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Investigating the Influence of Container Design and a Bulge Reduction Technique in Corrugated Fiberboard Containers under Static Compression

Jay Singh * and Koushik Saha **

Abstract

This study explored the bulge effect in corrugated fiberboard boxes caused by excessive weight, leading to compromised stacking strength and potential product damage. It investigated how container design, specifically the height variations of regular slotted containers (RSCs), affects bulging under compression and its vulnerability to environmental conditions. Testing met ASTM standards, with samples conditioned according to ASTM and TAPPI protocols, revealing that changes in box height influence bulge displacement. Subsequent research examined the impact of top-to-bottom static compression loads on bulging in tape-reinforced RSC designs, evaluating bulge reduction and compression strength across various tape placements and environments. Notably, previous studies had not explored the effect of reinforcement tape on bulging reduction. Using specialized equipment, 120 samples representing five container designs with different tape placements were tested. Statistical analysis affirmed that reinforcement tape notably reduces out-of-plane displacement of container panels under ambient conditions, although its effectiveness diminishes under higher humidity. Evaluation of compression strength did not exhibit a clear pattern concerning tape presence under ambient conditions. These findings provide valuable insights for packaging engineers aiming to optimize corrugated fiberboard containers, stressing the importance of considering both container design and environmental factors to reduce material usage while improving stacking strength and rigidity.

Keywords: Bulge effect, Corrugated fiberboard, Stacking strength, Container design, Regular slotted containers (RSCs), Reinforcement tape, Compression strength

1. Introduction

The transportation of packaged products involves numerous risks, including damage from physical, chemical, microbiological, and climatic sources. Protecting products during transportation requires containers that offer adequate protection, with attention often given to compression and shock performance, but limited research has focused on bulging performance. Bulging occurs when containers experience material fatigue due to prolonged stacking, potentially damaging the product inside. Environmental factors, such as humidity, further complicate this issue by weakening paper-based materials. While increasing product headspace may reduce compressive force damage, it could destabilize pallet loads and decrease shipping efficiency [1]. RSCs made of C-flute single-wall corrugated fiberboard are common in the packaging industry, making their performance optimization crucial. Corrugated fiberboard containers have become the dominant form of transport packaging since their introduction in the late 19th century, with the global industry generating substantial revenue [2].

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Deformation-related damage, including creasing, crushing, and bulging, is common in corrugated fiberboard containers. Bulging, a deformation caused by compressive forces during stacking or internal product forces, compromises container integrity. As part of unit loads stacked on pallets, corrugated fiberboard containers often experience outward deformation, destabilizing pallet loads and affecting geometric dimensions [1]. However, no specific studies have addressed the bulging characteristics of these containers. While standardized tests evaluate compression strength, impact resistance, and vibration challenges, they do not adequately address bulging issues. The Rail Committee on Information Standards distinguishes between compression bulge and filling bulge (Figure 1), which respectively refer to expansion due to external downward pressure or filling processes [3].

The Grocery Manufacturers Association (GMA) pallet, with standardized dimensions of 101.60 cm x 121.92 cm, is widely used in distribution, while corrugated fiberboard boxes adhere to a Corrugated Common Footprint (CCF) established by The Fibre Box Association, allowing either five or ten boxes to fit on a standard GMA pallet without overhang or under-hang, known respectively as "5-Down" and "10-Down" container dimensions (Figure 2) [4] [5].

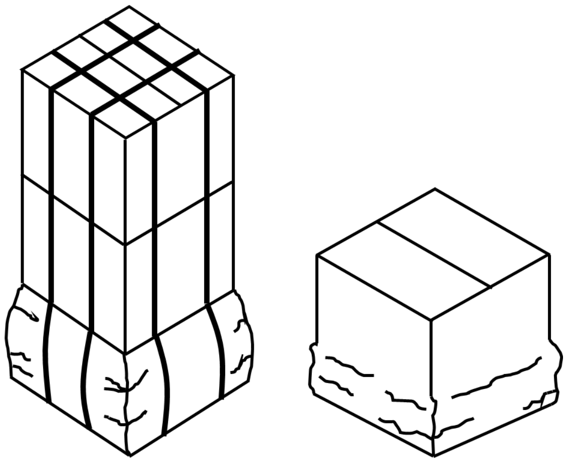

Fig. 1. Compression Bulge (left) and Filling Bulge (right) [3]

