glass WORLDWIDE

FEA studies of impact loads on NNPB refillable bottles

Dr Wenke Hu, William G Slusser and Gary Smay discuss impact load considerations when using NNPB forming technology for refillable beer bottles.

In a previous study, the internal pressure and vertical load performance of refillable bottles was evaluated through computer stress analysis. The evaluation compared the same bottle designs made by both the narrow neck press and blow (NNPB) process and the blow and blow process using two different approaches[1]: (a) The minimum thicknesses were maintained constant, while the maximum and average thicknesses were allowed to fluctuate based on typical maximum to minimum (max-to-min) thickness ratios for the NNPB and the B/B processes; and (b) the average thicknesses were maintained constant, while the minimum and maximum thicknesses were allowed to fluctuate, based on typical max-to-min thickness ratios for the NNPB and the B/B processes.

In the present study, the discussion is extended to include impact forces. The same approach from the previous study was used for four different beer bottle sizes and designs (330ml, 500ml, 650ml and 750ml), as shown in figure 1. The impact stress indices of each design were obtained through finite element analysis (FEA), utilising an Autodesk mechanical simulation programme[2, 3].

In these studies, the physical dimensions of the bottles were maintained constant throughout the analyses. This was done to avoid dimensional changes that would add complexity to the stress analysis. It is understood that keeping the dimensions constant will affect the overflow capacities. For the current bottle designs, these were found to vary by about 3%. While this volume variation would have to be taken into account in actual commercial practice, it did not significantly alter the results of the stress analyses.

CONTAINER FINITE ELEMENT ANALYSIS

Thickness distributions and computer modeling: The max-to-min thickness ratios that were used in this study for the NNPB and B/B processes are shown in table 1. These values are based on numerous measurements of bottles made by the B/B and NNPB processes in unrelated studies. The minimum thickness values for refillable beer bottles were chosen based on the body diameter of the container and the carbonation level of typical beers, as established by worldwide specifications.

A 3D symmetrical model was created using Solidworks for each of the four glass container designs. The outer surface profile was created from information that was provided on technical drawings of these four specific bottles. The glass weights shown in table 2 were calculated on a theoretical basis starting from the minimum thicknesses, while simultaneously considering the max-to-min thickness ratios for each of the two forming processes, along with the two approaches being evaluated in this study.

Impact analysis: For any given impact, three stress modes are generated as shown in figure 2: (a) The contact mode on the outside glass surface at the impact site; (b) the flexure mode on the inside surface, directly opposite of the impact site; and (c) the hinge mode that occurs on the outside surface at a distance away from the impact site[4].

The prediction of these stresses in a container subjected to an impact load is difficult due to the dynamic nature of impact. Fully dynamic analysis requires substantial computational modeling and time. Alternatively, for a low speed impact of just metres per second (velocities typically encountered by glass containers), a quasi-static approach can be accurately used to evaluate the impact stresses, since the duration of an impact is long in comparison to the time period of the fundamental frequencies[2].

A methodology has been developed that permits the prediction of impact stresses by combining finite element analysis with an impact index concept[2]. The impact index can be written as

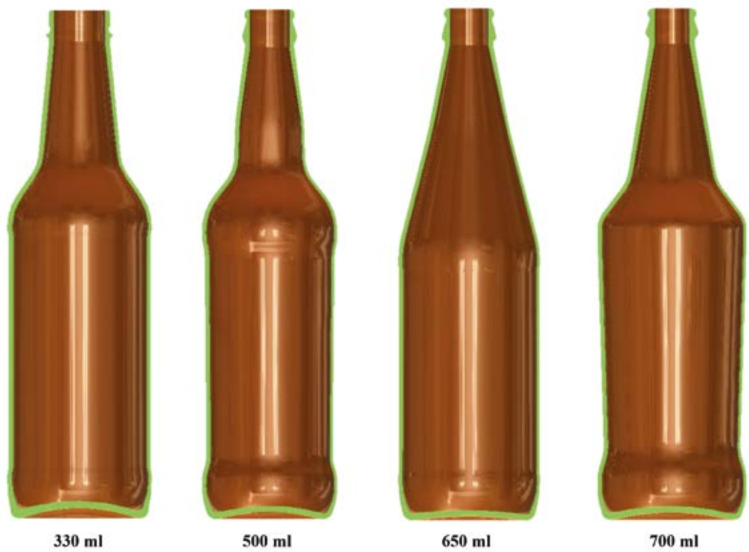

Figure 1: 3D Solidworks model for four different bottle sizes. The green coloured region represents the thickness distribution.

