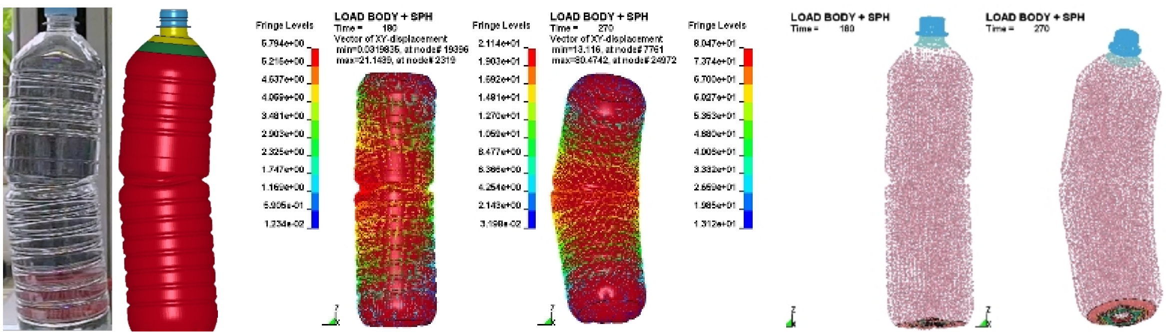
Deformation behaviour of filled and capped PET Bottles in the High-Speed Labeling Machine

Bharat Chittepu, Matthias Hörmann, Ulrich Stelzmann, CADFEM GmbH, Germany
Harald Wels, Thomas Albrecht, KRONES AG, Germany

Summary:

The increasing use of PET bottles has been and continues to be a dramatic growth story in the packaging industry. The adaption of PET bottles for soft drinks, juice drinks, water, food and other products continues to provide exciting packaging opportunities. Increasing use meant increase in demand and the need for saving time in the process chain of the packaging industry. One area where a high speed process is possible is labeling.
In higher output ranges in the labeling technology, PET bottles are subjected to undesirable deformations which in turn might result in bottle losses in the machine carrousel or to a bad placement of the label. Information on this deformation should be available in the earliest possible stage of machine planning, such that the desire to simulate comes into play.
Before simulating such a high speed labeling process, it is necessary to have a reliable filled PET bottle model which is justified to be used in the simulation of the real process. The first step in this approach is to simulate the top load performance of an empty PET bottle and validate the simulation results with experimental results by comparing load and buckling deformation. Sensitivity studies are carried out with respect to material, geometry and Finite Element parameters to obtain an optimized parameter set which ensures a reliable model of the empty PET bottle. This model is then the basis to simulate the top load performance of liquid filled PET bottle.
For the filled PET bottle the right modeling approach to account for the presence of liquid, i.e. water and its associated physics (inertia, compressibility and hydrostatic pressure), must be determined. Control Volume, Smoothed Particle Hydrodynamics and Arbitrary Lagrangian Eulerian approaches are discussed to highlight the benefits and drawbacks of each approach for accurately simulating the top load performance of filled PET bottle. Load-deformation curves and bucking shapes of the top load test are compared with simulation results to justify the usage of a reliable filled PET bottle.
The third and final step is to simulate the high speed labeling process by identifying the right approach to account for the machine kinematics and the inertia effects of the liquid. Added element mass or SPH approach for accounting inertia of the liquid in combination with machine kinematics is investigated in order to identify the most accurate combination for bottle deformation in the labeling process.



Keywords:
Packaging, Buckling, Instability, Sloshing, SPH

1 Introduction

The KRONES group designs, develops, manufactures and installs both machines and complete filling and packaging lines, and also a long-term customer of CADFEM. This article describes an explicit LS-DYNA analysis of the deformation behavior of filled and capped PET bottles in the high speed labeling machine.

The increasing use of PET bottles has been and continues to be a dramatic growth story in the packaging industry. Increasing use meant increase in demand and the need for saving time in the process chain of the packaging industry. One area where a high speed process is possible is labeling. Capable of labeling 67,500 containers per hour, KRONES Contiroll HS (high speed) wrap-around labeling machine (Fig 1) is the trend setter in labeling technology.

