MODELING FLEXIBLE PACKAGE/GRANULAR MATERIAL INTERACTION THROUGH COMBINATION OF DISCRETE ELEMENT METHOD (DEM) AND FINITE ELEMENT METHOD (FEM)

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Abstract

A variety of applications use flexible film for shipping solid granular materials. The film/packages must have sufficient toughness and/or strength to endure impact during shipping and handling. Package performance is commonly evaluated using a drop test typically from a certain height specified by ASTM and/or ISTA standards. One limitation of the drop test is that it can only qualitatively determine whether a package will survive. In order to better understand impact type loading which can lead to package failure, more quantitative information such as stresses/strains developed during the drop tests is required.

We have developed a model to simulate drop tests of a flexible package containing solid particles. The model utilized some of the capabilities available in Abaqus software package¹, such as Abaqus/Explicit, Finite Element Method (FEM), and Discrete Element Method (DEM) to capture the interaction between the flexible package and a large amount of solid particles inside. Preliminary results compare well with drop tests carried out in our laboratory.

Experiments

Drop tests were conducted using 6.8 kg (15 lb) dog food packages purchased from local supermarket, to gain some basic understanding of package performance. For each test, one bag of pet food was dropped from 1.5 m and the package fell on its bottom side. The package was dropped repeatedly until failure occurred. High speed videos of the drop process were taken and used for comparison with simulation prediction. Tensile samples cut from undamaged areas of the broken packages were sent for tensile testing to obtain the stress-strain curve of the package film.

Figure 2 shows several still photos of the drop test taken from high speed video. After the package hit the floor, it started to bulge as pet food pellets started pushing from inside the package. Meanwhile, the top part of the package shows folding. As package deformation reaches a threshold point (at 25 ms), failure was initialized at a spot on the seam where the two faces of the package join together (red arrow in Figure 2). The failure then propagated along the seam, leading to the final damage of the package.
Figure 2. High speed photos of the drop test.

Figure 3 shows the failure surface of one tested package. The failure origin was close to the base of the package. The failure then propagated along the edge of a seam where the two faces join together. As noted by the red arrows, the failure surface shows the film has been stretched and peeled off along the seam surface, though no extensive stretching was found in the adjacent seal.

Figure 3. (a) Broken pet food package; (b)-(c) Magnified view of region B and region C in (a).

**Model Development**

Although FEA is widely used for structural analysis of continuum solids, it would be impractical to model each pet food pellet with FEA due to extremely high computational cost. DEM provides an ideal solution to model events involving a large number of solid pellets. The model combines both methods so that the interaction between pet food pellets and package film can be taken into account. Figure 4 shows the floor and the package in the model, which are simulated with shell elements. The pet food pellets are simulated with special DEM elements available in Abaqus/Explicit. Each pellet is simulated as a rigid sphere using a single node element located at the sphere center. More details about the DEM technique in Abaqus/Explicit are discussed in a following section.

**Simulation Steps**

A DEM simulation typically begins with one step to settle particles. As shown in Figure 5(a), a collection of pellets are first placed inside the package without causing any overlap among them. Then each pellet starts to fall freely under gravity and interact with other pellets and the package wall (Figure 5(b)). Eventually all particles can find their stable locations, providing an initial package configuration for subsequent analysis, as shown in Figure 5(c).

Given the limited space inside the package, it is difficult to place the required amount of pellets in one settlement step without causing overlap. An alternative solution is to add a second settlement step so that more pellets can be added to bring their total amount close to
that of a real pet food package, as shown in Figure 5(d)-(f).

The pellets settlement steps determine the shape of a filled package and the stable locations of each pellet inside, providing an initial condition to simulate drop tests. The simulation starts from the moment when the package initially makes contact with the floor. The package and the pellets have a predefined initial velocity \(v_0\), which depends on the drop height \(h\) as

\[ v_0 = \sqrt{2gh} \]

where \(g\) is the gravity constant. For a package drop from 1.5 m, its initial velocity \(v_0 = 5.465 \text{ m/s}\). The rigid floor remains fixed throughout the simulation.