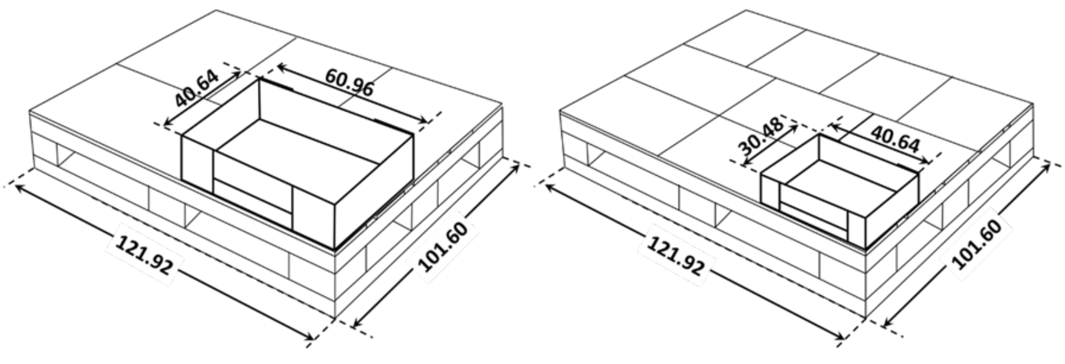

Fig. 2. Full/5-down (left) and Half/10-down (right) CCF Containers (dimensions in cm).

The bulge effect in container packaging occurs when loose content inside exerts pressure, displacing container panels from their original plane. This effect can be mitigated by increasing the bending stiffness of corrugated fiberboard, achieved through factors like linerboard grade, flute size, and box dimensions. Larger flute sizes increase stiffness but also raise material costs. Reducing overall box dimensions enhances rigidity, though maintaining sufficient size for the product is essential. Bulge effect is reduced along the direction of flutes due to their shape. Moisture content from the environment or product can decrease bending stiffness by breaking cellulose fiber bonds. Compression bulging from external downward loads can occur during distribution, simulated in labs using compression testing machines. Initial bulge happens during and immediately after filling due to internal pressure, categorized as time dependent. Compression strength, determined by McKee formula or lab testing, is crucial for withstanding static and dynamic compression in distribution. Stacking strength considers distribution hazards and environmental factors but is lower than compression strength. Factors affecting stacking strength include stacking duration, pattern, humidity, and handling.

This report summarizes the findings of two investigations conducted by the authors. The first study examined how altering the height of a fiberboard container affects its bulging performance under compression in different environmental conditions, with testing conforming to ASTM standards. The second study analyzed the effect of top-to-bottom static compression load on the bulging of RSCs, comparing standard RSCs made of corrugated fiberboard to tape-reinforced designs and assessing bulge reduction through various tape placements and conditioning environments.

2. Study I: Impact of Fiberboard Container Design on Compression Bulge Displacement

2.1 Materials and Methods

2.1.1 Containers

To investigate the correlation between bulging performance affected by compression and fiberboard container design, RSCs conforming to the common footprints (Figure 2) were built. These containers were constructed using single-wall C-flute corrugated fiberboard with a basis weight of 205/112/205 g/m^2, an ECT value of 7.36 ± 0.18 kN/m and burst strength of 0.98 ± 0.32 kgf/ cm^2.

The six design parameters included two footprint options, 5-Down and 10-Down, with heights of 241.3 mm, 292.1 mm, and 342.9 mm for both footprints. To simulate a flowable product as a worst-case scenario, each container was filled with high density polyethylene (HDPE) plastic pellets to approximately 75% of the container (Figure 3).

Fig. 3. Filling Setup of Experimental Container Designs Studied

2.1.2 Equipment

Singh and Kutz's patented bulge measuring apparatus was utilized to measure the out-plane displacement of the side and bottom faces of a container (Figure 4) [6]. This apparatus, featuring an extensible frame and inner ledge for a snug fit, employs sensor assemblies including a platen to measure out-of-plane displacement of panels. The platen contacts the center of the panel to gauge maximum displacement, while a digital reader displays displacement values from each axis on an Easson ES-10 reader (Easson, Suzhou city, China). Different platens measure the long, short, and bottom faces of the container, with the Lansmont Compression Tester (Lansmont, Monterrey, California, USA) applying external compressive force to induce bulging.