Figure 1: KRONES Contiroll Labeling Machine (Courtesy of KRONES AG)

However in higher output ranges in the labeling technology, PET bottles are subjected to undesirable deformations due to its lower Young's Modulus and much thinner walls compared to glass bottles. For a particular machine speed, information on the deformation behavior early during machine planning will be useful. To obtain this detail, LS-DYNA was used for this work.

The sequence of steps carried out is

- Top load simulation & verification of empty PET bottle: To obtain reliable empty PET bottle model
- Top load simulation & verification of filled PET bottle: To obtain reliable filled PET bottle model
- Process simulation of filled PET bottle in the high speed labeling machine: To inspect deformation behavior of PET bottle

2 Quasi-Static Buckling Analysis of Empty Bottle

Prior to the quasi-static buckling analysis, sensitivity studies were carried out with respect to material, geometry and finite element parameters to obtain an optimized parameter set. This set, when used in the quasi-static buckling analysis, yielded a nice fit of the pre- and post-buckling behavior with the test data (Fig 2). This proved the reliability of the optimized parameter set.

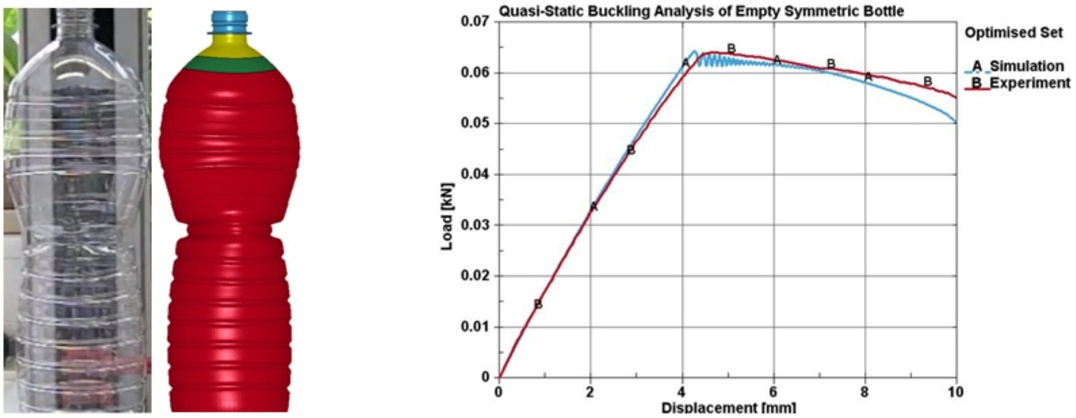


Figure 2: Structural Response of Empty Bottle

The moderate differences observed in the load-displacement curves is mainly due to the usage of simple material model (*MAT_PIECEWISE_LINEAR_PLASTICITY) in LS-DYNA, which does not consider the complex behavior of PET material in reality. Type 16 (fully integrated) shell elements with proper warpage treatment were preferred to Type 2 (reduced integrated) shell elements to avoid non-physical initialization of buckling.

3 Quasi-Static Buckling Analysis of Filled Bottle

Having now obtained a reliable empty bottle, presence of water & air along with its physics (compressibility, inertia and hydrostatic pressure) need to be accounted for a filled bottle. Control Volume (CV), Smoothed Particle Hydrodynamics (SPH) & Arbitrary Lagrangian Eulerian (ALE) methods were evaluated in LS-DYNA for ease of implementation, computation effort, and most importantly, to simulate the liquid physics accurately. Studies performed on these three approaches have shown the following:

- CV approach: Simplest, most accurate and computationally least expensive method to account for the compressibility effect. Since mass of the liquid cannot be modeled with this approach, inertial effects cannot be accounted for.
- SPH approach: Accounts for the inertial effects, but fails to account for the compressibility effect accurately due to non-realistic gap between the walls of the bottle & water (SPH particles). In addition, modeling of both air and water with SPH is infeasible.
- ALE approach: Computationally, the most expensive. Existence of potential leakage problems and extreme sensitivity of a parameter (PFAC) to fluid-structure coupling leads to an unreliable result.

