall.

Equation 1 suggests that the lateral to vertical pressure ratio (k-value) increases as vibration re-orientes kernels to the

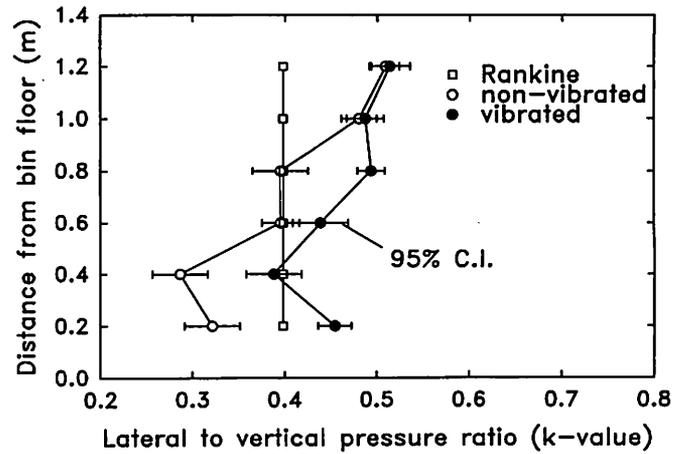


Fig. 5. Lateral to vertical pressure ratios (k-values) obtained by fitting average measured static lateral pressures to Janssen's equation.

preferred orientation. The measured static pressure data were fitted to Janssen's equation (Ketchum 1919) to determine k-values at the six measuring levels. It was assumed that the coefficient of friction between grain and the bin wall was constant and the vertical stress in the grain mass was uniform across the bin diameter. The fitted k-value decreased from the top to the bottom before and after vibration. After vibration, the k-value increased slightly in the upper portion of the bin and significantly in the lower portion (Fig. 5). The k-value at the bottom level increased from 0.32 to 0.45, or 41%. The k-value averaged over all six measuring levels was 0.40 before vibration and 0.46 after vibration, i.e., vibration caused an increase of 15% in the average k-value. It was noticed that the average k-value before vibration was almost the same as the Rankine coefficient $[(1 - \sin \phi) / (1 + \sin \phi)]$. This implies that it may not be appropriate to use the Rankine lateral to vertical pressure ratio for bins which were previously subject to vibration.

Vertical load shifted from the floor to the wall after the bin was vibrated. The increase in the vertical load on the wall was 0.21 kN/m (from 0.96 to 1.17 kN/m), or 22%, after vibration.

Effect of vibration on dynamic loads during discharge

Vibration changes flowability of grain in the bin, thus affecting dynamic loads during discharge. For the non-vibrated bin, the lateral pressure in the lower part of the bin increased sharply immediately after the discharge gate was opened and a slight pressure change was observed at the top level. Whereas, for the vibrated bin, the lateral pressure in the lower part of the bin stayed nearly constant and the pressure at the top layer increased slightly at the initial stage of discharge (Fig. 6). Smaller increases in lateral pressure during discharge in the vibrated bin might be attributed to the existence of a funnel flow mode, because grain was consolidated by vibration and became more difficult to flow. An attempt was made to observe the flow mode by inserting twenty 2-mm diameter and 45-mm long steel rods into the grain mass through small holes in the wall. The rods were evenly placed at heights from 197 to 1413 mm (measured from the floor).

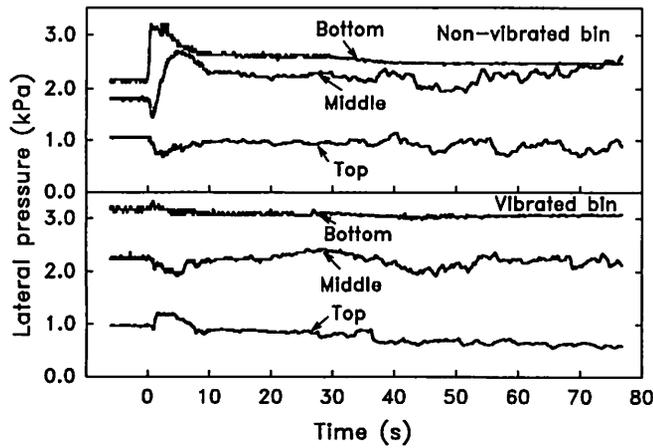


Fig. 6. Typical measured dynamic lateral pressures on the bin wall at three depths during discharge. (Top: 1152 mm from the bin floor; Middle: 768 mm from bin floor; and Bottom: 192 mm from bin floor).