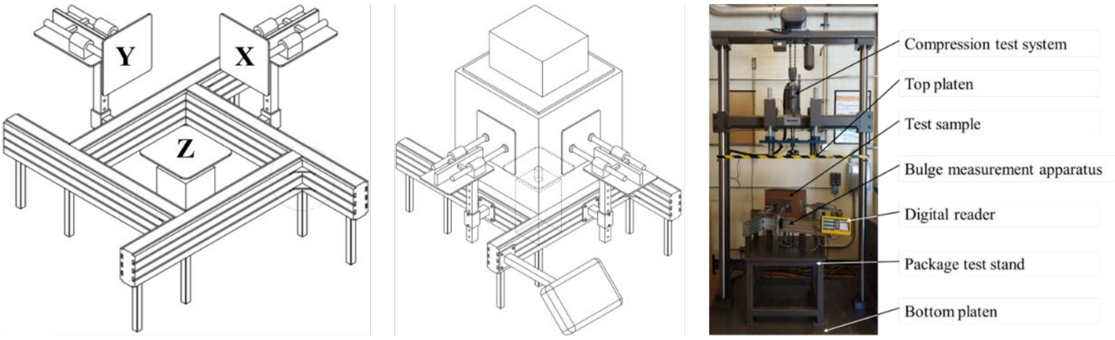

Fig. 4. Bulge Measuring Apparatus [Adapted from US Patent US8746085B2] [6]

2.1.3 Conditioning

All samples underwent pre-conditioning according to Technical Association of the Pulp and Paper Industry (TAPPI) 402 SP-13 standards and subsequent conditioning following ASTM D4332-14 guidelines for ambient, tropical, and refrigerated conditions [7, 8]. A Darwin environmental chamber (Darwin Chambers Company, USA) was utilized for pre-conditioning and conditioning.

2.1.4 Compression Testing

A standardized procedure was developed, including steps such as positioning the bulge tester beneath the compression tester, adjusting the frame to fit the container snugly, labeling all container faces according to ISTA 1A guidelines [9], closing the bottom flaps, filling the sample with HDPE plastic pellets, positioning the container within the frame, lowering the compression tester platen, placing platens over centroidal container areas, zeroing out axes on the digital reader, initiating a compression test, and recording peak force, deflections, and XYZ (bulge) Corrugated Common Footprint (CCF) values. Table 1 summarizes the various treatments included in this study.

Table 1. Experimental Design

	Refrigerated (12 °C, 85% RH)		Ambient (23 °C, 50% RH)		Tropical (40 °C, 70% RH)	
Height (mm)	5-Down	10-down	5-Down	10-down	5-Down	10-down
241.3	3	3	3	3	3	3
292.1	3	3	3	3	3	3
342.9	3	3	3	3	3	3

2.1.5 Results and Discussion

The study analyzed the impact of height and pallet footprint dimensions on bulge amount across three environmental conditions: ambient, tropical, and refrigerated (Table 1). Bulge amount in the X and Y axes was observed and recorded at peak load. A preliminary study data led to a full factorial power analysis with a target power level of 80%, utilizing effect size and standard deviation of bulge amount as inputs. The analysis indicated a maximum replicate amount of three was needed to reach the desired power level. Additionally, bulge amount in the Z axis was minimal and not observed in the main study. The results, depicted in Figures 5 and 6, underwent one-way analysis of variance (ANOVA) for both X (long face) and Y (short face) panel bulge in each pallet footprint and environmental condition. Furthermore, a general linear model ANOVA was conducted for both X and Y panels in each pallet footprint across all environmental conditions, given the data met requirements of equal variances and normal distribution.

Figure 5 displays the out-of-plane displacement or bulge observed in 5-down RSC containers across various heights, influenced by environmental conditions. ANOVA analysis showed no significant effect ($p > 0.05$) on the X-panel's (long face) bulge displacement across all three box heights in ambient, tropical, and refrigerated conditions. Similarly, no significant effect was observed on the Y-panel's (short face) bulge displacement across all heights in tropical and refrigerated conditions. However, in ambient conditions, a significant effect ($p \leq 0.05$) was noted on the Y-panel's bulge displacement across the three box heights. Subsequent Fisher's LSD analysis revealed that containers with a height of 342.9 cm exhibited significantly higher bulge on the short face compared to heights of 292.1 cm and 241.3 cm.

