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Measurement and Analysis of Deformation Shapes on Corrugated Cardboard Logistical Boxes under Static and Dynamic Compression

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Abstract: On the field of compression strength of packaging the researchers, studies and standards mainly focus on the short-time measurements. The derived results from these accelerated tests can be used with a large tolerance in reality. These measurements do not give response that how long the packaging is able to tolerate the given calculated or measured stress during a long-term storage in the supply chain without damages in the aspect of product or packaging. The tests in this paper were done to analyse the possible deformation shapes, which could be a first step into the process of final damage. The samples were tested under both static and dynamic compression. The deformations were observed by TRITOP system in order to prove the different deformation processes between the static and dynamic compression. This paper is a first phase of a research program, which deals with the effect of real compression and physical environment of logistics boxes on long time storage and stacking.

Keywords: packaging, compression test, TRITOP

1. Introduction

Tests of various international standards (FEFCO, ISO, ASTM, TAPPI) use only short-time measurements to assess the compression strength of packaging materials made of corrugated cardboard sheet (HPL) and this is partly when they have contents during the time of the measurement [1][2][3][4]. Historically, HPL industry has established the nature and scope of compression strength measurements. Experts believe that the measurement results derived from BCT (Box Compression Test) allow them to evaluate the compressive behaviour of the boxes. Compression strength measurements were mainly developed for quality control purposes. Furthermore, large production volumes do not allow any of the test methods to be applied for a relatively long duration.

Some previous studies dealing with the mechanical behaviours of these packaging structures under static compression [5][6][7], and some other papers show results and brief reviews of designing and modelling the stack-ability of cardboard boxes using finite element method (FEM) [8][9]. However, deformation images and shapes occurring during quasi-dynamic laboratory testing and static load have not been dealt with so far. This paper is aimed to examine deformation events occurring through static load and deformation events occurring during laboratory measurement, and then compare them. These kind of quasi-dynamic and static tests are usually applied to observe the cushioning and strength effect of other packaging materials [10][11] such as plastic foams. The results of these tests are applied as input data to decision support models and processes to choose the right protective packaging system [12]. However, it is well known that the long time distribution environment and storage can affect the real strength of the packaging especially the corrugated paper box packaging [13].

This study begun with the conduction of traditional BCT tests, and box sidewalls were inspected for deformations. Load was then gradually reduced on the packaging material all the way until the packaging material had the ability to carry the static load for at least 1 hour. This method was also used to analyse the deformation processes of the sidewalls under static load.

During the tests, a press recognised in the standards was used for the analysis of the deformation images, and also a system called TRITOP. Type and quality of the corrugated cardboard box used is FEFCO 0201 - 26C. The main flutes are composed of 175KL (Kraftliner), 150HP (semi-chemical fluting) and 200TL1 (Testliner 1) with a weight of 597 g/m2. Box dimensions were 600 mm x 400 mm x 300 mm (L x W x H).

Tests and results presented in this paper constitute the first stage of a research that will eventually focus on the more accurate estimation of static compressive strength of corrugated cardboard boxes as a function of load and compressive resistance. The research may be able to answer the question of how much the results of the methods used in laboratory practice are suitable for the evaluation of actual compression strength.

2. Measurement system and setup

The deformation processes were analysed with the mentioned TRITOP system above. This measurement system is an industrial optical measurement system for three-dimensional acquisition of discrete object points. While in operation, the instrument marks every essential object point and employs a photogrammetric camera to capture images about the object, and then it records the measurement from various angles. Subsequently, the instrument software automatically calculates the three-dimensional coordinates and physical properties of the markers using the digital images.

