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Comparison of loads on smooth- and corrugated-wall model grain bins**

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A b s t r a c t. Wall and floor loads exerted by wheat on a corrugated-wall model bin were measured. The 7.3 m high bin with a diameter of 2.44 m was centrally filled with wheat. Tests were conducted for a filling height to bin diameter ratio equal to 2.75 for center and off-center discharge conditions. Loads and the resultant moment of force were compared to the results of an earlier investigation performed with a smooth-wall bin of similar dimensions. Observed differences in the load response of the two bins can be attributed primarily to the difference in frictional behaviour of grain on smooth and corrugated galvanized steel. Only slight wear-in effects on the corrugated-wall bin were observed during the initial period of operation. The dynamic-to-static wall load ratio on the corrugated-wall bin was observed in a range from 1.0 to 1.14 which was lower than similar values for the smooth-wall bin which ranged from 1.08 to 1.3. No slip-stick frictional effects or upward friction force, which were observed for the smooth-wall bin, occurred in the corrugated-wall bin. Resultant moments of force showed similar characteristics in both bins with maximum values occurring for a discharge orifice eccentricity ratio of about 0.7. The resultant moments for the corrugated-wall bin were approximately 3 times smaller than those measured for the smooth wall bin.

K e y w o r d s: wheat, bins, silos, loads, friction

INTRODUCTION

Earlier investigation by the authors performed on a smooth-wall bin filled to a height to diameter (*H/D*) ratio of 2.75 showed pronounced variation of wall loads during the initial period of bin operation (Molenda *et al*., 1996). The vertical wall load-to-total grain load ratio was found to decrease from 52.7% for the first loading cycle (LC) to 28.3% for the 10th LC. Simultaneously, the dynamic-to-static wall load ratio increased from 1.08 to 1.24. Changes in the coefficient of friction were shown to be a major factor contributing to the observed variability of loads (Bucklin *et al*., 1989).

Funnel flow or plug flow may take place during discharge of the bin. In funnel flow all grain movement occurs through an internal core with no movement occurring along the bin wall. During plug flow grain movement occurs along all or part of the bin wall (ASAE Standars, 1997). Plug flow discharge results in an increase of the loads imposed by grain on the bin wall. The mode of flow in flat-bottomed bins depends on the *H/D* ratio of the bin fill. ISO 11697 (International Standard ISO 11697, 1995) recommends using over-pressure coefficients for *H/D* ratios higher than 1.0. ASAE Standard EP433 (ASAE Standars, 1997) indicates that plug flow will exist in a bin with *H/D* ratios greater than 2.0 and recommends an overpressure factor of 1.4 for determination of the lateral wall pressure during discharge. Plug flow associated with a dynamic load increase was observed at the onset of discharge of a smooth-wall bin for an initial fill depth as low as an *H/D* ratio equal to 1.5 (Molenda *et al*., 1996).

Non-uniformity of distribution of bin loads may lead to buckling of a circular bin wall. Nohr (1985) stated that during eccentric discharge this distortion can become severe and cause permanent damage. The highest asymmetry of bin loads occurs during eccentric unloading through an orifice located at an eccentricity ratio of 0.67. The other factors contributing to non-uniformity of load distributions are differences of bulk density and the coefficient of wall friction. Anisotropy of the angle of internal friction within the grain bedding may also contribute to an asymmetry of loads. The existence of friction in contacts between granules results in an uneven pressure distribution in granular media in static

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equilibrium, and the actual distribution of stress depends on the load history of the material (Deresiewicz, 1958).

This experimental investigation was performed to determine the variation of loads and flow characteristics in an initial period of operation of a corrugated-wall, flat-floor bin.

The specific objectives were to:

· determine the effects of changes in wall friction and mechanical properties of wheat on bin loads and grain flow characteristics;
· determine the resultant moment of force exerted on the wall of a model bin during filling and discharge;
· determine the effects of initial filling height on bin loads and grain flow characteristics.

The results are compared to those found earlier for a smooth-wall bin of similar dimensions (Molenda *et al*., 1996). The comparison of loads on two model bins, which differ only in the wall surface configuration can provide information relevant for design (Thompson and Prather, 1985; Zhang *et al*., 1991).