A general linear model analysis examined interactions between variables. It indicated no significant differences ($p > 0.05$) in compression bulge displacement across X and Y panels for all box heights and environmental conditions in the Five down footprint. This suggests that for a footprint of a specific size, the heights of the boxes and various environmental conditions didn't affect compression bulge displacement on both the long (X-Panel) and short faces (Y-Panel). However, this conclusion is only valid for the box heights examined in this study.

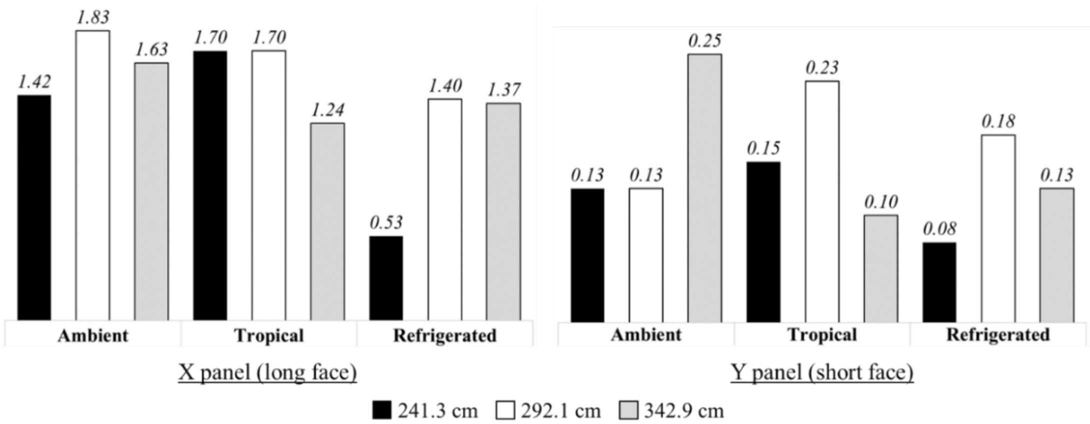

Fig. 5. 5-Down RSCs Compression Bulge Displacement (cm) for the Container Heights

The study also analyzed the out-of-plane displacement, or bulge, of 10-down RSC containers across varying heights under different environmental conditions. Figure 6 depicts the observed bulge displacement. ANOVA analysis showed no significant effect ($p > 0.05$) on X-panel (long face) bulge displacement for 10-Down RSC containers across all three box heights stored in tropical and refrigerated conditions, nor on Y-panel (short face) bulge displacement. However, ambient conditions did have a significant effect ($p \leq 0.05$) on X-panel bulge displacement across the box heights. Subsequent Fisher's LSD analysis revealed that containers with a height of 241.3 cm exhibited significantly higher bulge, followed by heights of 292.1 cm and 342.9 cm.

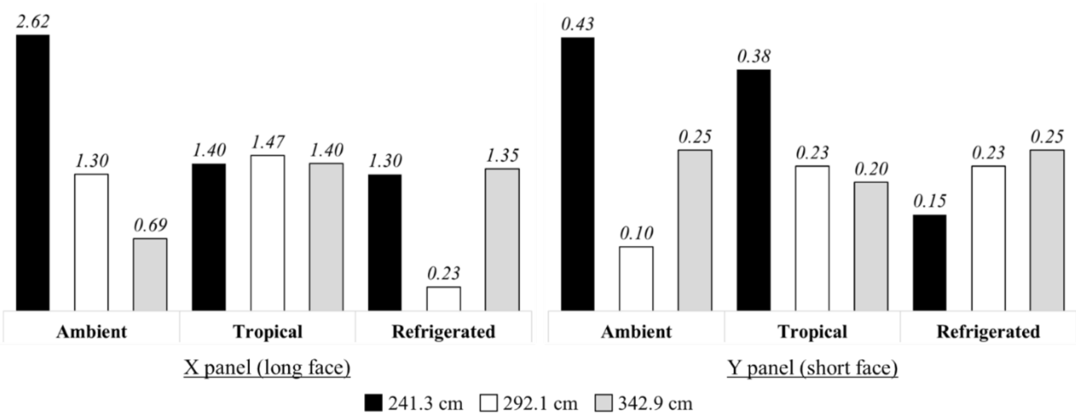

Fig. 6. 10-Down RSCs Compression Bulge Displacement (cm) for the Container Heights

