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Assessing a Durability Test for Wood Pellets by Discrete Element Simulation

Dust generation is related to the durability of products, in other words the wear rate of particles subject to forces. During transport, storage and handling the wood pellets are undergoing different forces within different pieces of equipment. For example impact forces when particles fall down or impact geometries and compressive forces when in storage.
The objective of this paper is to assess the representativeness of the so-called tumbling can test in relation to handling conditions in the supply chain for wood pellets. Therefore forces acting on particles in the tumbling can on the one side and during loading and discharging of a flat bottom silo on the other side were compared by Discrete Element Model simulations.
It can be concluded that in the presented cases the tumbling can underestimates the handling conditions of the material in reality.

Keywords: *mechanical durability, biomass, wood pellets, Discrete Element Method, DEM, filling, discharge, tumbling can.*

1. INTRODUCTION

Biomass still remains an upcoming market in Europe driven by targets set by the European Commission. Numerous initiatives are taken to develop and produce new ‘green’ products such as torrefied pellets. While emphasis is on the product development side, the logistic chain concerning the handling and distribution of the products is often left out of consideration. Transport and storage of these products seems not to be an issue. However, looking at recent accidents in solid biomass handling (wood chips and wood pellets) it is clear that focus on the handling is very important from a safety, but also from an optimized handling point of view. In particular with wood pellets (Figure 1) the generation of dust plays an important role throughout handling.

Figure 1 Wood pellets

Dust generation is related to the durability of products, in other words the wear rate of particles subject to forces. During transport, storage and handling the products are undergoing different forces within different pieces of equipment. For example, impact forces when particles fall down or impact geometries and compressive forces when in storage (Figure 2).

Over the years a standard for wood pellets (EN15210 or ISO/NP17831-1 [1]) has been developed to assess the durability of materials amongst others applied to wood pellets, such as a tumbling can (Figure 3). However, it is unlikely that this is representative for the handling in the whole supply chain because real operational conditions can greatly differ in terms of forces from tests on lab-scale. Also, in industry the problem of dust and fines remains despite a standard being in place.

Figure 2 Example of a silo with bottom reclaimer (www.laidig.com)

The objective of this paper is to assess the representativeness of the tumbling can test in relation to the handling steps in the whole supply chain, more specific the loading and bottom discharge of a flat bottomed silo. Therefore, first durability tests will be introduced, whereafter the focus will shift to the tumbling can or rotating drum. Secondly, the numerical approach using Discrete Element Method will be described. This method is chosen as it allows to analyse forces acting on particle level. Both the tumbling can

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and a model that represents operational conditions on an industrial scale are modelled. Subsequently the forces acting on the wood pellet particles during operation will be analysed and compared. Finally, conclusions will be given on the representativity of the tumbling can test within the existing supply chain.

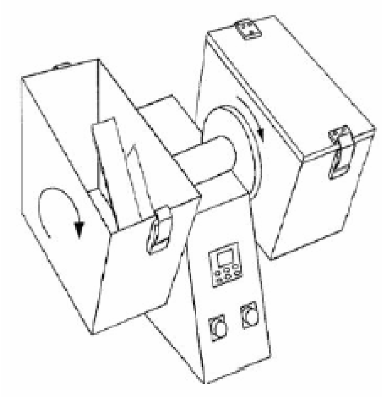

Figure 3 Tumbling can tester for pellet durability test according to EN15210-1

2. Tumbling Can durability tester

The tumbling can (Figure 3) is a test device with which the durability of wood pellets is determined under mechanical handling conditions. Other durability testers, such as the Holmen durability tester and the Ligno tester focus on the pneumatic handling of pellets. These methods use an airstream to transfer and circulate the sample material in a conduit pipe or test chamber. Compared to the tumbling can, both Holmen and Ligno tester operate in a smaller time frame, where the pellets are exposed to higher destructive forces [2]. Nevertheless, according to Temmerman [3] more repeatable and reproducible results are achievable with the tumbling can compared to the Ligno tester.

The tumbling can test is assessed for this research, as it simulates mechanical handling, which is commonly used during the logistics chain [4] and provides repeatable results. The standard ISO/NP17831-1 (equivalent to EN15210) [1] prescribes the measurement procedure: a test portion of 0,5kg of the material is weighted to the nearest 0,1g and placed in the tumbling box. The sample is tumbled at 50 (±2) rpm for 500 rotations, then it is removed and passed through a sieve with round screen holes of 3,15 mm diameter and 40cm diameter for manual screening. The result of the test is the Mechanical Durability derived from the measured number of fines created in the test. These fines are the result of forces acting on the particles as these will lead to degradation and breakage of particles.