EQUIPMENT, PROCEDURE AND MATERIAL PROPERTIES

Tests were conducted on a flat-bottom bin 2.44 m in diameter and 7.3 m high. The wall of the bin was made of horizontally oriented, corrugated, galvanized steel which had a pitch and depth of 67.5 and 13 mm, respectively. The cylindrical wall of the bin and the flat floor were each supported independently on three load cells to isolate wall and floor loads. Load cells supporting the wall cylinder and the floor were spaced at an angular distance of 120° around the circumference of the bin. The bin was centrally filled from a spout at a flow rate of approximately 250 kg min^{-1}. After filling the grain was allowed to equilibrate during a holding or detention period of 0.5 h. The bin was discharged through an 89 mm diameter orifice which produced a sliding velocity along the bin wall during plug flow of 3.1 m h^{-1}. The wall and floor loads during loading, detention, and discharge were measured at 1 min intervals until discharge was completed. To observe the dynamic response of the loads at the start of grain discharge, the loads were measured at 0.1 s time intervals prior to opening the unloading orifice and for two minutes thereafter. The loads were measured with an accuracy of ±50 N. The load cell data was recorded using a high speed data acquisition system.

The vertical wall load, F_z, and the resultant moment exerted by grain on the bin wall, M, were calculated using the vertical loads measured by the load cells supporting the wall (Horabik *et al*., 1992):

$$F_z = F_1 + F_2 + F_3 \quad (1)$$

$$M = \sqrt{M_x^2 + M_y^2} \quad (2)$$

where: $M_x = R\left(F_1 \sin\alpha_1 + F_2 \sin\alpha_2 + F_3 \sin\alpha_3\right), M_y = R\left(F_1 \cos_1 + F_2 \cos_2 + F_3 \cos_3\right)$, F_1, F_2, F_3 – force indicated by load cells 1, 2, and 3 (N); R – radial distance of load cells (m), α_1, α_2, α_3 – angular coordinate of load cells (0°, 120° and 240°, respectively).

The vertical wall load-to-total grain load ratio (*VWL/TGL*) was defined as the ratio of the vertical wall load F_z to the total grain weight in the bin. The dynamic- to-static load ratio (*D/S*) was defined as the ratio of the vertical wall load F_z measured during discharge to the vertical wall load F_z after the detention period of 0.5 h.

Two series of tests were performed with centric filling of the bin. The first series conducted with initial grain heights at a *H/D* ratio of 2.75 investigated wear-in effects and the influence of eccentric discharge on bin loads. Six tests were performed with centric discharge followed by 14 tests conducted with eccentric discharge. Seven antipodal orifices used in the eccentric discharge tests were located along the diametrical cord of the bin floor. These orifices had eccentricity ratios of: 0.135; 0.270; 0.358; 0.541; 0.676; 0.811; and 0.946. The first test series were ended with one center unloading test with the grain fill at an *H/D* ratio of 2.75.

The second series of tests investigated the effects of grain loading depth on bin loads and grain flow characteristics. It consisted of a series of 15 center discharge tests with initial fill *H/D* ratios of 0.5, 1.0, 1.5, 2.0 and 2.75. Tests at each fill *H/D* ratios were replicated three times.

The test programme with the corrugated-wall bin was planned to allow for comparison of the results with those reported earlier on a smooth-wall bin of similar dimensions (Molenda *et al*., 1996). Both bins were filled with soft red winter wheat. For the investigations with the corrugated-wall bin the wheat had an initial uncompacted bulk density of 760 kg m^{-3} and a moisture content of 13.2% (wb). For the investigations with the smooth wall bin, the grain had an initial uncompacted bulk density of 750 kg m^{-3} and a moisture content of 11.5% (w.b.). The frictional properties of the wheat were determined on galvanized metal samples before and during the test programme. These included the coefficient of internal friction (μ_{int}), the coefficient of friction against corrugated steel (μ_c), and the coefficient of friction against smooth steel (μ_s). Triaxial compression tests and the sliding friction on a galvanized steel plate were performed for the grain used with the smooth-wall bin. A modified direct shear test was conducted on the grain used in the corrugated-wall bin tests. The values of the various coefficients of friction are presented in Table 1.