A general linear model (GLM) analysis found no significant differences ($p > 0.05$) in compression bulge displacement across Y-panels for all box heights and environmental conditions in the 10-down footprint. However, significant differences ($p \leq 0.05$) were observed across X-panel bulge displacement for all box heights and environmental conditions in the 10-down footprint. Furthermore, a two-way interaction between height and environmental conditions was noted. Specifically, X-panel bulge displacement decreased with increasing box heights in ambient conditions but was relatively unaffected in tropical conditions and lower in refrigerated conditions for the 292.1 cm samples. This suggests that box heights and environmental conditions significantly contribute to X-panel compression bulge displacement in the 10-down footprint, with differences dependent on the specific environmental condition. These findings are limited to the box heights considered in the study.

2.1.6 Conclusions for Study I

The study indicates that the height of RSC boxes can significantly influence compression bulge displacement under certain conditions. For RSC boxes with a 5-down footprint, there is a notable increase in compression bulge displacement on the short face as box heights increase, particularly under ambient conditions. However, this trend is not consistently observed under tropical and refrigerated conditions. Conversely, RSC boxes with a 10-down footprint tend to exhibit reduced compression bulge displacement on the long face with increasing box heights under ambient conditions, contrasting the trend seen in 5-down footprint boxes. This discrepancy may stem from the smaller load-bearing area of 10-down RSC containers, although the study's analysis does not confirm this hypothesis. The findings suggest that while RSC dimensions may influence compression bulge displacement, material properties of corrugated fiberboard, such as grade and moisture content, play a significant role. Further research is recommended to explore these material properties' relationship with compression bulge displacement in Regular Slotted Containers.

3. Study II: Assessing a Bulge Reduction Technology in Corrugated Fiberboard Containers Under Static Compression

3.1 Materials and Methods

3.1.1 Reinforcement Tape and Containers

The reinforcement tape utilized in this study was Sesame® Tape (H.B. Fuller Company, St. Paul, Minnesota, USA). This filament tape consists of filament fibers coated with a hot melt adhesive on both sides and is typically applied within the corrugated structure using a dispensing system during corrugator operation. Activated by the corrugator's heat, the tape bonds to both the linerboard and medium. In this study, the tape had a width of 1.1 cm and a minimum breaking strength of 333 N. Two tape placements were examined: out-board placement, applied to the outside of the outer linerboard, and in-board placement, applied to the inside of the outer linerboard, as illustrated in Figure 7.

Fig. 7. Out-Board Placement (left) and In-Board Placement (right) of Reinforcement Tape

This study included four container designs made of C-flute single wall corrugated sheets, featuring a basis weight of 205/112/205 g/m^2, an ECT value of 7.36 ± 0.18 kN/m, and burst strength of 0.98 ± 0.32 kgf/ cm^2. The internal dimensions of the RSCs were 45.7 cm x 35.4 cm x 30.5 cm. As illustrated in Figure 8, the designs varied based on the presence, quantity, and placement of reinforcement tape on the vertical panels. These designs included RSC (no tape), STC (Single Tape Container) with tape applied in-board at 50% height, DTC-30-70 (Double Tape Container) with tape applied out-board at 30% and 70% height levels, and DTC-20-80 with tape applied in-board at 20% and 80% height levels. Tape placement varied randomly due to limitations, with some placed externally for relative comparison. Notably, the containerboard lacked moisture resistance properties. HDPE pellets were chosen as dead weight to induce bulging during compression testing, filling the containers to approximately 75% depth with a total weight of 18 kg (Figure 3).

