# EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON THE STABILITY OF CYLINDRICAL SHELLS

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**Abstract:** The stability of thin-walled cylindrical shells under axial pressure is investigated. The results of both experiments and numerical simulations are presented. An appropriate finite element model is introduced that accounts not only for geometric imperfections but also for non-linearities. It is found that small geometrical imperfections within a given tolerance range have considerable negative effect on the buckling load compared to perfect geometry. Various post buckling shell shapes are possible, which depend on these imperfections. The experiments and simulations show a very good correlation.

**Keywords:** stability, thin shell, finite element simulation, imperfection

## 1. INTRODUCTION

Aerosol or bevarage cans are shell structures and there are many studies dedicated to such parts. Likewise, article [1] deals with the metallurgy of alloys for beverage cans. New material models, statistical methods and tests are reviewed to support an efficient and economic production. Furthermore, [2] is also mentioned as it demonstrates how suitable the finite element (FE) method is to support the manufacturing and forming process of aluminium cans. Comparisons with experimental results are also provided to confirm the correctness of the findings. Paper [3] focuses on the side wall wrinkling during sheet metal forming. It intends to predict the circumstances of its occurance using the finite element method.

The stability of structures has long been a topic of interest by scientists. A comprehensive summary of the most important results are well gathered and available in books [4-6]. Regarding the buckling behaviour of cans, the finite element method seems to be the most efficient way to tackle the issue. Articles [7-9] detail the circumstances of buckling and the effect of multiple parameters on its occurance and behaviour. Probably the most important circumstance is the presence of geometrical imperfections. During early experiments, a significant fluctuation was found in the critical (buckling) force of cylindrical shells. Koiter [10] was the first to give an acceptable reason: there are minor errors in the visibly perfect geometry which result these fluctuations. Such imperfect structures can generally bear lower loads than perfect ones. Articles [11] by Sawant and Venkatesh and [12] by Hegadekatte and Shi focus on the simulation of the maximum load bearing capabilities of axially loaded beverage aluminium cans, including the effect of existent geometrical imperfections. In article [13] simulations and experimental investigations are provied. The loading is compressive axial force and internal pressure. With the presented non-linear numerical model the aim is to find the circumstances of buckling to

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comply the European Packaging Standard. Paper [14] attempts to find the deflection of cylinders experimentally by means of the Ligtenberg moiré technique. In [15] the structural optimization of two-piece can bottoms is tackled. Comprehensive finite element studies are presented to understand the influence of the design parameters on the buckling strength. Cylindrical food cans under axial loads and instantaneous sealing pressure are investigated in [16] with the Riks method. Efforts are made to find the optimum and maximum sealing pressure. Both numerical and experimental studies of cylindrical steel shells are performed under combined membrane and shear loading in [17]. Account for geometrical imperfections is made. The authors propose new design rules based on their novel findings. Article [18] delivers non-linear studies to focus on the effect of longitudinal dents on the elastic buckling and post-buckling behavior of cylindrical shells. The loading is external pressure. Paper [19] numerically investigates the effect of local fabrication misfitst in a cylindrical shell. Meanwhile, gathers different approaches to predict the stability of composite shells with geometric imperfections. These methods include non-linear and dynamic analyses as well.

In this article, experimental and numerical investigations are presented to find the lowest buckling load of aluminium aerosol cans with their bottom cut. The commercial non-linear finite element software Abaqus CAE 6.13 is used. Our long term goal is to be able to predict – through simulations – the critical (buckling) load of aerosol cans prior to production. Thus, to be capable of choosing the sufficient number of forming steps, the geometry of the forming tools and the support conditions for an economic, effective and reliable manufacturing process.

## 2. EXPERIMENTAL SETUP

There are a lot of factors that have to be considered when tackling the mentioned can problems. These are, for example, the geometry, material and initial stress state. In the current case, the outer diameter of the can is 45 mm, the nominal wall thickness is 0.34 mm and the total height is 120 mm. Although the geometry is visually perfect, according to measurements, there are various shape errors in a given tolerance range as shown in Figure 1. These must not be neglected during modelling [4]. So simplified axisymmetric finite element models can not be used for stability investigations. In Abaqus, first, some eigenshapes are extracted and various combination of these are imposed on the perfect geometry to find the lowest buckling load. Imperfect geometries are generated by superimposing diverse combinations of the scaled displacement field of the eigenshapes on the geometrically perfect can. As per the measurements, the maximum deviation from the nominal diameter always remained within a reasonable +0.02/-0.01 mm tolerence range. The FE model uses 2D thin shell elements and the can geometry is replaced by its mid-surface.