In this paper Discrete Element Method software is used to quantify these forces. As a result the forces in the durability tester can be compared to forces acting on pellets during handling.

3. Method

The tumbling can test and the unloading process of a silo with bottom reclaimer were modelled by Discrete Element Method (DEM) to compare the forces acting on the particles in both situations. DEM is a particle based method [5] and allows to study the forces on individual elements. In this work EDEM 2.6.1 was used with the Hertz-Mindlin (no-slip) contact model to calculate the particle-particle and particle-geometry interactions between particles and particles and geometry.

The wood pellets are cylindrical in shape and were modelled as monosized particles of 8 mm in diameter and 15 mm in length by adding three 8mm particles inline (Figure 4). The material characteristics were derived from Wu [6 and implemented in the model as shown in

Table 1. The coefficient of restitution $C_{R,p}$ was determined by a simple drop test.

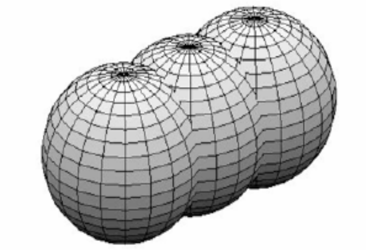

Figure 4 Model of a wood pellet, composed of 3 identical spheres with a diameter D of 8 mm and a length of 15mm.

A single chamber of the tumbling can was modelled according to the standard as a stainless steel box with dimensions of 0.3x0.3x0.125m (Figure 5). Inside the box a stainless steel baffle is mounted to one of the sides with dimensions of 0.23x0.05m.

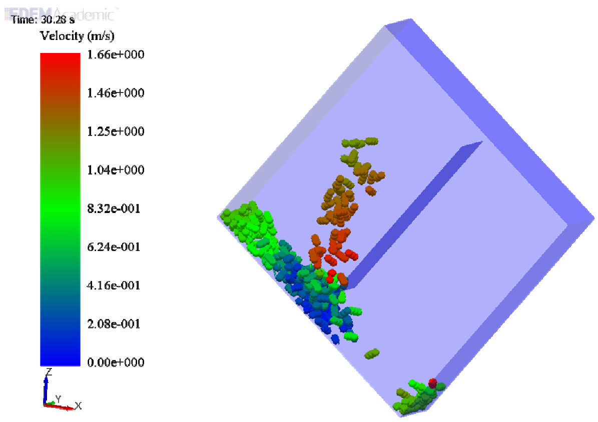

Figure 5 Tumbling can model

Table 1 Simulation settings

Parameter	Value	Parameter	Value
D	8 mm	ρ_w	7800 kg/m^3
L	15 mm	E_w	7e10 Pa
ρ_p	1687 kg/m^3	ν_w	0.3
$\mu_{s,p-p}$	0.93	$C_{R,w}$	0.02
$\mu_{r,p-p}$	0.01	Δt	1.156 e-5 s
$\mu_{s,p-w}$	0.325		
$\mu_{r,p-w}$	0.01		
E_p	1e08 Pa	Silo	
ν_p	0.1	Δt	6.909e-6 s
$C_{R,p}$	0.02	$\mu_{s,p-w}$	0.01

The amount of material (500g) as well as operating conditions (constant rotational speed of 50rpm) were similar to the procedure described in the standard. An excerpt was made to the number of rotations, because initial simulations showed that a steady state was reached after 20 seconds (instead of the 600 seconds prescribed in the standard). The sliding friction between particles and the can (μs,p-w) was calibrated with the data from [6].

The loading (freefall) and discharge process (horizontal extraction process at the bottom) of a silo were modelled in 3 phases (Figure 7):

Filling (1): the material is released into a square column with a wall friction of 0.01 with an initial velocity depending on the silo height. The downward velocity is limited at the terminal velocity for free-fall from 21m with 15m/s [6] and the load rate is 2kg/s. The terminal velocity was calculated by equation (1)

$$v_t = \sqrt{\frac{2mg}{\rho_{air} A C_d}} \quad (1)$$

where m is the mass of the particle, g is the gravitational constant, ρ_{air} is the density of air (here 1.293 kg/m^3 at 20°C and at sealevel), C_d is the dragcoefficient taken as 1.05 similar to [7].

The drop height ranges from 1-21 m and resemles realistic drop heights that occur in the wood pellet supply chain.