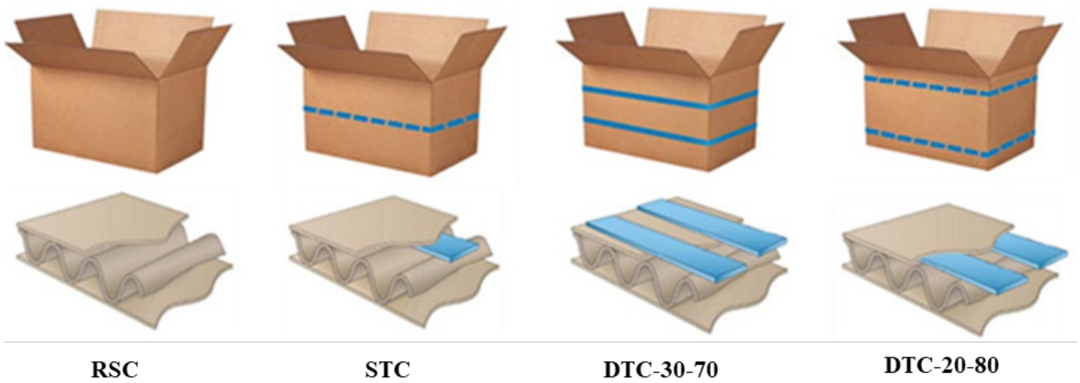

Fig. 8. Representation of the Four Container Designs Studied

3.1.2 Equipment, Conditioning and Testing

This study utilized identical equipment, conditioning, and testing procedures as those employed in the first study (Section 2).

3.1.3 Results and Discussion

The analysis of the test data involves three statistical procedures: ANOVA, Dunnett's comparisons, and Tukey's comparisons. ANOVA assesses whether there is a significant difference between the means of multiple groups or treatments. Dunnett's test compares the means of several container design groups with a control group mean, identifying any significant differences from the control group mean. Tukey's test, also known as Tukey Kramer's Honest Significant Difference test, examines all pairwise differences in group means to determine specific group mean differences when compared with each other, utilizing the studentized range distribution.

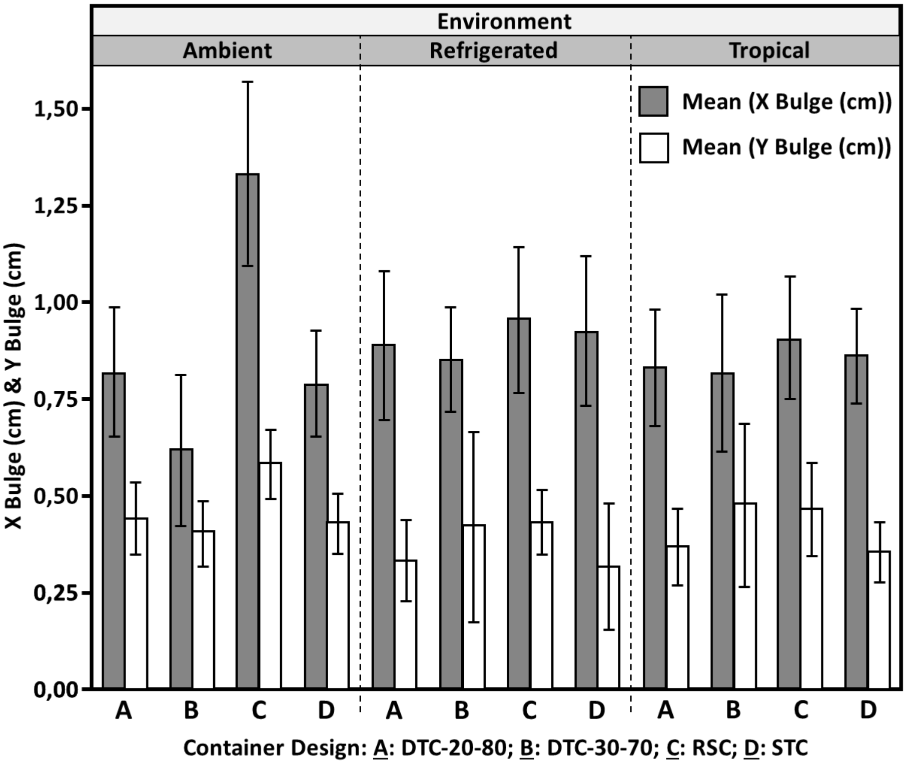

Fig. 9. Overview Chart of Mean (± Std Dev) of Bulge by Container Design and Environment

Figure 9 illustrates the mean maximum compression bulge in the X and Y directions across conditioning environments and container designs. Each bar represents the mean bulge based on eight samples, with error bars indicating one standard deviation from the mean. The chart highlights that X bulge exceeds Y bulge due to longer panel span. In ambient conditions, RSC container's X bulge surpasses that of tape designs. However, subsequent Dunnett's test assesses if X and Y bulges for tape containers significantly differ from the reference container.