Since fluid compressibility is the most important effect for predicting the correct buckling load in a quasi-static buckling analysis, CV approach is considered for top load simulation of the filled bottle. The initial slope and the buckling load, which are most important for KRONES, fit nicely with the test results (Fig 3). Also the post-buckling shape of the filled bottle from simulation resembles the test (Fig 3). The post-buckling regime is influenced mostly by the missing inertial effects in CV approach.

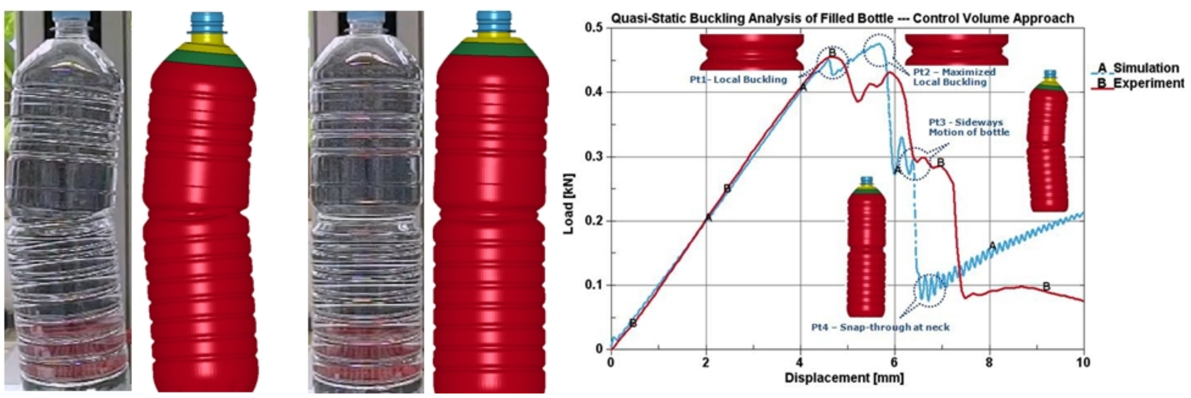


Figure 3: Structural Response of Filled Bottle

4 Process Simulation in Labeling Machine

The goal of the process simulation is not to check for the bottle labeling procedure, but to predict the deformation behavior of the bottle due to the inertial forces (Centrifugal & Coriolis). The bottle experiences these forces due to the two kinds of rotations (with respect to table and with respect to itself) during the labeling process. Since the inertial forces acting on the bottle are governed mainly by the mass of the water, idealization of water with SPH particles was considered for accurately accounting the inertial effects of water. Moreover CV's for both air and water were retained in the model setup (Fig 4) to account accurately for the compressibility effects of air and water respectively.