A significant (α=5%) decrease in the internal friction of approximately 0.05 (approximately 10%) occurred during the first 21 loading cycles. The coefficient of friction on the corrugated steel decreased from 0.44 to 0.41(approximately 7%). This was probably a result of a change in the grain surface, because no wear-in effect was observed in the

T a b l e 1. Coefficients of friction of wheat used in tests: internal - μ_{int}; on corrugated sheet - μ_c; on smooth sheet - μ_s

Parameter	Smooth wall bin		Corrugated wall bin	
	initial	after 23 tests	initial	after 21 tests
μ_{int}	0.47±0.02	0.41±0.02	0.48±0.03	0.43±0.01
μ_c	-	-	0.44±0.01	0.41±0.01
μ_s	0.45	0.16	0.150±0.009	0.135±0.002

replicated friction tests on corrugated steel with different samples of grain taken after the same sequence of loading cycles. Friction of grain on smooth steel was measured on metal samples from which the bin walls were fabricated. The smooth sample was taken from the rolled sheet before it was corrugated. For this sample, the coefficient of friction decreased from 0.150 to 0.135. An approximate threefold decrease in the coefficient of friction was observed (from 0.45 to 0.16) for the steel sheet which was used to form the smooth wall bin. The difference in the frictional behaviour of the two lots of galvanized steel was probably a result of metallurgical processes resulting in different surface characteristics.

RESULTS

Loads during the initial stage of bin use

A small decrease in the static vertical wall load-to-total grain load (*VWL/TGL*) ratio was observed during the first 21 loading cycles (LCs) performed immediately after assembling the corrugated test bin. The *VWL/TGL* ratios calculated immediately after completion of bin filling and after two minutes of discharge are shown in Fig. 1. *VWL* did not decrease during the rest period. There was no detectable consolidation that effected the *VWL*. For the first five LCs the *VWL/TGL* ratio decreased from 66.8 to 59%. A slower decrease of *VWL/TGL* was observed during the next 16 LCs down to 53.4% for LC21. No dynamic load shift from the bin floor to the wall occurred during first two loading cycles. In

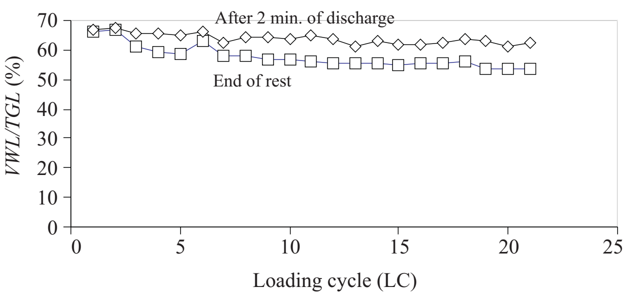

Fig. 1. Ratio of static vertical wall load-to-total grain load in the corrugated wall bin as affected by detention period and loading cycle.

the subsequent 19 LCs the dynamic-to-static wall ratio (*D/S*) was observed in a range of 1.10±0.04 with no clear relation to the number of the LC.

Flow zone

Grain discharged from the test bin by plug flow until the grain level reached an *H/D* ratio of 1.37 to 1.71. Below this level it discharged by funnel flow. An *H/D* ratio at which funnel flow was observed to initiate showed a tendency to decrease as the number of LCs (n) increased. A linear regression model of the data was:

$$H/D = 1.67 - 0.0056n. \qquad (3)$$

The coefficient of correlation for the model was 0.75.

Grain was observed moving along the bin wall too as low as 0.80 m (*H/D* = 0.32) above the floor for the first several seconds. Below this level, no grain movement at the wall was detected. During the next 30 s, the level at which no grain movement was observed on the bin wall increased to approximately 1.8 m (*H/D* = 0.74) above the bin floor. Thereafter, this level remained essentially constant until grain discharge changed from plug to funnel flow. Based on this information, the half cone angle of the flow channel was calculated by assuming a straight-line between the discharge orifice and the lowest point at which flow occurred on the bin wall. The mean values of the half-cone angle (α_s, angle between a vertical axis and the flow channel) of the flow channel calculated for all centric unloading tests with an initial grain height in the bin of *H/D* equal to 2.75 were:

at start of discharge $\alpha_s = 48°±8°$
during plug flow $\alpha_s = 34°±6°$.