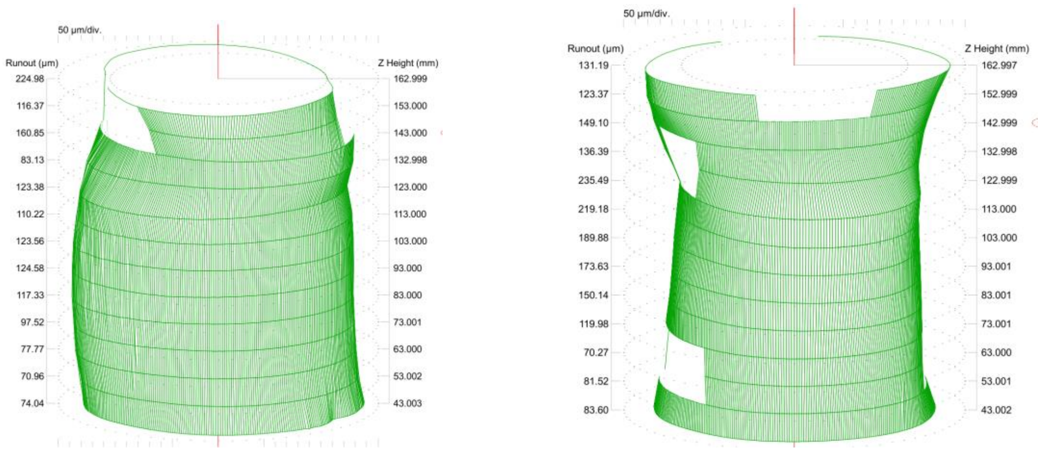


Fig. 1. Some typical (magnified) shape errors.

The material is a standard Al99.5 (EN AW 1050) with a yield stress of 120 MPa. Furthermore, the modulus of Elasticity is 73,000 MPa and the Poisson number is 0.33. The stress-strain characteristic was measured and is shown in Figure 2. There is a linearly elastic and a nonlinearly plastic segment. In Abaqus, an isotropic, linearly elastic and linearly plastic behaviour was assumed. The reason is that, buckling generally begins in the elastic range [18] and the plastic behaviour rather affects the post buckling behaviour. The later one is out of interest now.

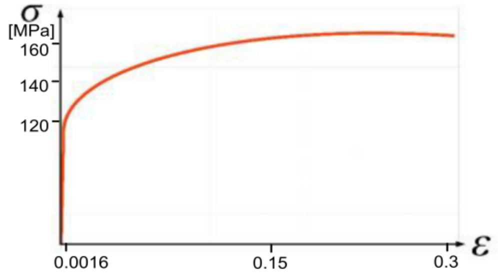


Fig. 2. The stress-strain characteristics of the can material.

Since such cans are drawn from the blank, there are initial stresses. However, the inner and outer surfaces are generally coated, which steps are followed by heat treatment, primarily, to dry the paint. This heat effect makes the cans quasi stress-free according to our findings. Therefore, there is no need to account for initial stresses in the numerical model. During the experiments, cans were placed between two rigid plates in a device as shown in Figure 3. With the ball srews on the sides, the displacement of the upper plate was gradually increased in small, static increments and the load (reaction force) was monitored in the meantime to record illustrative diagrams. A multitude of visually identical cans were tested since all of them has minor but diverse shape errors (as shown in Figure 1) that could influence the experiments. The extreme values of the findings were neglected and the remaining data were averaged with a sufficient confidence from the aspect of production.

For the FE simulations, kinematic constraints were used in the numerical model. At the bottom of the can, nodes were fixed against axial motion, while at the top there was a prescribed displacement. The Abaqus model was geometrically non-linear with large deformations because linear models can erroneously overestimate the buckling loads [3]. The Risk method was used to find the lowest critical load. Various elements and multiple mesh sizes were tested to find converged results.

Fig. 3. The experimental setup.

## 3. RESULTS AND DISCUSSION

The initially perfect geometry - mapped with S4R elements - is shown in Figure 4. Furthermore, some typical eigenshapes are plotted in Figure 5. In these normalized shapes, the maximum (unit) displacement occurs at areas with red colour and the minimum at blue colour. Higher eigenshapes contain more waves than lower ones. These shapes were extracted using the Linear perturbation/Frequency step. Then, non-linear stability investigations were carried out using the Static/Riks step in Abaqus. The related equilibrium paths (reaction force – displacement diagrams) reveal the buckling load (limit point). Perfect and imperfect (perturbed) geometries were also selected and compared with experiments.

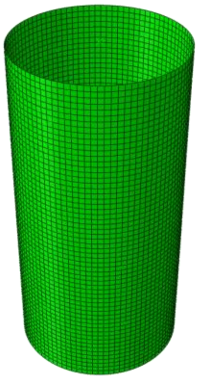

Fig. 4. The meshed initial can geometry.