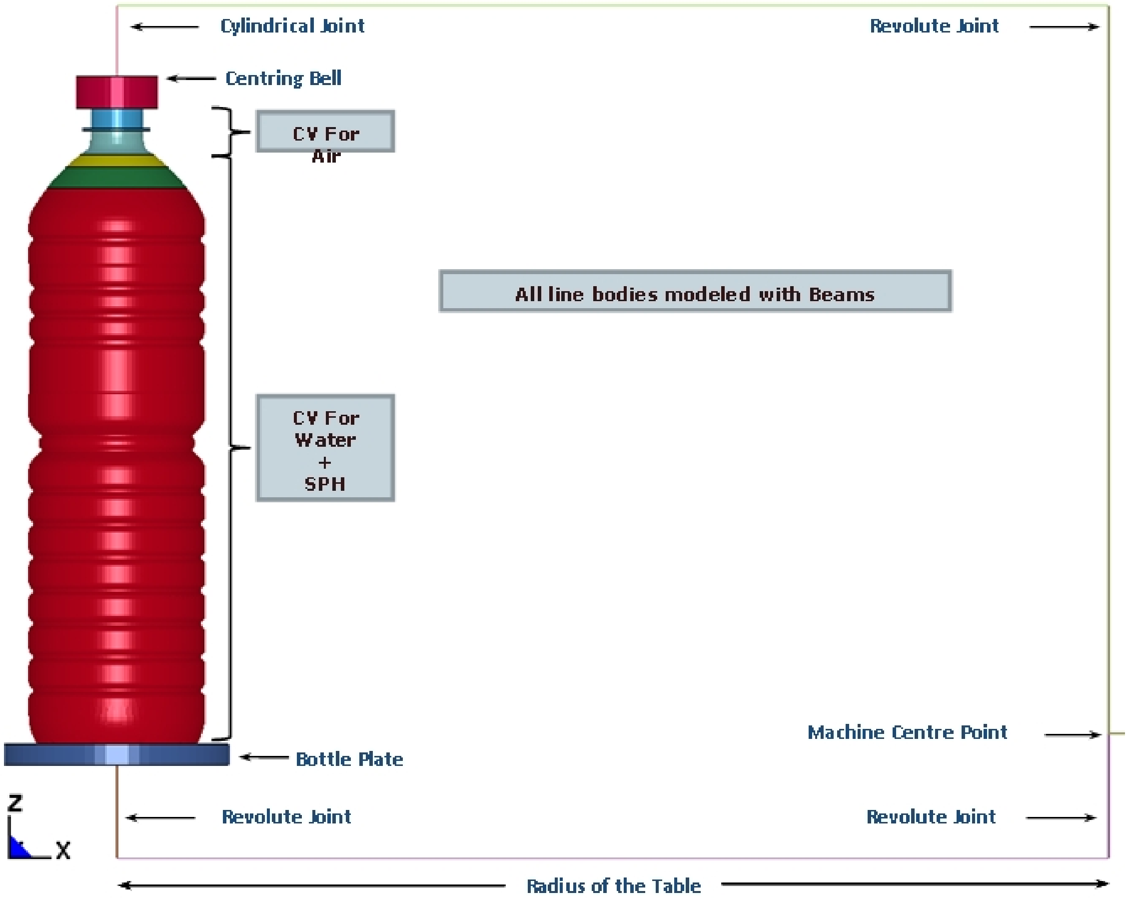


Figure 4: Model setup for process simulation

Concerning the kinematics, or how the two rotations are described, full rotation approach (where the bottle is physical moved as it occurs in reality) and load body approach (where imagining that the observer is sitting on top on the bottle, inertial loads are calculated and applied on a still standing bottle) were evaluated. As in reality, liquid (SPH particles) inside a rotating bottle feels the inertial forces only after a certain amount of time once it also starts rotating, full rotation approach was preferred to load body approach to account for this effect naturally.

As the time taken for a single bottle to undergo such a quick and dynamic process is only 803 ms it was very hard for KRONES to obtain any test data about the deformation behavior of the bottle. However for any machine to be termed reliable it has to fulfil certain requirements and it are these requirements which have served as a means for validating the simulation results. The major requirements which were supposed to be fulfilled and are fulfilled are as follows:

- Bottle not supposed to be thrown out of the labeling machine i.e. machine usage guaranteed.
- Bottle not allowed to buckle at any point of time in the labeling machine i.e. usability of the bottle is guaranteed.
- Allowable lateral deformation (Fig 5) of the bottle for the label to be in put in the proper location is small, i.e. promotion of brand quality guaranteed.