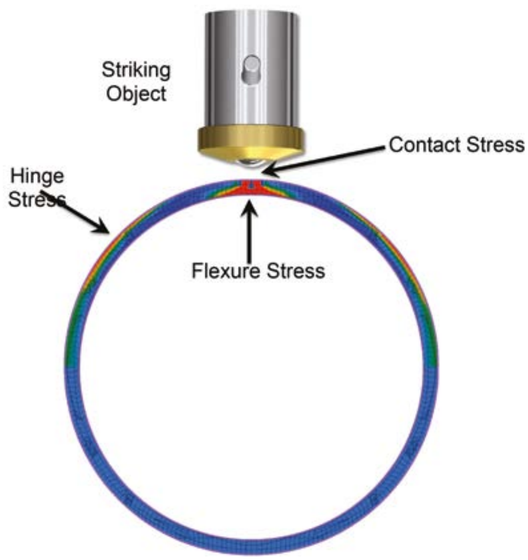

Figure 2: Tensile stresses developed during impact.

$$\frac{\sigma}{V} = \frac{\sigma}{F} \times \frac{F}{V} \quad (1)$$

where σ is the stress, V is the impact velocity and F is the peak force generated during the impact. While σ/F can be obtained directly from finite element analysis, the force index F/V can be written as follows[2,5]:

$$\frac{F}{V} = \sqrt{km} \quad (2)$$

where m is the effective mass and k is the contact stiffness. These values are dependent on the centre of gravity, radius of gyration, bottle dimensions and bottle weight and must be determined for each unique bottle design being considered[5].
Combining equations (1) and (2) results in:

$$\frac{\sigma}{V} = \frac{\sigma}{F} \times \sqrt{km} \quad (3)$$

The use of equation (3) results in an impact stress per unit velocity index that can be used to evaluate container impact performance in a manner similar to the way in which an internal pressure stress index is currently used[2].

In this study, the unit impulse force in the FEA analyses was applied directly to the minimum thickness location at the shoulder and heel contact of the subject bottles. The stresses generated in the model for key regions (such as the contact point, flexure region, in-plane hinge region and shoulder and heel hinge regions) were calculated. The flexure stress occurred on the inside surface, directly opposite of the impact point and the in-plane hinge stress occurred on the outside surface at the same height as the impact point. The maximum hinge stress usually occurred in the upper shoulder region for the shoulder impact, while the maximum hinge stress usually occurred in the lower most heel region, below the contact point for the heel impact. Moreover, bearing surface hinge stresses occurred in the bearing surface region. The stresses in each of these key regions were obtained for each of the four designs and for both manufacturing processes.

	Sidewall region	Bottom region
NNPB	1.50-to-1	1.25-to-1
Blow and Blow	2.00-to-1	1.50-to-1

Table 1: Typical maximum to minimum thickness ratios for the NNPB and the B/B processes.

Bottle Size	Identical Minimum Thickness		Identical Average Thickness	
	NNPB	Blow and Blow	NNPB	Blow and Blow
330 ml	153	177	177	177
500 ml	231	266	266	266
650 ml	261	302	302	302
750 ml	315	366	366	366

Table 2: Calculated glass weights.