**Modeling Pet Food Pellets with DEM**

The DEM technique in Abaqus/Explicit models each individual pellet as a rigid sphere with a specified radius and density. It uses a single node element (element type: PD3D) to represent the sphere center. Despite being a rigid sphere, the compliance of pellets can be indirectly defined by specifying a proper soft contact model between pellets, as well as between pellets and other surfaces.

A typical contact model for DEM elements includes normal and tangential contact. In the tangential direction, a friction coefficient can be defined (0.3 is used here). The normal contact model is represented by a spring and dashpot model shown in Figure 6.

![Figure 6. Contact model between particles in DEM](image)

Contact stiffness \(K\) determines the normal contact force \(F\) as a function of penetration distance \(\delta (\delta = R_1 + R_2 - d)\) as \(F = dF / d\delta\). The Hertz contact model is used in this study\(^3^4\), which calculates the contact force \(F\) as:

\[
F = \frac{4}{3} E^* \sqrt{R} \sqrt{\delta^3}
\]

\[
R = \frac{R_1 R_2}{R_1 + R_2}
\]

\[
\frac{1}{E^*} = \frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2}
\]

where \(E_1\) and \(E_2\), \(\nu_1\) and \(\nu_2\) are the Young’s modulus and Poisson’s ratio, respectively, of the two contacting spheres. In Abaqus/Explicit, the normal contact force between particles can be defined using data tables of contact force versus penetration distance to replicate the Hertz solution.

Damping coefficient \(\eta\) controls kinetic energy loss when particles collide with other objects. The loss of kinetic energy can be quantified using the coefficient of restitution, \(e\), defined as:

\[
e = \frac{V_f}{V_i}
\]

where \(V_i\) and \(V_f\) are the relative velocity at the contact point before and after collision. Coefficient of restitution is related to damping coefficient \(\eta\). For a special case where a particle collides with a flat surface, the coefficient of restitution \(e\) is related to the damping coefficient as follows\(^3^4\):

\[
e = \exp \left[ -\frac{\pi(\eta / \eta_c)}{\sqrt{1 - (\eta / \eta_c)^2}} \right]
\]

where \(\eta_c\) is the critical damping coefficient corresponding to the case where the particle does not rebound, i.e. \(e=0\). For a particle of mass \(m\), it can be derived as \(\eta_c = 2\sqrt{mK}\) using the spring and dashpot model shown in Figure 6. A benchmark study was conducted using DEM in Abaqus/Explicit to calculate the coefficient of restitution for a single sphere colliding with a flat surface. Figure 7 verifies that the damping coefficient \(\eta\) for particle contact actually obeys Equation 5 in Abaqus/Explicit. In this study, the contact damping is defined in terms of the fraction of critical damping \(\eta_c / \eta\).
Given the lack of data for contact stiffness and contact damping of pet food pellets, a parameter study was performed over a wide range of pellet stiffness and contact damping coefficients. Comparison between the prediction and drop tests identifies the optimal parameter values with the closest agreement.

The spherical shape of DEM elements is different from the irregular shape of typical pet food pellets. In the model, the sphere radius is set equal to 5 mm, which is close to the maximum dimension of a pet food pellet. The total number and weight of pellets are also close to that of the 6.8 kg pet food package. The number of pellets added by the two stage settlement is about 25,800, which is close to the amount of pellets inside a 6.8 kg pet food package (~23,000 pellets, based on weight measurement of individual pellets). The intrinsic density of pellets is set equal to 502 kg/m$^3$ so the total pellet weight in the FEA model is about 6.8 kg (15 lb).