The pellet material that will experience the worst case impact loading is the first 500g of material that impacts the concrete floor and fills up the floor cavity. It is this 500g that will be evaluated.

Compaction (2): When the silo is being filled further the pressure on the 500g of pellets at the bottom of the silo builds up. Filling is done first gradually due to the remaining 2.5kg of pellet material, then abruptly between t=2s and t=3s to the maximum static value due to the generation of the heavy 'bulk' particles. Filling is done following the laws of hydrostatic pressure as the wall friction was taken very low. In reality the wall partly takes up the vertical stress according to equation (2) [8], therefore here a load column of 11 m resembles a silo height of 21 meter as can be seen in Figure 6.

$$\sigma_v = \frac{D_{silo}\rho_b g}{4\tan\varphi_w k}\left(1-e^{-(4\tan\varphi_w k/D)H}\right) \quad (2)$$

where D is the silo diameter, ρ_b is the bulk density in kg/m^3, φ_w is the wall friction angle, k is the lateral stress ratio, and H the depth in the silo in m.

Figure 6 presents the vertical stress versus column height for both hydrostatic pressure in a silo situation with D=20m, bulk density of 600 kg/m3, lateral stress ratio of 0.35, wall friction of 45 degrees. From here on hydrostatic pressure height (hp height) will be used to indicate the stress resulting from the load column and acting on the discharge plane. As illustrated in the figure a hp height of 11m represents the stress situation in a silo of 21m height.

Discharging (3): At t=4s, the discharge push floor is activated at a constant speed of 0.5m/s. The pellet material in the floor cavity (0.1x0.1x0.05m) is sheared along the concrete floor and the material column on top, until the cavity is aligned with the discharge cavity and the material exits the model. This is assumed to represent a bottom reclaimer.

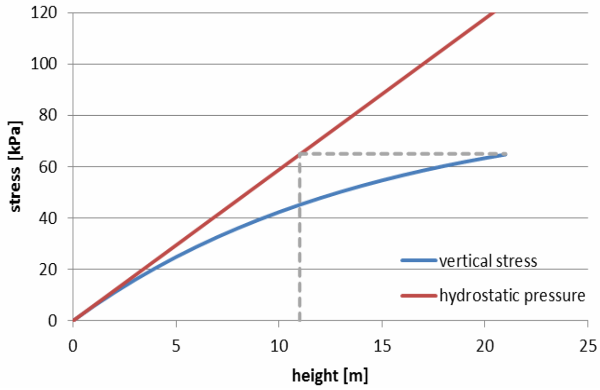

Figure 6 Vertical stress at the bottom of a silo as a function of height

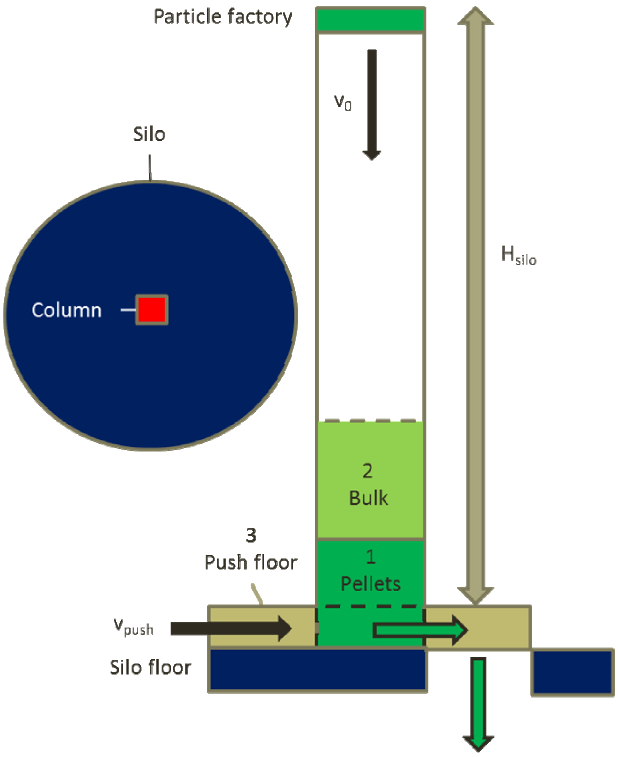

Figure 7 Loading and discharge model

For analysis, the following parameters are used to compare the results of the tumbling can and the silo simulations:

- Impulse (J): Sum of average contact forces times collision duration for all collisions (equation 3), will be used to compare loading of the silos with the condition in the tumbling can.

$$J = \sum_{contacts} \bar{F} \cdot \Delta t_{coll} \quad (3)$$

Where $\bar{F}$ is the average contact force and Δt_{coll} the collision duration. Contacts are the impacts occurring between elements, and are in progress. Collisions are complete impacts. When two particles or elements collide it will register as one collision, regardless of how long the elements stay in contact for [9].