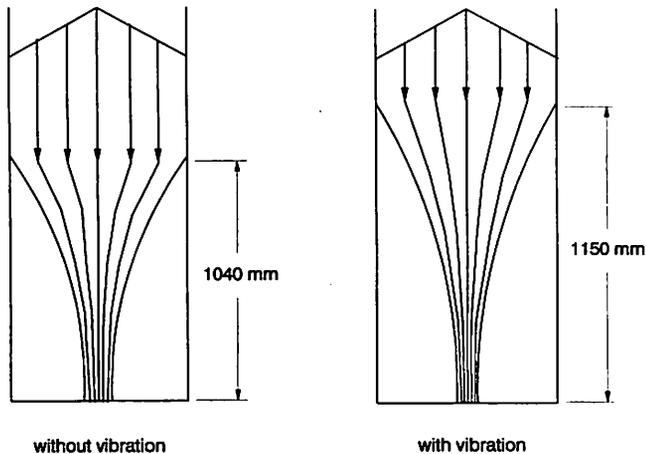


Fig. 7. Observed flow regions at 10 s of discharge.

For the non-vibrated bin, all rods tilted from the beginning of discharge, which indicated that grain near the wall moved and mass flow occurred in the entire bin. For the vibrated bin, not all rods tilted during discharge. For example, after the initial 10 s (an arbitrarily chosen time), rods in the upper part (1150 mm above the floor) tilted, whereas, rods in the lower part did not tilt until the grain depth became close to or lower than the elevations of the measuring points, which showed that grain did not move along the wall (funnel flow) in this region. Schematics of flow regions constructed from the observed rod movements are shown in Fig. 7 for a discharge time of 10 s. At this particular time, the height of the stagnant grain region in the vibrated bin was 11% greater than that in the non-vibrated bin. A greater region of stagnant grain means a smaller mass flow region and a smaller increase in loads (Gaylord and Gaylord 1984).

The measured pattern of lateral pressure distribution agreed with the observations of flow mode. For the vibrated

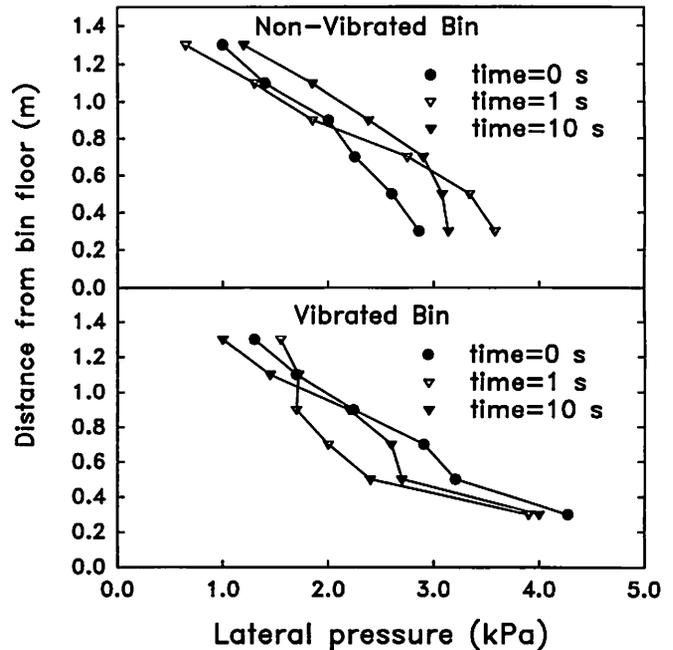


Fig. 8. Average measured lateral pressure profiles at different stages of discharge.

bin, the lateral pressure at the top level increased at the beginning of discharge (1 s), while pressures at all other levels stayed below the static pressure all the time (Fig. 8). This demonstrated that mass flow occurred only in the top portion of the bin while funnel flow existed in the lower portion. For the non-vibrated bin, lateral pressure increased noticeably in the lower portion of the bin at the beginning of discharge (1 s) (Fig. 8). As the pressure peak travelled upwards, pressures in all depths became higher than the static pressure (10 s).

Figure 9 shows the measured vertical wall force for a typical force transducer (the vertical force measured by one transducer was approximately one-third of the total vertical wall load). For both vibrated and non-vibrated conditions, the total vertical force on the wall increased sharply when discharge started, but the vertical force for the non-vibrated bin increased more (from 0.30 to 0.40 kN/m, or 33%) than for the vibrated bin (from 0.36 to 0.40 kN/m, or 11%). Regardless of the higher static vertical force for the vibrated bin, the peak dynamic forces were almost the same for both bins approximately 50 s after discharge (Fig. 9).

