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How small is a point load? – A preliminary study of the deformation and failure of cartons subjected to non-uniform loads

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ABSTRACT

Consumer packaging made from carton board is subjected to a variety of loads as it moves through the value chain. Packaging designers need tools for predicting the strength of packages under these loading conditions. For evenly distributed loads, there are methods for measuring and estimating compression resistance that can provide useful guidance. For loads concentrated to a small area, little work has been published. The aim of this preliminary study is to aid the development of a future test method for point loads by investigating how the size of the load application site influences the mechanical behaviour of the package. Rigid spheres of a range of sizes were used to compress packages. Small spheres gave rise primary damage in the form of a vertical yield line and secondary damage in the form of a parabolic yield line. Larger spheres produced a series of parabolic yield lines of increasing size. No vertical yield line appeared for the larger spheres. The larger spheres showed a stiffness transition at a displacement that could be estimated by considering the geometry of the test.

INTRODUCTION

Consumer packaging made from carton board is subjected to a variety of loads as it moves through the value chain; from the producer, via the wholesaler, to the retail store until it finally ends up in the consumer's home. In the earlier stages of distribution, many items of the consumer package are typically handled as a group either in a larger box or on a pallet (transport packaging). In these stages of distribution, loads are evenly distributed and relatively easy to predict. This has led to the development of the box compression test, which is used extensively throughout the packaging industry.

As the packages reach the point of retail, the transport packaging is removed and consumer packages are displayed on shelves or in other similar ways. From this point, the packages enter a realm of less predictable loads. As consumers pick up packages, turn them over, investigate the list of ingredients and place them in shopping carts, they use forces that threaten to damage a poorly designed package.

For the packaging designer, there is a constant trade-off between over-packaging and under-packaging. It is not difficult to design a package that can withstand all of the loads it will be subjected to, but this comes at a cost of material use. Several studies over the last decades have provided good tools for predicting the strength of packages under evenly distributed

loads [1–4] (or see [5] for a comprehensive review). A number of studies on how the strength of corrugated boxes changes when they are stacked in a less optimal way have also been performed, showing reductions in strength up to 50 % for small stacking faults [6, 7]. For other load cases, only a small number of studies have been conducted, e.g. [8, 9].

Ristinmaa et al. [3] noted that predicting damage formation was the key to predicting compression resistance. Therefore, studying damage formation seems like a reasonable first step when trying to understand other loads as well. Previous research has indicated that for concentrated loads, the damage formation starts with a compressive failure in a direction transverse to the applied load [9]. As load application site is allowed to grow, this point load-like behaviour is bound to change at some point.

The aim of this preliminary study is to aid the development of a future test method for point loads by investigating how the size of the load application site influences the mechanical behaviour of the package measured as strength and stiffness. Other testing needed before developing a test method is also surveyed.

MATERIALS AND METHODS

All measurements were performed in a uniaxial testing machine (Lloyd Instruments LR5K). The machine was fitted with a 500 N load cell. Figure 1 shows a schematic of the test setup. The load was applied by a spherical object being pushed towards the package, which rested on a fixed 10 mm aluminium plate. The spherical object moved downward compressing the package with a speed of 60 mm/min. It travelled from -2 mm to 8 mm. Zero was defined as the point where a force of 0.5 N was needed to compress the package.

Force and displacement were measured continuously during the test. The spherical surfaces had radii ranging from 15 mm to 55 mm. All spherical surfaces were stiffer than the packages by more than one order of magnitude. Tests were filmed from two directions, from the front and from the side, for subsequent analysis. Six tests were performed for each combination of radius and inset.

Packages were of the ECMA type A20.20.03.01 [10] manufactured in a commercial converting factory. A cutout sketch with dimensions can be seen in Figure 2. The material was BillerudKorsnäs White 290. Material properties are given in Table 1. The board consists of four plies couched together with clay coating on both sides. The top and bottom plies are 100 % bleached chemical pulp and the middle plies contain a mixture of bleached chemical pulp and bleached CTMP.

Packages were erected four days prior to the first test. During that period, they were stored on one shelf in a cabinet with more than 5 cm of space to all walls. In the middle of the shelf, a climate logger measuring temperature and relative humidity every minute was placed. The climate data shows that the relative humidity has been stable at 39–44 % and temperature at 18–20°C.

Two results, stiffness and strength, were defined and calculated for each test. Stiffness was defined as the greatest slope of load displacement curve during the loading phase. Strength was defined as the force at the first maximum of the force displacement curve, c.f. Figure 3. Defining the results in this way makes it possible to present the data in a more accessible format.

Change of Contact Mode

If a sphere makes contact with the crease, as shown in Figure 4, the standing panel will be compressed directly. While this is geometrically possible for all combinations of radius and offset tested in this study, it is possible that the package will fail before this happens, especially when the radius is small. If the sphere makes contact with the crease, there should be an increase in stiffness since the standing panel is much stiffer than the transverse panel.

Consider Figure 4. The hypothesis states that transition to stiffer behaviour occurs when the ball makes contact with the point A as seen in the figure. Displacement d is counted as the sphere moves from point B to point D. A line from the point A meets the line segment OD in a right angle at the point C. For the right triangle OAC, Pythagoras's theorem gives

$$d - a = R - \sqrt{R^2 - y^2}. \quad (1)$$

The radius R is known for the spheres used in this experiment. The distance y was measured in the video footage for all force-displacement curves showing a stiffness transition and the displacement at transition was noted. With R and y known, $d - a$ was computed. The calculated and the measured displacement at transition were compared.

