Influence of the Arrangement of Corrugated Board Flap Boxes on their Resistance to Static Pressure

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The authors examined how the arrangement of corrugated board boxes influences the loading unit's resistance to static pressure. The obtained values were compared with the basic strength test of a single box commonly used, which is the resistance to static pressure of BCT boxes. The subject of the study was FEFCO 201 flap boxes with touching flaps. The scope of work included measuring the static pressure resistance BCT of a single box and eight boxes stacked in two layers in two different ways, which are the most popular techniques for stacking boxes on a pallet when creating a loading unit. The strength of a single box, eight boxes stacked in columns, and eight boxes stacked in a blocking arrangement with overlapping edges was determined. The measurement results were compared, and conclusions were drawn.

DOI: 10.15376/biores.20.4.10725-10740

Keywords: Corrugated board box; Compressive strength of boxes; Load unit; Corrugated board; Strength properties

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INTRODUCTION

The packaging process is a strategic element in the trade of goods, both domestically and internationally. Packaging is an essential element in product handling. Without it, product handling is inefficient. Packaging plays many important roles: it protects the packaged goods from not only mechanical hazards but also contamination in the distribution environment, facilitates transport and storage, and acts as a "silent" salesperson by providing information about products and promoting them (Hägglund and Carlsson 2011). Robertson (1990) listed six basic functions of packaging: containerization, protection, division, unification, convenience, and communication. The functions of packaging not only influence product design, production, transport, distribution, storage, and marketing tools, but are also important in ensuring a competitive advantage for the company. Internationalization is increasing the distance between producers and consumers, contributing to a growing need for useful and competitive packaging systems (Dominic and Olsmats 2001). Internationalization is now the most important business strategy for companies. Most consumer and industrial products move through the supply chain in the form of unit loads for at least part of the distribution cycle. Unit loads streamline handling, storage, and distribution. Packaging logistics, according to Dominic *et al.* (2000), is defined as an approach that aims to develop packaging and a packaging system to support the logistics process and meet the needs of customers or users. According to Saghir (2004), packaging has a significant impact on the efficiency and effectiveness of the retail supply chain.

A universal method of transporting various types of goods, and a commonly used unit load consists of corrugated board boxes stacked on a pallet. Corrugated board packaging has many advantages over other packaging materials, such as plastic, metal, and wood. Currently, very important advantages of corrugated board boxes are low production costs and environmental friendliness. Important aspects include biodegradability, as well as the possibility of recycling and reuse (Talbi *et al.* 2009; Fadiji *et al.* 2018; Fehér *et al.* 2023).

Corrugated board boxes can be stored flat, which reduces storage and transport costs. They are also lightweight, which makes them easy to use and does not significantly increase the weight of the transported goods. The ease with which pallets can be moved, loaded onto means of transport, and unloaded in warehouses makes them the most commonly used method of transport today. Due to the high demand for corrugated board boxes for unit loads, accurate prediction of box compression strength is critical in preventing damage to packaging during stacking. Scientists measure the static pressure resistance of BCT boxes by conducting compression tests in accordance with standards such as TAPPI T804 (2020), ASTM D642 (2020), and ISO 12048 (2022). The TAPPI method is used to measure the resistance of corrugated board or solid cardboard shipping boxes to external compressive forces using an instrument with rigidly mounted load plates. The pressure plates exert an even load on the tested box at a speed of 13±2.5 mm/min. A preload value equal to 5% of the maximum value that the tested box can withstand is used. The standards developed by ASTM and ISO describe the measurement of static pressure resistance using rigidly mounted load plates, or with the upper plate mounted on a joint and the lower plate mounted rigidly. The measurement speeds of the ASTM and ISO standards are 12.7 ± 0.25 mm/min and 10 ± 3 mm/min, respectively.

Little (1943) identified the main parameters affecting box compression strength as box size, edge crush resistance (ECT), and bending stiffness (BS) of the corrugated board from which the box is made. Using these parameters, Kellicutt and Landta (1951, 1958) developed models for predicting the BCT of boxes. In 1963, McKee, Gandera, and Wachuty published the most popular method in the industry for predicting the BCT of boxes, which is still used today and is commonly used in most available programs. Attempts have also been made to improve the McKee equation by modifying constants and exponents (Allerby *et al.* 1985; Avilés *et al.* 2012; Garbowski *et al.* 2020a), taking into account the dimensions of the box (Batelka and Smith 1993) and adding the Poisson coefficient (Urbanik and Frank 2006).