Loads for different initial depths of fill

The *VWL/TGL* and *D/S* ratios were calculated using measured values of loads for five different levels of grain fill in the test bin. Values for these parameters are presented in Table 2 with the *VWL/TGL* ratio given at both the end of filling and at the end of a 0.5 h rest period.

The *VWL/TGL* ratio at the end of filling ranged from 19.2 to 54.2% and was dependent on the height of fill. No significant (α = 5%) change in the *VWL/TGL* was observed during the rest period of 0.5 h.

The values of the *D/S* ratio presented in Table 2 were calculated for wall load measurements of 10, 20 and 100 s after the start of discharge. No significant (α = 5%) differences between the *D/S* values for grain fill depths with *H/D* ratios higher than 0.5 were observed.

Funnel flow was observed from the onset of discharge for filling depths with *H/D* ratios of 0.5 and 1.0. For initial fill depths with *H/D* ratios equal to 1.5, 2.0 and 2.75, discharge pattern changed from plug to funnel flow at grain depths in the bin with *H/D* ratios in the range of 1.37 to 1.58. The mean value of the *H/D* ratios at which grain flow

T a b l e 2. Percent of total grain load supported by the bin walls (*VWL/TGL*) and *D/S* after 10, 20 and 100 s of discharge time for five initial filling depths (*H/D*: 0.5, 1.0, 1.5, 2.0 and 2.75). Mean values and standard deviations

H/D	*VWL/TGL* (%)		*D/S*		
	end fill	end rest	10 s	20 s	100 s
0.5	19.2 ± 0.42	19.6 ± 0.40	1.04 ± 0.03	1.04 ± 0.04	0.93 ± 0.03
1.0	32.1 ± 0.06	31.1 ± 0.60	1.13 ± 0.03	1.15 ± 0.03	1.16 ± 0.03
1.5	41.0 ± 0.26	41.3 ± 0.60	1.11 ± 0.02	1.13 ± 0.03	1.16 ± 0.03
2.0	47.3 ± 0.21	47.4 ± 0.87	1.12 ± 0.01	1.14 ± 0.03	1.17 ± 0.01
2.75	54.0 ± 0.17	54.2 ± 0.17	1.12 ± 0.01	1.13 ± 0.01	1.15 ± 0.01

changed was 1.50 ± 0.07 with no clear relation to the initial depth of fill. A dynamic increase in the vertical wall load occurred for an initial filling depth at a *H/D* of 1.0, in which case plug flow was not observed.

Non-symmetrical loads during centric and eccentric discharge

Asymmetry of wall loads results in moment of force acting on the bin wall during unloading. Figure 2 shows the wall moment for centric filling and discharge of the model bin. During the initial stage of filling of the bin, the wall moment increased quickly to a fill height of *H/D* ratio of approximately 1.3. After reaching this grain height the wall moment stabilized at a level of approximately 2.5 kNm and did not change appreciably until the end of filling at an *H/D* ratio of 2.75. The observed asymmetry of loads during centric filling was a result of imperfect centric filling. The grain transported by the overhead drag conveyor used for filling the bin had a horizontal component of velocity when it reached the discharge spout. Consequently, the path of the stream of grain falling into the bin did not follow a straight vertical line corresponding to the bin axis. As the height of the grain in the bin increased, the grain dropped closer to the axis, which resulted in more uniform distribution of pressure on the horizontal cross-section of the bin. Geometrical inaccuracies of the cylindrical bin wall and/or non-uniformity of wall friction throughout the wall surface likely contributed to wall load asymmetry as well. Ramps visible on the unloading curve reflect an instability of the formed structure of the grain bedding. A rearrangement of grain in the bin along the cone of repose occurs after some amount of grain deposits on its surface.

The opening of the centric discharge outlet resulted in the formation of a passive state of stress, an increase in wall load, and the initiation of plug flow with grain sliding along the bin wall. The onset of plug flow resulted in a rapid drop in the wall moment down to approximately 2 kNm. During continuing unloading the wall moment showed a slow decrease. After the grain height decreased to an *H/D* ratio of approximately 1.9, another drop in the value of the moment down to approximately 800 Nm was observed. A change in the flow pattern from plug to funnel flow took place during this phase of grain discharge. The movement of grain along the wall ceased and a flow channel formed inside the grain mass. During this phase of unloading wall friction effects did not contribute to load asymmetry and only a small amount of grain remained in motion which formed the channel above the centric outlet in the bin floor. The last phase of unloading below a fill *H/D* ratio of 0.5 resulted in a stable level of grain on the wall and a gradual change of shape of the top surface of the grain. A further decrease in wall moment occurred during this period until the outflow ceased after the grain surface formed an inverted flow cone with an apex at the discharge orifice.