- Maximum contact force values F_{max}, in normal, tangential direction as well as compressive force on particles. This will be used to compare the tumbling can conditions with the discharging conditions of the silo.
- Friction work: Sum of tangential contact force times slide distance for all contacts (equation 4). Also used to compare the conditions in the tumbling can with discharging a flat bottomed silo.

$$W_f = \sum_{contacts} F_t \cdot \Delta s \quad (4)$$

Where F_t is the tangential force and Δs the sliding distance.

4. RESULTS

4.1 Sensitivity analysis

A sensitivity analysis for the drum test has shown that a C_R increase by a factor 10 leads to a significant increase of the average normal forces and the maximum normal forces. This is explained by the decrease of the damping force and thus an increase in resulting normal forces. However, as the focus in this paper is to compare two systems with identical material input properties, this will not be elaborated further here.

Also the particle size distribution was varied, but a significant effect was not found, therefore the results are obtained with the monosized distribution as defined in section 3.

4.2 Filling of the silo: Collision Impulse

The results for the collision impulse show that the collision impulse in the drum test is much lower than in the filling process of silos (Table 2). The results of the 11 and 21 meter drop height are very close because the velocities of the particles are close: 14 and 15m/s respectively. The impact velocity of the 1 meter drop height is around 4-5 m/s.

Table 2 Collision impulse on particles in the tumbling can (500 rotations) compared to loading

Collision impulse J [Ns]	Tumbling can	Drop height		
		1m	11m	21m
Average	26	37	145	153
LB 95% CI	7	36	143	148
UB 95% CI	46	38	146	159

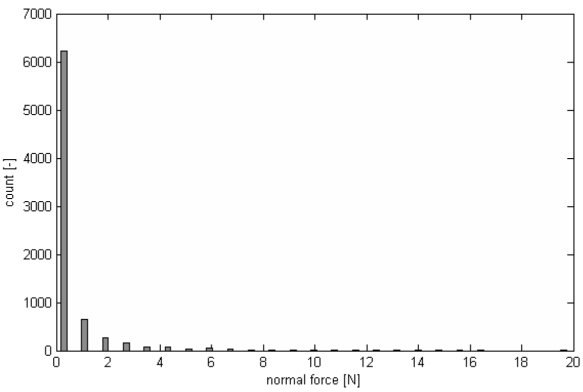

Figure 8 Histogram of normal forces acting on particles in tumbling can (1 rotation)

The histogram of the forces acting on the particles in the tumbling can for 1 rotation (Figure 8) shows that the 99% of the particles are subject to a force of 0-0.5N and 1 single particle accounts for the maximum force of almost 20N.

4.3 Discharge of a silo: Maximum forces

For determining the maximum contact normal and tangential force the 99.9 %tile was considered as to exclude jammed particles which would cause excessive values.

Table 3 Maximum normal, tangential and compressive forces on particles in tumbling can compared to discharge for 3 hydrostatic pressure height conditions (3 repetitions)

Forces [N]	Tumbling can	hp height		
		1m	11m	21m
Max normal	1.81	2.16	33.8	24.6
Max tangential	1.34	0.91	14.9	10.5
Max compress	2.64	74	315	402

During discharge with a material column up to 21 meters on top the contact forces are much higher than in the tumbling can with 500g of material. Also the number of contacts and the contact duration differs greatly as the processes are quite different. In the tumbling can there are approximately 300 particle-particle contacts and 290 particle-wall contacts during 1 rotation, whereas in the cavity a total number of 834 and 199 were observed respectively. As expected the highest contact forces occur in the shear planes.

4.4 Discharge of a silo: Friction Work

Friction work is assessed by summing the friction force times the absolute relative displacement (Δs) of the particle for all contacts (equation 2). The results of the friction work are shown in Table 4.

Table 4 Friction work [Nm] in tumbling can (1 rotation) compared to discharge for 3 hydrostatic pressure height conditions (1 strike)

Friction Work W_f [Nm]	Tumbling can	hp height		
		1m	11m	21m
Average	0.69	3.7	23.4	49.1
LB 95% CI	0.55	2.7	11.1	42.8
UB 95% CI	0.83	4.6	35.7	55.4

To arrive at an average friction work per particle the values from Table 4 are divided by the number of relevant contacts. In the tumbling can all contacts (590) are relevant whereas in the discharge the particles in the shear plane are relevant (199). The average for the tumbling can is then 11e-4Nm and for the discharge 19e-3 to 25e-2Nm. This means that the conditions in the tumbling can extremely underestimate the actual shear condition.