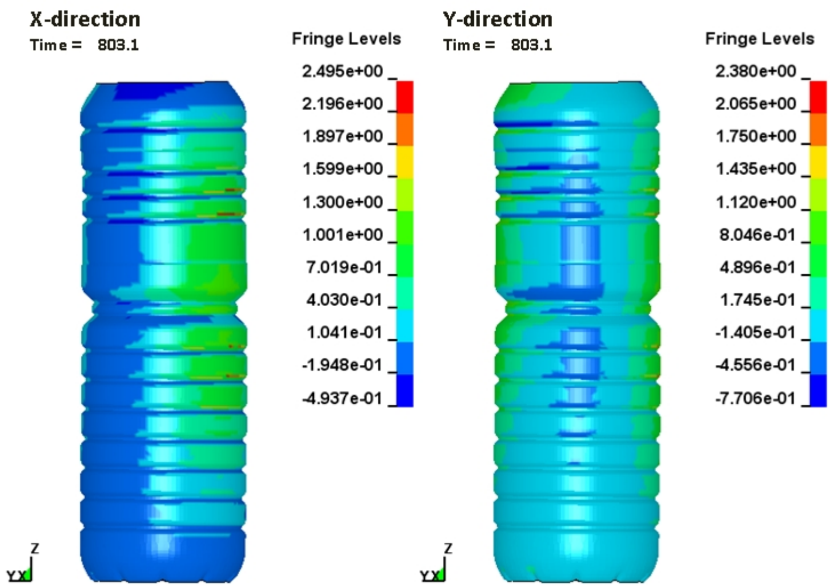


Figure 5: Deformation of the bottle body

In addition, SPH particles represent an inclined free surface of the liquid which is normally expected due to the outward movement of the particles once the bottle starts to rotate with the table (Fig 6).

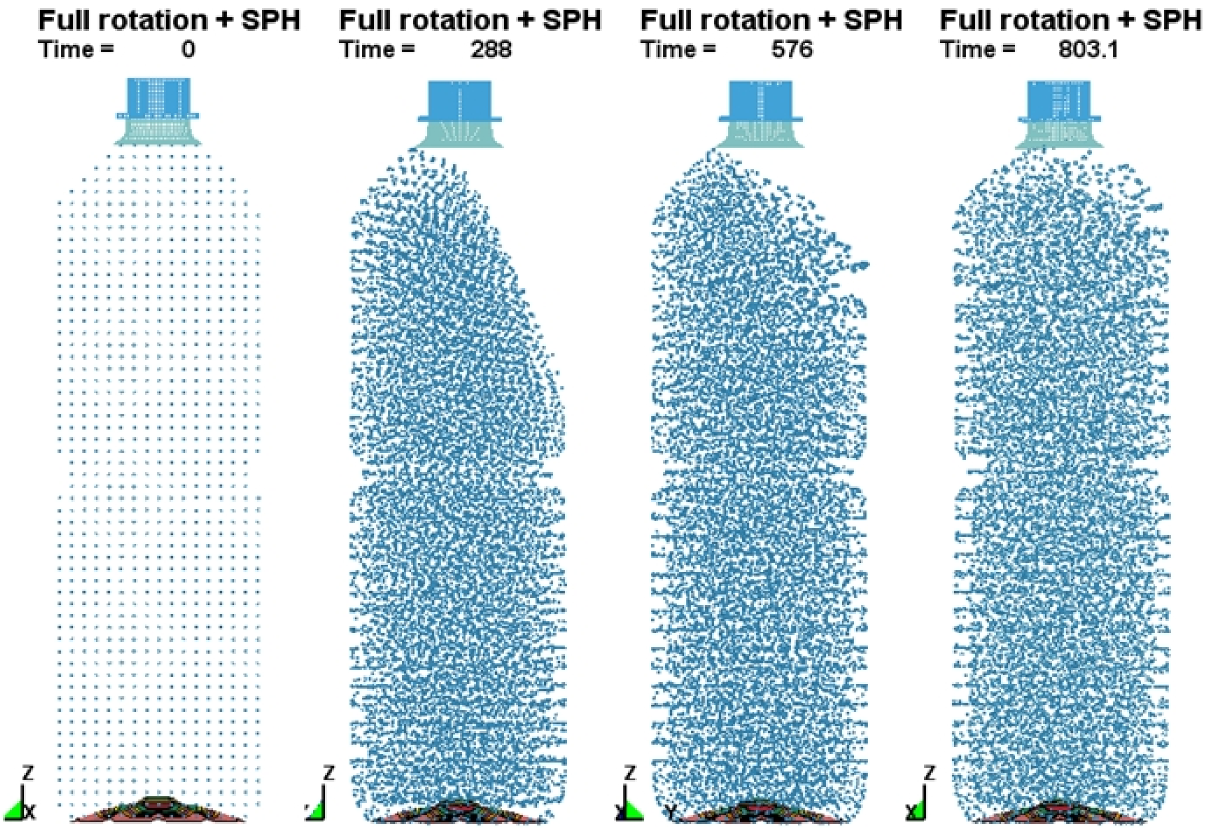


Figure 6: Movement of SPH particles in the bottle (body hidden)