Times of peak discharge loads

For the vibrated bin, the time of peak lateral pressure varied from 1 s at the top measuring level (1152 mm from the floor) to 54 s at the fourth measuring level (576 mm from the floor), and no pressure peak occurred below the fourth measuring level (Table II). An opposite trend was observed for the non-vibrated bin. The lateral pressure reached the peak at the bottom earlier than at the top (Table II). The peak pressure at the lowest measuring level (192 mm from the floor) occurred later than the level above it because the lowest measuring level was located below the stagnant grain zone. Analysis of variance indicated that the time of peak lateral pressure for the vibrated bin was significantly ($\alpha = 0.05$) shorter in the

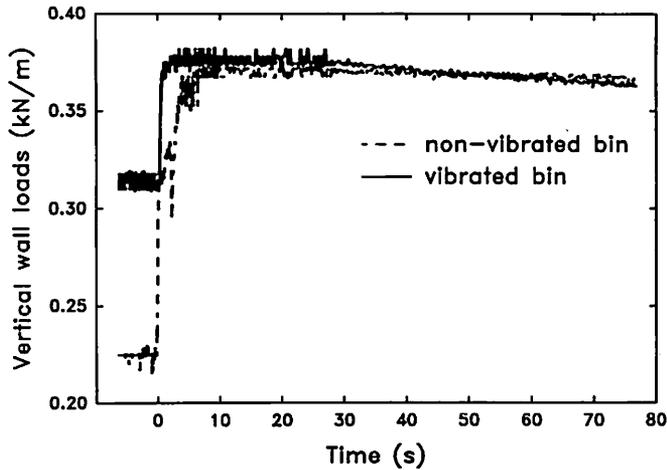


Fig. 9. Typical measured vertical forces from one transducer which was approximately one third of the total vertical force on the wall.

Table II. Measured times of peak lateral pressures during discharge

Measuring level	Height ⁺ (mm)	Without vibration		With vibration	
		Mean* (s)	(SD) (s)	Mean* (s)	(SD) (s)
1	1152	13	(9.9)	1	(0.4)
2	960	9	(2.9)	1	(0.6)
3	768	5	(0.5)	25	(18.3)
4	576	2	(0.5)	54	(24.4)
5	384	2	(0.0)	‡	-
6	192	7	(9.4)	‡	-

* Mean of four replications

+ Measured from the floor

‡ No pressure peak occurred

upper two layers and longer in the lower layers than those for the non-vibrated bin in the corresponding layers.

The time of peak vertical resultant force was significantly affected ($\alpha = 0.05$) by vibration. The vertical resultant force reached the peak in 0.8 s for the vibrated bin, which was 10 times faster than for the non-vibration bin (8 s).

SUMMARY AND CONCLUSIONS

Static loads and dynamic loads during discharge were measured in a corrugated model bin 1.5 m high and 1.0 m diameter filled with wheat at 12% wb moisture content. The bin was vibrated for 20 minutes in the vertical direction at a frequency of 30 Hz and amplitude of 10 mm after it was filled. Vibration induced significant increases in static lateral pressure in the lower portion of the bin. The lateral pressure at the bottom measuring level (192 mm above the bin floor) increased from 2.73 to 3.78 kPa, or 39%. Static lateral pressure in the upper portion of the bin was not significantly affected by vibration.

Vibration re-distributed vertical load from the bin floor to the wall. The total vertical force on the bin wall increased from 0.96 to 1.17 kN/m, or 22%. The bulk density and the average lateral to vertical pressure ratio (k-value) increased 5% and 15%, respectively, after vibration. This suggests that using a higher k-value in predicting vibration induced loads might be more important than using a higher bulk density value.

For the non-vibrated bin, lateral pressure increased at all measuring levels (192 to 1152 mm from the floor) during discharge. The maximum pressure was 1.43 times higher than that before discharge, which occurred at a measuring level 384 mm from the floor. For the vibrated bin, pressure increases were negligible during discharge. However, the maximum lateral pressure and vertical force on the wall which the vibrated bin experienced were 3.78 kPa and 1.50 kN/m, respectively, slightly higher than those experienced by the non-vibrated bin (the non-vibrated bin experienced a maximum pressure of 3.57 kPa and vertical force of 1.42 kN/m).

It was concluded from this study that low amplitude vibration had significant effects on both static and dynamic loads in grain storage bins. Further research should be conducted to systematically investigate bin loads as affected by vibration characteristics (e.g., frequency, amplitude, and direction), bin configuration, discharge rate, and properties of stored grain.

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