In an ambient environment, the Dunnett test compared to the RSC control group, revealed significant reductions in out-of-plane displacement (bulging) in both X and Y directions for all tape-reinforced containers, namely DTC-20-80, DTC-30-70, and STC containers (Figure 10). The reductions were notable compared to the RSC design, particularly for DTC-20-80 containers (X p-value < 0.0001, Y p-value = 0.0076), DTC-30-70 containers (X p-value < 0.0001, Y p-value = 0.0006), and STC containers (X p-value < 0.0001, Y p-value = 0.0026). Additionally, a Tukey Kramer's test was conducted to assess whether the average maximum compression bulge values differed significantly among the containers. The results indicated significant differences, as illustrated in Table 2, where container designs with different letters exhibited mean values that significantly differed from each other. Specifically, the mean X and Y out-of-plane displacements for RSC containers were significantly higher (letter "A") compared to containers with tape reinforcement (letter "B"), confirming the Dunnett test results. However, no significant difference in mean Y out-of-plane displacement was observed among the different tape-reinforced container designs, all assigned the letter "B".

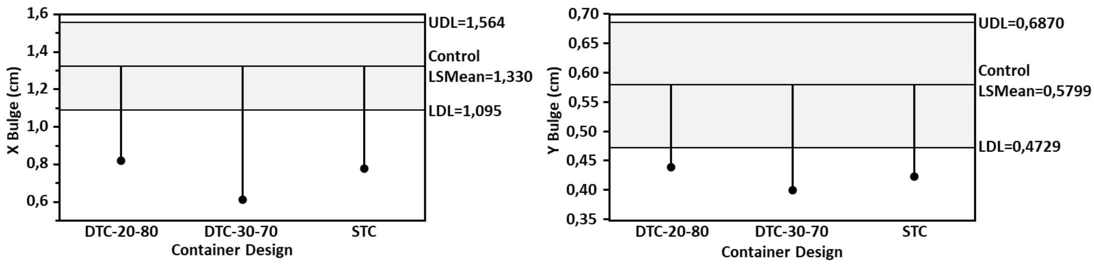

Fig. 10: X and Y Bulge Means Comparison for Ambient Environment Using Dunnett's Method, with RSC as the Control Group

Table 2. X and Y Bulge Means Connecting Letters Report Using Tukey Kramer's Method

Container design	X Bulge			Y Bulge		
	Letters		Mean (cm)	Letters		Mean (cm)
RSC	A		1.378	A		0.601
DTC-20-80		B	0.848		B	0.456
STC		B	0.816		B	0.439
DTC-30-70		B	0.640		B	0.417

Figures 11 and 12 present the results of the Dunnett test, with RSC containers as the control group, indicating the X and Y bulge in tropical and refrigerated environments. The charts reveal a decreasing trend in mean out-of-plane displacement for both directions compared to RSC containers, though not significantly different from the control group. Specifically, for tropical conditions, the differences in X and Y bulge for DTC-20-80 containers (X-p-value = 0.6812, Y-p-value = 0.4151), DTC-30-70 containers (X-p-value = 0.5857, Y-p-value = 0.9995), and STC containers (X-p-value = 0.9255, Y-p-value = 0.2930) are not significant. Similarly, in refrigerated conditions, the differences for DTC-20-80 containers (X-p-value = 0.8519, Y-p-value = 0.4948), DTC-30-70 containers (X-p-value = 0.6207, Y-p-value = 0.9998), and STC containers (X-p-value = 0.9916, Y-p-value = 0.3551) are not significant. While tape-reinforced containers show potential to reduce bulge in both directions in tropical and refrigerated environments, they are not statistically different from RSC containers. However, in an ambient environment, all tape-reinforced containers significantly reduce bulge.