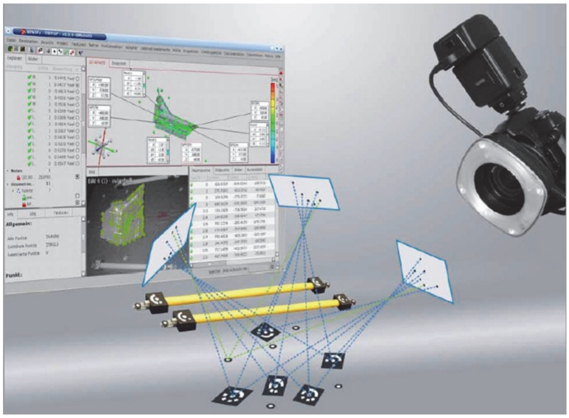

Figure 1 – Structure of the TRITOP system

The basic idea of measuring light intensity is that it views points from multiple directions and uses light rays to calculate the three-dimensional coordinates. The reference points shown in the figure below must be fixed relative to each other. Consequently, camera position relative to the reference points can be calculated for each specific case using images captured from various angles. During the acquisition of the image set, the aim is to record reference points from several angles of view so that they can show one another the largest possible angle. This is demonstrated in Fig. 2.

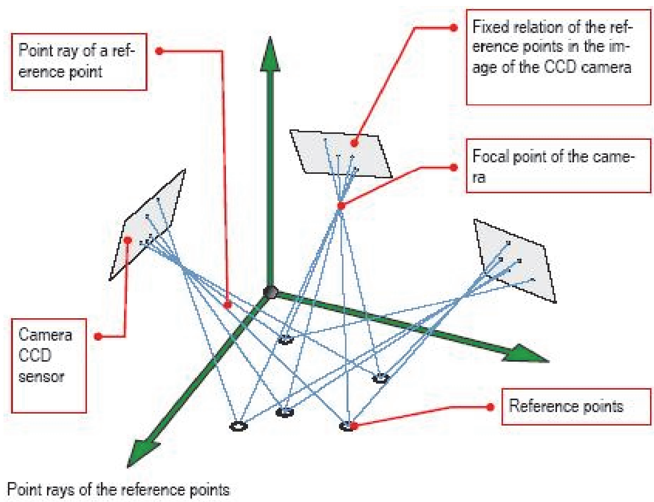

Figure 2 – Spatial operating principles of the TRITOP system

The legends, shown in the figure, have the following meaning:

Point ray of a reference point:	Point ray of a reference point
Camera CCD sensor:	Camera CCD sensor

Fixed relation of the reference points in the image of the CCD camera

	Fixed relation of the reference points in the image of the CCD camera
Focal points of the camera:	Focal points of the camera
Reference points:	Reference points

The main goal of the software is to accurately locate omissions and gaps (a bird's-eye view of the reference points) in each image within the image set and in 3D directions of the image. Measurement data can be evaluated in the TRITOP system (CAD comparison). The coded reference points of TRITOP allow the setting of an image that evaluates and automatically calculates the locations of the camera. When capturing an image, the aim is to see as many reference points as possible and preferably reach beyond the entire object so as to obtain an accurate measurement.

Figure 3 – ID marks of the uncoded points of the TRITOP system

The orientation crosses are factory-equipped with coded points. Uncoded reference points (Fig. 3.) are used to determine the 3D coordinates and are identified automatically by the instrument. If the uncoded reference points are positioned on the object, the measurement method determines the location of these points. For determining the dimensions reference is provided by scale bars (Fig. 4). The software package of the system then also allows you to determine how much each single point has migrated from their original location in the X:Y:Z coordinates. The extent of how much each single point has migrated from its original location can be determined with an accuracy of 1/1000th of a millimetre.

Figure 4 - Scale bars of the system

3. Measurement and observation method

The following measurement programme was devised for observing the deformation processes:

- 25 boxes of identical corrugated cardboard material and identical geometric size were selected and kept under identical climatic conditions.
- 5 boxes were measured for standard BCT values.
- 5 boxes loaded into the press based on the BCT value were provided with the markers of the TRITOP system and subjected to load with quasi-permanent feed until the boxes collapsed. But since the TRITOP system operates on the principle of imaging, we stopped increasing load while the pictures were being taken. Load was set so as to increase compression force with 50N increments using constant feed rate, then feeding was stopped, the images regarding compression were taken (an approximately 5-minute period of time), then load was again increased with the standard feed rate of 50N, feeding was stopped, images were taken and this process continued until the box got completely damaged.
- Based on the BCT value, 5 boxes were respectively loaded with an evenly distributed static compression that equals 80%, 70% and 60% of the BCT value and the TRITOP system was used to take pictures every 24 hours for deformation analysis. Naturally, the box was kept under the same climatic conditions during static compression.
- Under static compression, TRITOP images were only evaluated for boxes, which were able to withstand static compression for at least 1 hour.