Figure 3 shows the wall moment during eccentric discharge recorded 100 s after the start of grain discharge for a fill *H/D* ratio of 2.75 as affected by the eccentricity ratio

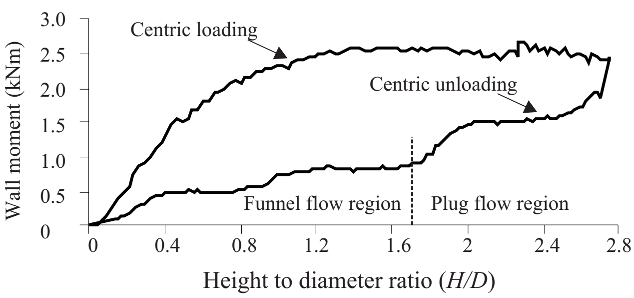

Fig. 2. Resultant wall moment during centric loading and discharge of the corrugated wall bin.

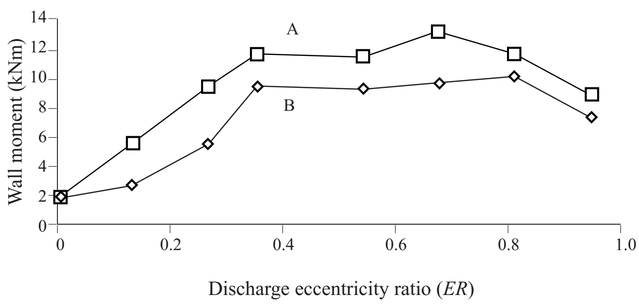

Fig. 3. Resultant wall moment created during eccentric discharge of the corrugated wall bin for *H/D* ratio of 2.75 and two opposite locations of discharge orifices (A and B) related to the bin axis.

(*ER*) of the discharge orifice. Two separate characteristics of the moment versus *ER* were obtained for unloading through antipodal orifices located along the diametrical cord of the bin floor. Wall moments observed for unloading on one side (A) of the bin axis were always lower than for unloading on the opposite side (B) at the same *ER*. Since the tests were performed in random order and the distances of pairs of discharge orifices from the bin axis were equal, the non-uniformity of the bedding was a probable cause for the observed difference. The maximum wall moment of 13.1 kNm was observed at the bin orifice eccentricity ratio of 0.68. This value was five times higher than the maximum moment observed during centric unloading of the bin. Wall moments in a range from 9.2 to 13.1 kNm were recorded for *ER* ranging from 0.36 to 0.81.

Comparison of the corrugated- and smooth-wall bins

The total vertical wall loads in the smooth-wall and corrugated-wall bins during centric loading and unloading are shown in Fig. 4. The vertical wall load at the end of filling (*H/D* = 2.75) supported by the smooth-wall was 80.5 kN and decreased to 75.9 kN during the detention time of 30 min. The total vertical wall load for the corrugated-wall bin at the end of filling was equal to 139.5 kN and no change of this value was observed during the detention time. A load spike was observed in both bins immediately following the onset of discharge. The load on the corrugated wall increased to 157.5 kN, while on the smooth wall it reached 91.8 kN, which represented *D/S* ratios of 1.13 and 1.21, respectively. Vertical wall loads for the corrugated-wall bin during unloading were greater than the filling loads for most of the period of discharge, while for the smooth wall bin, they were lower than filling loads for a *H/D* ratio below approximately 1.8. A maximum negative friction force of approximately 20 kN was observed for the smooth-wall bin. Little or no negative friction force was observed for the corrugated-wall bin.

Differences in the load characteristics for these bins can be attributed to different frictional behaviour of wheat on smooth and corrugated galvanized steel. The high coefficient of friction on the corrugated steel results in a larger vertical wall load which in turn results in lower relative increase in the wall load at the onset of discharge. A larger vertical wall load is also associated with a lower vertical pressure inside the bulk of grain, a smaller elastic deformation of grains, and a negligible value of negative friction force observed in the corrugated-wall bin.