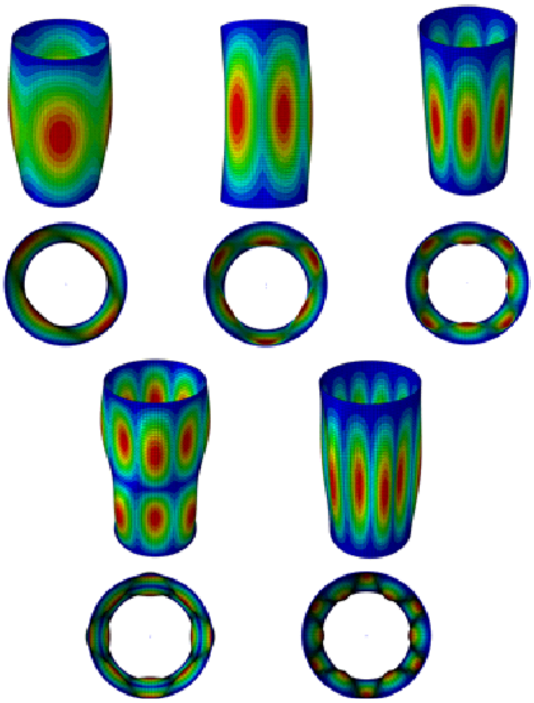

Fig. 5. Some possible eigenshapes of the selected can.

When the perfect geometry was modelled, it showed the best load bearing abilities, i.e., the greatest critical load was obtained then. However, introducing small initial geometric imperfections within the manufacturing tolerance range resulted in the decrease of the maximum load. The typical figures are 6.3 kN for perfect and between 5.3-5.6 kN for imperfect geometries (depending on the used eigenshape combinations). As can be seen, this later critical load only slightly depends on the selected combination of the eigenshapes. As per our expectations, buckling always initiated in the elastic range. Various post buckling can shapes could be obtained via these simulations, which experience is in complete accord with our series of experiments.

The typical load-displacement curves are shown in Figure 6. The correlation between experiments and simulations is found to be very good. The same goes for the related can shapes shown in Figure 7 after 2 mm of prescribed displacement. The colour gradient shows the von Mises stress distribution with red being the greatest. Simulations, in general, overestimated the critical load and underestimated the critical displacement a bit. The difference is not relevant.

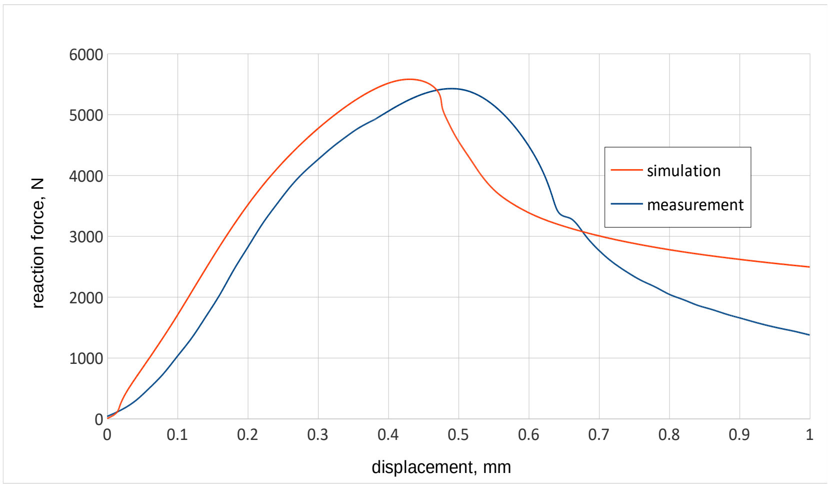


Fig. 6. Reaction force – displacement diagrams.

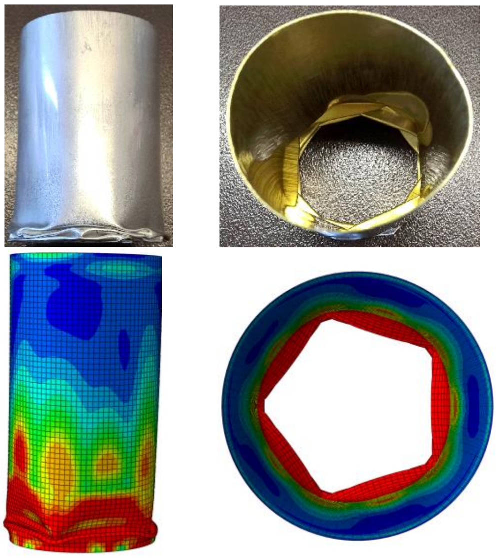

Fig. 7. Possible post buckling geometries: experiment vs simulation.

## 4. CONCLUSIONS

The buckling of thin cylindrical shells was investigated using experiments and numerical simulations. After assessing the most important characteristics of the problem, an appropriate finite element model was created and evaluated. It was found that the existence of geometrical imperfections have considerable effect on the buckling load. Moreover, the imperfection shape combinations only have a slight effect on the buckling load, but more on the post buckling shapes. The experiments and simulations showed a very good correlation.

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