5. DISCUSSION

From the results in the previous section it is clear that the forces acting on the particles in the tumbling can are not representative for the forces acting during loading (large heights) and discharge (flat bottomed silo). For small drop heights such as 1m the confidence intervals for the collision impulse of the tumbling can and the loading situation overlap. Therefore for smaller drop heights the tumbling can might actually be a good representation depending on the developed speed of the falling particles. This requires more detailed investigation.

The particle model used here has rounded ends due to the composition of 3 identical spheres. This is not alike realistic wood pellets with irregular particle ends. It is these particle ends that most likely crumble off, create fines and cause dust. In future research the particle model will be adjusted to a more irregular shape at the particle ends, and further on extended by a model that allows crumbling off. This might also lead to a different force field throughout the tumbling can. Where an increase of forces is expected.

A preliminary sensitivity analysis of the tumbling can has shown that the difference in model output can be significant. It is advised to perform a detailed sensitivity analysis for both the tumbling can and the silo model to assess whether the results can be compared independent of the chosen model values. This has to be done in conjunction with calibrating the material parameters and as such to make sure the material model resembles realistic handling characteristics of the material.

6. CONCLUSION

In this paper the forces acting on wood pellet particles undergoing a tumbling can test were compared with the particles being handled in possible industrial scale handling conditions. This was done by Discrete Element Method simulations.

It can be concluded that in the presented cases the forces acting on particles in the tumbling can underestimate the realistic handling conditions assumed here: filling from large heights (up to 21m) and using a bottom reclaimer to extract material from a filled silo of maximum 21m in height. However, for further detailed comparison further research is required.

This comparative study was the first step in assessing the representativeness of the tumbling can for determining pellet quality throughout the supply chain. In the whole chain many other handling steps can be identified where large impacts or shearforces can take place such as transfer points, chain conveyors, apron plate feeders. These are all worthwhile looking into when a calibrated material model has been developed for wood pellets.

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NOMENCLATURE

C_d	drag coefficient
D	particle diameter
D_{silo}	silo diameter
$C_{R,p}$	coefficient of restitution of the particle
$C_{R,w}$	coefficient of restitution of the wall / geometry
E_p	Young's modulus of the particle
E_w	Young's modulus of the wall
$\overline{F}$	average contact force
F_t	tangential force
g	gravitational constant
H	silo heigth or depth
k	lateral stress ratio
L	particle length
m	mass of particle
v_t	terminal velocity

NOMENCLATURE continued

Greek symbols

Δt	time step
Δt_{coll}	collision duration
φ_w	wall friction angle
$\mu_{s,p\text{-}p}$	sliding friction coefficient between particles
$\mu_{r,p\text{-}p}$	rolling friction coefficient between particles
$\mu_{s,p\text{-}w}$	sliding friction coefficient between particle and wall
$\mu_{r,p\text{-}w}$	rolling friction coefficient between particle and wall
ρ_{air}	air density
ρ_b	bulk density
ρ_p	particle density

ρ_w	wall density or geometry density
σ_v	vertical stress
ν_p	poisson ratio of the particle
ν_w	poisson ratio of the wall

ПРОЦЕНА ТЕСТА ИЗДРЖЉИВОСТИ КОД ДРВЕНОГ ПЕЛЕТА МЕТОДОМ ДИСКРЕТНИХ ЕЛЕМЕНАТА

Д. Л. Шот, Р. Танс, Ј. Дафномилис, В. Ханкок, Г. Лодевијкс

Стварање прашине је повезано са издржљивошћу производа, тј. брзином хабања честица изложених дејству сила. У току транспорта, складиштења и руковања различити делови опреме дејствују различитим силама на дрвени пелет. На пример, ударне силе када честице падају или ударна оптерећења и силе притиска у току складиштења.
Циљ овога рада је процена репрезентативности тзв. испитивања у кутији за тумбање материјала у односу на руковање дрвеним пелетом у ланцу допремања. Силе које дејствују на честице у кутији, с једне стране, и за време пуњења и пражњења равне површине дна силоса, с друге стране, упоређене су применом методе дискретних елемената.
Може се закључити да код приказаних случајева испитивање са кутијом за тумбање недовољно укључујуће реалне услове руковања материјалом.