Figure 5 presents a comparison of the dimensionless resultant moment determined in the tests on the corrugated-wall bin and earlier tests performed on a smooth-wall bin at a fill height *H/D* ratio of 2.75 (Molenda *et al.*, 1996). The resultant horizontal wall moment, *M*, (Eq. (2)) was divided by the product of total weight of grain in the bin, *m*g, and the bin diameter, *D* (Horabik *et al.*, 1995). The relationships between the dimensionless moment, *M*/*m*g*D*, and the orifice eccentricity ratio, *ER*, were similar for both the corrugated-wall and smooth-wall bins. The moments were found to be the highest for the discharge orifice locations between 0.36 and 0.81 for both bins. The average moment for five eccentricity ratios above 0.135 for the corrugated-wall bin was found equal to 0.0164 ± 0.0038, approximately 1/3 of the value of 0.0492 ± 0.0078 found for similar orifice positions for the smooth-wall bin.

CONCLUSIONS

Only a slight variation in loads on the corrugated-wall bin was observed during the initial period of operation. During the first 21 loading cycles after the bin was assembled, the ratio of vertical wall load to total grain load decreased from 66.5 to 55.4%, in part as a result of a decrease in the frictional properties of the grain. No change was observed in the vertical wall load during a 0.5 h detention period for any of the filling heights. The dynamic-to-static (*D/S*) wall load ratio on the corrugated-wall bin was observed in a range from 1.0 to 1.14. This was lower than values for smooth wall bin that ranged from 1.08 to 1.3. No

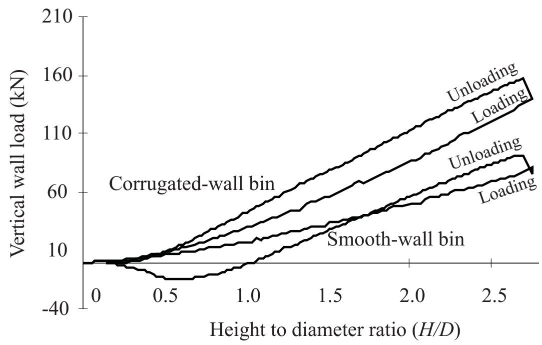

Fig. 4. Vertical wall load on corrugated and smooth wall bins during centric loading and discharge.

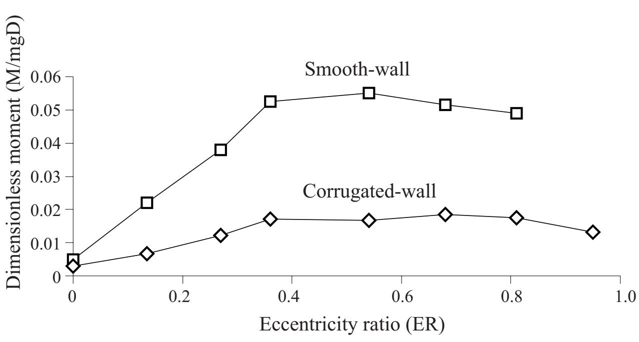

Fig. 5. Dimensionless wall moment for eccentric discharge of the corrugated and smooth wall bin.

slip-stick frictional effects or upward friction force, which were observed in the smooth-wall bin, occurred in corrugated-wall bin. These differences in the mechanical behaviour of smooth-wall and corrugated-wall bins originates in the different frictional behaviour of wheat against smooth and corrugated steel. Friction tests showed a considerable wear-in effect for smooth sheet steel. Wear-in was not observed on corrugated sheet steel.

Plug flow occurred in the test bin at the start of discharge when the bin was filled with grain to a height to diameter (*H/D*) level of 1.5 or greater. For these conditions, the *H/D* level at which flow actually changed from plug to funnel flow was observed in the *H/D* range from of 1.37 to 1.58.

The resultant moments of force created by eccentric discharge showed similar characteristics in both bins with maximum values occurring through an orifice located at an eccentricity ratio of 0.67. The resultant moments for the smooth-wall bin were approximately three times higher than the resultant moments for the corrugated-wall bin.

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