The measurement results were compared with and evaluated against deformation images captured during the test. During the evaluation of the deformation images, it was determined from within the inside of the box whether the deformation appeared concave or convex for each side.

4. Results and discussion

The original BCT value of the box was measured at 1340N on average. During static testing, the box was able to resist loading for longer than 1 hour if the compression was as low as 80 kg – any higher compression caused the box being tested to collapse right away. The measurement results are shown in Table 1.

Table 1. The measured BCT values and the period to collapse during static testing besides varied BCT load

	BCT (N)	***Static 80% BCT***		***Static 70% BCT***		***Static 60% BCT***	
S.	***Measured values***	***Time to collapse (min, hour)***					
1	1 360	< 1 min	-	< 1 min	-	> 1 hour	✔
2	1 320	< 1 min	-	< 1 hour	-	> 1 hour	✔
3	1 240	< 1 min	-	< 1 min	-	> 1 hour	✔
4	1 390	< 1 min	-	< 1 hour	-	> 1 hour	✔
5	1 310	< 1 min	-	< 1 min	-	> 1 hour	✔

Deformation under 80 kg of compression within the first 24 hours and deformation produced on the last day of compression (day 18) is presented in Fig. 5a and Fig. 5b respectively. Intermediate states are not published for considerations of space.

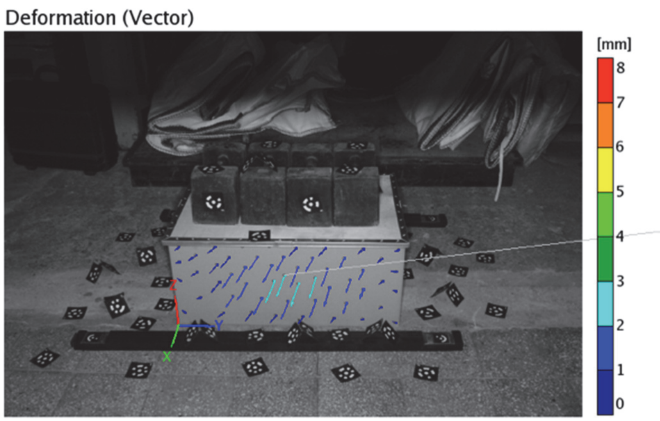

Figure 5a – Deformations occurring as a result of 800N static load after the first 24 hours of measurement

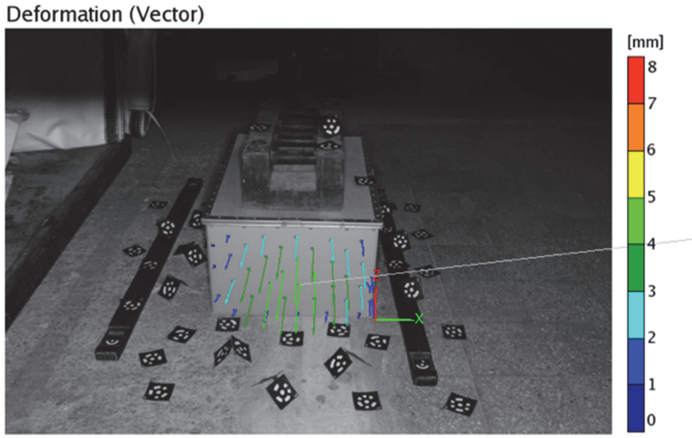

Figure 5b – Deformation occurring as a result of 800N static load after 18 days

Deformation occurring at a load of 1200N during quasi-standard BCT testing is shown in Fig. 6a and 6b. As the reduction of the feed rate reduces the peak load of BCT measurement to a significant extent, this phenomenon occurred here as well, and the box cracked under a load of 1250N.