RESULTS AND DISCUSSION

The results from the evaluations of the four different bottles produced the same general trends. Consequently, for simplicity of the discussion, only the results from the >

Shoulder Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	3.80	3.76
In-Plane Hinge	0.46	0.44
Maximum Hinge	0.66	0.64
Stiffness x 10^3	6.2 kg_f/cm	6.2 kg_f/cm

Heel Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	4.55	4.50
In-Plane Hinge	0.52	0.49
Maximum Hinge	1.02	1.00
Bearing Surface Hinge	0.50	0.49
Stiffness x 103	6.6 kg_f/cm	6.6 kg_f/cm

Table 3: Impact load stress indices for 330ml bottle with identical minimum thickness.

analyses of the 330ml capacity bottle will be presented here.

Approach No 1 - Identical minimum thicknesses: With identical minimum thicknesses, the resulting glass weights were approximately 14% lighter for bottles made by the NNPB process than for bottles made by the B/B process, as shown in table 2. This weight reduction was expected, since the typical max-to-min thickness ratios were less for the NNPB process compared to the B/B process. Consequently, bottles made by the NNPB process have greater glass thickness uniformity and therefore, less overall weight when the minimum thickness is fixed.

As shown in table 3, the flexure and various hinge impact stress indices, for both shoulder contact and heel contact impact sites, were consistently 1% to 6% higher for bottles made by the NNPB process compared to the B/B process. This increase for the hinge stress is due to the slightly lower glass thicknesses and consequently, more glass compliance in the hinge regions of the bottles. Lack of structural reinforcement also allows for more flexibility at the point of impact and consequently, slightly increased flexure stress. The contact stiffness was similar for bottles from the two processes, since the impacts were directed at the same minimum thicknesses and contact stress is very localised.

Approach No 2 - Identical average thickness: When the average glass thickness was maintained constant, the calculated bottle weight resulting from the use of the NNPB process and the B/B process were identical, as shown in table 2. This was due to the higher minimum glass thicknesses from the NNPB process being essentially offset by the lower maximum glass thickness for the same process. As shown in table 4, the impact stress indices for the NNPB bottles were consistently 4% to 14% lower, compared to the bottles made by the B/B process.

These stress index reductions were due to the higher minimum thicknesses achieved with the NNPB process, which is the result of less thickness variation and improved glass distribution. It should be noted that the contact stiffness increases with the NNPB process due to less bending deformation during the impact associated with the higher minimum thickness. Thus, bottles made by the NNPB process in these considerations of nearly equal bottle weight, would exhibit significantly lower flexure and hinge stresses compared to bottles made by the B/B process. The exception would be the contact stresses, which are associated with the stiffness of the impact site.

CONCLUSION

In this study, both identical minimum thicknesses and identical average thicknesses for NNPB and B/B processes were analysed for shoulder and heel impacts through finite element analysis. It was concluded that:

- When minimum thicknesses were maintained at the same value, bottle weight can be reduced approximately 14% through the use of the NNPB process. This weight reduction can be achieved with only small increases in the impact stress indices.
- When the average thicknesses are held at the same value, impact flexure and hinge stress indices can be significantly decreased through the use of the NNPB process while the bottle weight remains unchanged. Glass stiffness and the resulting contact stresses will be somewhat greater for bottles made by the NNPB process and these values would have to be carefully considered in making any decisions relative to the use of the NNPB process.

Further discussions are planned to include the strength of glass and failure criteria considerations, in order to determine ultimately the effects of the NNPB process on refillable bottle performance. These discussions will be reported in the third and final paper in this series. ■

Shoulder Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	3.55	3.76
In-Plane Hinge	0.38	0.44
Maximum Hinge	0.59	0.64
Stiffness x 10^3	8.0 kg_f/cm	6.2 kg_f/cm

Heel Impact	Stress Indices (MPa/cps)	
Key Bottle Regions	NNPB	Blow and Blow
Flexure	4.30	4.50
In-Plane Hinge	0.45	0.49
Maximum Hinge	0.93	1.00
Bearing Surface Hinge	0.46	0.49
Stiffness x 103	8.9 kg_f/cm	6.6 kg_f/cm

Table 4: Impact load stress indices for 330ml bottle with identical average thickness.

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