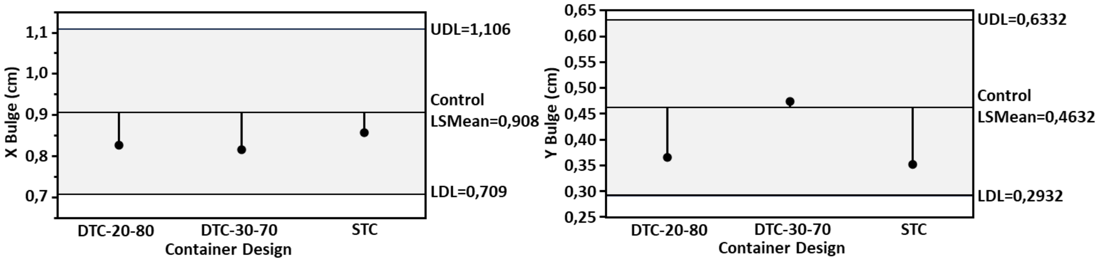

Fig. 11: X and Y Bulge Means Comparison for Tropical Environment Using Dunnett's Method, with RSC as the Control Group

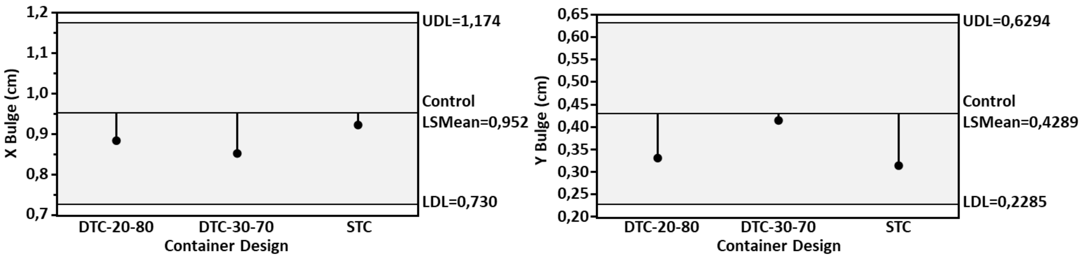

Fig. 12: X and Y Bulge Means Comparison for Refrigerated Environment Using Dunnett's Method, with RSC as the Control Group

3.1.4 Conclusions for Study II

This study investigated the impact of top-to-bottom static compression load on filled RSCs with reinforcement tape. Four container designs, RSC, STC, DTC-30-70, and DTC-20-80, were tested under ambient, tropical, and refrigerated conditions. Implementation of Sesame® Tape notably reduced bulging under standard conditions, with a significant decrease in out-of-plane displacement observed in ambient conditions. While a trend of reduced displacement was observed in tropical and refrigerated conditions for three container designs, it was not statistically significant. Optimizing board stiffness alongside reinforcement tape could customize a container's resistance to compression bulge, suggesting potential for bulge reduction. Further research is needed to determine optimal board stiffness for effectiveness in tropical and refrigerated conditions. This study aids packaging engineers in utilizing reinforcement tape effectively for bulge reduction. Moreover, additional investigation is warranted to determine optimal tape placement for specific box configurations, with consultation from HB Fuller, the tape manufacturer, recommended for assistance in tape selection and placement.

4. Overall Conclusions

The study highlights the significant impact of RSC box height on compression bulge displacement, particularly evident in 5-down footprint boxes where an increase in box height correlates with higher bulge displacement on the short face, especially under ambient conditions. Conversely, for 10-down footprint RSC boxes, there is a tendency towards reduced bulge displacement on the long face with increasing box heights under ambient conditions, contrasting the trend observed in 5-down footprint boxes. While the smaller load-bearing area of 10-down RSC containers may explain this discrepancy, the study's analysis does not confirm this hypothesis. It underscores the influence of material properties like grade and moisture content of corrugated fiberboard on compression bulge displacement.

Meanwhile, the investigation into reinforcement tape's effect on filled RSC containers reveals notable bulge reduction under standard conditions, particularly in ambient environments. Although the trend of reduced displacement is observed in tropical and refrigerated conditions for three container designs, it lacks statistical significance. The study suggests potential for customizing a container's resistance to compression bulge by optimizing board stiffness alongside reinforcement tape, warranting further exploration into optimal board stiffness for tropical and refrigerated conditions.

This research aids packaging engineers in effectively utilizing reinforcement tape for bulge reduction, emphasizing the need for additional study to determine optimal tape placement for specific box configurations, with guidance from HB Fuller, the tape manufacturer, recommended for tape selection and placement assistance.

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