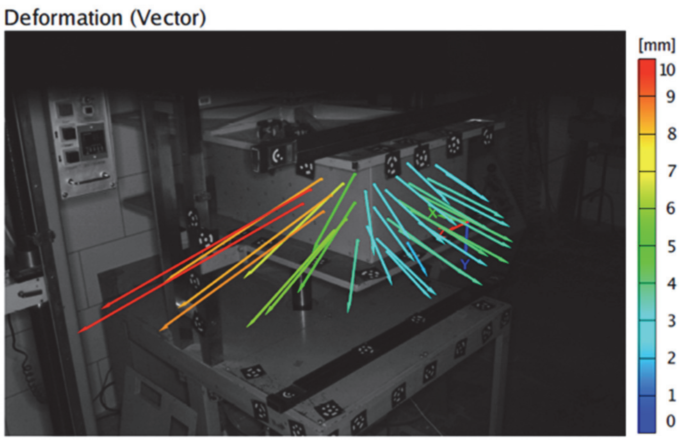

Figure 6a – Deformation occurring at a load of 1200N during quasi BCT testing (left side)

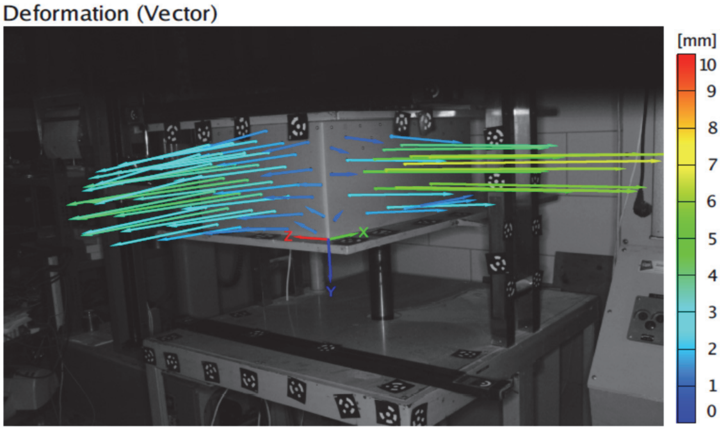

Figure 6b. – Deformation occurring at a load of 1200N during quasi BCT testing (right side)

Table 2 shows the shape of deformation of each sidewall of the boxes under static and quasi-dynamic loads. Deformation is characterised by either a convex or a concave shape depending on whether the deformation of the sidewall is evaluated from inside the boxes. The results show that it was only in a total of 3 cases that the deformation of a sidewall was concave out of the 20 sidewalls of the five samples. However, in the case of quasi-dynamic measurements, each pair of the opposing walls almost always suffered concave deformation viewed from the inside.

Table 2. Shape of deformation during the tests

Sample number			Quasi dynamic	Static
1	Short sides	left / right	convex / convex	convex / convex
	Long sides	left / right	concave / concave	convex / convex
2	Short sides	left / right	convex / concave	convex / convex
	Long sides	left / right	convex / convex	convex / concave
3	Short sides	left / right	concave / convex	convex / concave
	Long sides	left / right	concave / concave	convex / convex
4	Short sides	left / right	convex / concave	concave / convex
	Long sides	left / right	concave / concave	convex / convex
5	Short sides	left / right	concave / concave	convex / convex
	Long sides	left / right	convex / convex	convex / convex

5. Conclusion

The measurements described above verify the following:

- There is a significant difference between the deformation images of BCT measurements and static load measurements. The two measurements are not considered compatible with each other.

- The deformation images of the BCT value measured in laboratory practice are not in accordance with the deformation images of the boxes captured in real life circumstances.
- The two different measurement methods show significantly varying skews with the alternating side walls bending in both convex and concave direction seen from the inside in the case of BCT, and with each side wall bending in convex direction seen from the inside in the case of static load.
- The results of this study can be adapted to determine the possible damages under a real storage period, thereby to reduce the protective packaging costs, and also to provide more sustainable solutions.

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