**Modeling Flexible Packages with FEM**

The 0.14 mm thick plastic package is modeled with deformable shell elements (element type: S4R and S3R). It is assumed the package film is isotropic and exhibits no strain rate dependence. The film is then modeled as a monolayer using the isotropic, elastic-plastic model in Abaqus/Explicit. Stress-strain data were obtained by testing samples cut from tested pet food packages along their vertical directions. The tests were conducted at loading rate of 25.4 mm/min. In the model, the film has Young’s modulus $E=724.5$ MPa and Poisson ratio $\nu=0.39$. The material model assumes that isotropic hardening begins after yield (10 MPa).

**Results and Discussion**

**Predicted Package Deformation during Test**

This model simulates the drop test of a 6.8 kg pet food package from 1.5 m. It uses stress-strain data from the package film as input for its mechanical properties. The number and weight of pellets are similar to that of a real pet food package. The contact stiffness and contact damping of pellets have been tuned to obtain the best qualitative match between prediction and tests.

Figure 8 and Figure 9 compare the predicted package deformation with the high speed drop test video. It is clear that the model can qualitatively capture the general trend of package deformation after the drop impact fairly well. After the package touches the floor, its lower portion starts to bulge as the pellets inside collide on the package wall and push it outward. Meanwhile, the top edge of the package bends and tends to fold. Consequently, the package develops a pear-like shape as shown by the side view in Figure 9. The model can also capture very detailed features, such as the wrinkles of the deformed package.

Despite the qualitative agreement on the trend of deformation, the predicted deformation still shows some deviations from experiments. The deviation is associated with the fact that the initial package configuration in the simulation, i.e. package shape, pellet shape and pellet volume, is not exactly the same as the real package. This can be attributed to the settling of pellets into the package in the model, as well as the limitation that spherical pellets are used by the DEM in Abaqus/Explicit.

**Development of Stresses during Drop Test**

Figure 10 shows the distribution of von Mises stress in the package. The stresses are normalized by the maximum stress developed after drop impact. Significant stresses start to develop from the base of the package instantly after the impact and propagate upward toward the adjacent material. Several high stress regions are identified along the seams where neighboring faces join
one another. The maximum von Mises stress is located in several spots along the seams (denoted by red arrows). Material in the high stress region exhibits higher risks of yielding and premature failure. The high stresses are associated with localized deformation due to film wrinkling and collision with particles inside the package.

![Stress distribution in package after drop impact.](image)

Figure 10. Stress distribution in package after drop impact.

The drop tests show that the package tends to fail along the seam where neighboring faces join together. This is exactly where the model predicts high stresses should occur. Yielding will first happen to the material along the seam, leading to the initialization of failure.

**Dissipation of Kinetic Energy**

The total kinetic energy of a 6.8 kg pet food package dropped from 1.5 m is about 103 J. As shown in Figure 11(a), the total kinetic energy of the package decreases rapidly following the drop impact. Meanwhile, the flexible package deforms, resulting in an increase in the elastic and plastic strain energy as shown in Figure 11(b). By comparing the strain energy with the initial kinetic energy, only a small portion (<10%) of the kinetic energy is dissipated via the plastic and elastic strain of the package. A majority of the kinetic energy is dissipated by friction and damping between discrete particles.

![Dissipation of kinetic energy](image)

Figure 11. Dissipation of kinetic energy

**Conclusions**

A FEA model has been developed to simulate drop test of a flexible package containing granular material. The model applies Discrete Element Method to simulate solid pellets, which incorporates the interactions between pellets, as well as the contact between pellets and the plastic package, into the finite element structural analysis.

The model was applied to simulate the drop test of 6.8 kg (15 lb) pet food packages from 1.5 m. Validation of the FEA model was done by comparing the predicted package deformation with deformation observed in the drop test. Preliminary FEA results show a good qualitative agreement with drop tests. The predicted package deformation agrees qualitatively with the high speed video of drop tests. The predicted stress distribution agrees with the failure mode observed in drop tests. Stresses first develop from the base of package and then propagate upward. FEA shows high stresses occur in the area close to package base and along the package seam, which coincides with the location of package failure initialization during the tests.

**References**