RESULTS AND DISCUSSION

The results for strength and stiffness in the orientations A and B (see Figure 1) are summarized in Figures 5 and 6, respectively, along with still images from the video of the damage captured during the tests. Package stiffness seems was much more dependent on the radius of the sphere than package strength was. This result is compatible with the hypothesis when using the smallest radii, the package fails before the sphere makes contact with the crease and starts acting on the standing panel directly. The latter deformation mode is much stiffer and hence the stiffness varies a lot. However, the failure modes are similar and hence the strength varies to a smaller degree. There is a general rising trend for both stiffness and strength as the radius increases.

Figure 5 shows results for orientation A. For small spheres ($R \leq 32$ mm), primary damage is a vertical yield line followed by secondary damage in a parabolic shape. For larger spheres, no vertical yield line is observed and a series of parabolic yield lines develop instead.

Figure 6 shows results for orientation B. For indenters with radius 15 mm, primary damage is a vertical yield line followed by secondary damage in a parabolic shape. Note that no secondary damage develops for the two smaller spheres when offset is 10 mm. This behaviour was consistent for all samples of the of the two smallest spheres.

Strength shows relatively small variation with the radius of the sphere (Figures 5 and 6). As the radius increases 3.6 times, the strength only increases about 25 %, from 20–25 N to 25–30 N, depending on load case. It should also be noted that these values are far from the expected box compression resistance of the package, which can be estimated at 161 N and 276 N for orientations A and B respectively using the method described by Ristinmaa et al. [3] and Korin et al. [4]. Since the corner panels carry a large portion of the load in box compression, this is to be expected. For misaligned corrugated boxes, it is common to state the reduction in strength [6, 7] as a percentage of the uniform compression strength. Since the damage in this study is local, it is unlikely that a direct relationship to uniform compression strength exists, cf. [8].

Change of Contact Mode

For the spheres with larger radii, a change of stiffness was observed at some value for the displacement, see Figure 7 for an example. If the hypothesis holds that the transition should occur when the sphere makes contact with the crease and the standing panel is compressed directly, there should be a linear relationship between the theoretical displacement at transition as calculated using Equation 1 and the measured displacement at transition.

In Figure 8 a comparison between the actual displacement at transition and the displacement at transition, $d - a$ in Equation 1, is shown for both orientations A and B.

A linear correlation was found between the calculated and the measured displacement at stiffness transition. The slopes are slightly larger than 1. The reason for this is likely the buckling of the vertical panel, which allows the point A to move downwards. This interpretation is consistent with the fact that the slope for orientation B is greater than the slope for orientation A since the vertical panel is higher for orientation A. The intercept, which should be equal to y , for both orientations is in the region 1–2 mm, which is on the order of three times the board thickness. Micrographs published by Nagasawa et al. [11] show that the region damaged by creasing and subsequent folding is of roughly this size.

Needs for Further Testing

This study has shown the importance of geometric considerations when designing a test method for point loads. It has demonstrated a sensitivity to the geometry that should be taken into consideration. The test should be specified in such a way that the indenting sphere either makes contact with the standing panel or in such a way that it does not make contact with the standing panel. Combinations of radius and offset that make this contact uncertain will be highly sensitive to deviations in the placement of packages leading to unnecessary variability in the results. Another way to solve this problem could be using a different shape of indenter.

A problem with the setup is that the corners of the packages were not perfectly right angles. This meant that the actual offset from the crease was slightly different than the nominal. To alleviate this, the offset y was measured for each sample individually from the video footage. In the future, a solution could be to erect packages in a standardized way and to attach the package's back face to a vertical support.

There is a need for performing more tests. While this study has demonstrated the method, it remains to try the method on other dimensions and shapes of packages. It would be a good idea to test packages that have glued top and bottom making them immune to shearing that was a problem in this case. It would also be interesting to test packages at other locations x

along the length of the package to know if the behaviour changes as we get close to the corners of the package.

CONCLUSIONS

These results show the importance of geometry when designing a test method for point loads. It is clear that, for the package tested here, an important factor in deciding the mechanical behaviour is whether or not the indenter makes contact with the crease. This stiffens the behaviour considerably. However, the strength of the package was not as clearly affected by this change in contact mode.

If the collapse load is reached before the sphere touches the crease, primary damage in the form of a vertical yield line is produced and followed by secondary damage in the form of a parabolic yield line. This behaviour is the same as reported previously [9]. Larger spheres, on the other hand, produce a series of parabolic yield lines of increasing size. No vertical yield line appears with the larger spheres. For intermediate sized spheres, there is a transition zone where the behaviour is sensitive to variations in package and experimental conditions.

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Table 1. Material specification according to manufacturer.

Property	Value
Trademark	Thermoplastic
Bending Resistance MD 15°	Polypropylene
Bending Resistance CD 15°	Aluminium alloy
SCT MD	Polypropylene
SCT CD	Aluminium alloy
Thickness	425 μm
Grammage	290 g/m^2

Figure 1. Schematic of experimental setup. The distance x was 55 mm for all experiments carried out. For the inset y , 5 mm and 10 mm were used.

Figure 2. Cutout sketch of the studied package, A20.20.03.01. Measurements were $A = 78$ mm, $B = 50$ mm, $H = 110$ mm, and $F = 32$ mm.

Figure 5. Results for orientation A. Photos of the typical damage in the different loading conditions (left). Stiffness and strength measured under the different loading conditions (right). Every point is the average of six measurements. Error bars show ± 1 standard deviation.

Figure 6. Results for orientation B. Photos of the typical damage in the different loading conditions (left). Stiffness and strength measured under the different loading conditions (right). Every point is the average of six measurements. Error bars show ± 1 standard deviation.

Figure 7. A stiffness transition, an abrupt change in slope of the load–displacement curve, was observed for some tests.

Figure 8. Comparison between computed displacement at stiffness transition and measured displacement at stiffness transition.