The article (Kmita-Fudalej and Rudnicka 2024) analyzed the measurement results and conditions for performing BCT measurements of flap boxes using two measuring instruments. The first device had both load plates rigidly mounted, while the second had the lower plate rigidly mounted and the upper plate mounted on a joint.

In recent years, numerical methods based on finite element method (FEM) calculations have been used to analyze the compression strength of corrugated board boxes. The research by Urbanik and Saliklis (2003) combines the finite element method model with the geometric parameters of the box and the material properties affecting the buckling critical stress of the box walls to examine their response after buckling. The influence of the transverse shear stiffness of corrugated board was also analyzed (Nordstrand and Carlsson 1997; Nordstrand 2003). Many studies are based on the creation and validation of a numerical model for predicting the destructive force of corrugated board boxes of various designs, boxes with ventilation holes, carrying handles, cutouts in the side walls of various sizes and locations, and perforated boxes (Beldie *et al.* 2001; Biancolini and Brutti

2003; Han and Park 2007; Fadiji *et al.* 2017; Garbowski *et al.* 2020b; Garbowski *et al.* 2021; Pidl *et al.* 2022; Fehér *et al.* 2023).

Newer approaches, such as modeling using artificial neural networks, are also used in studies related to the compression strength of corrugated cardboard boxes (Malasri *et al.* 2016; Archaviboonyobul *et al.* 2020).

In the literature, there are publications in which tests were conducted on the resistance to static pressure of load units using corrugated board boxes arranged in various configurations. Kellicutt (1963) studied the compression strength of stacks of boxes made of A-wave corrugated board and observed a 55% decrease in the strength of stacks arranged in a block configuration and an 18% decrease in the strength of stacks arranged in a column configuration. This loss of box strength was not explained in his research. Other values for the decrease in box compression strength during stacking were obtained by Hillenius (1970), who also conducted tests on boxes made of A-wave corrugated board. In the case of boxes stacked in a block configuration, he obtained a 49% loss of strength, and in the case of boxes stacked in columns, a 13% loss for a single column and a 5% loss for multiple columns. Ievens (1975) also obtained other compression strength reductions depending on the stacking method. In his studies, he reported 45% lower compression strength values for boxes stacked in a blocking arrangement compared to a column arrangement. The above-mentioned tests were performed using different standards, TAPPI T804 and ASTM D642, which impose different measurement conditions: measurement speed, the use of different preload values, or no preload, which also has a significant impact on the measurement result. Boxes made of A-flute corrugated board were used, which is not a popular material for box production in the region where the authors of the article conducted their research, and also has a significant impact on the measurement results.

None of the above-mentioned studies on the static pressure resistance of cargo units depending on the stacking method considered the size of box deflection during loss of load-bearing capacity for a given stacking method in relation to the deflection obtained during the testing of a single box, as well as the method of deformation and the impact of the quality of the box on its load-bearing capacity and method of deformation. The above parameters are discussed by the authors in this publication, which gives this work a scientific character and introduces new elements to the field of science. The size of deflection is a very important parameter that should be taken into account when designing boxes. It informs the designer how to select the parameters of the packaging for the product being packaged in order to eliminate the possibility of the packaged product transferring the load and to properly secure it during transport and storage.

The main goal of the packaging industry and its customers today is to reduce costs and environmental impact. For many years, there has been a significant reduction in the amount of material used and the use of recycled materials in the production of corrugated board. According to the logs, there has been a continuous decrease in the weight of corrugated board. In Europe, the average weight in 1997 was 558 g/m^2, in 2010 it was 526 g/m^2, and in 2022 it reached 496 g/m^2 (FEFCO Annual Statistics). The factors mentioned above contribute to lower corrugated board quality and reduced strength of corrugated board boxes, which necessitate continuous testing of both corrugated board and boxes made of it to produce packaging in an economical manner that meets the requirements set for it. Another reason for the varying quality of corrugated board is its place of production in the world, which also contributes to different strength values of corrugated board and the boxes made from it.

The analysis and prediction of the compressive strength of corrugated board boxes when stacked are important for studying the response of long-established packaging to mechanical stress, as well as for designing new boxes to protect packaged goods during transport and storage.

EXPERIMENTAL

Materials

The study used standard Fefco 0201 flap boxes (Fig. 1), made of three-layer C-wave corrugated board, designed for use on an automatic packaging line. The selected box has no additional cutouts in the form of handles or ventilation holes. Packaging was manufactured with cross creases during sheet production, longitudinal creases, and slots made during packaging production on a processing machine. Table 1 presents the raw material composition and parameters of the corrugated board used to manufacture the tested boxes. Table 2 lists the internal and external dimensions of the boxes tested.

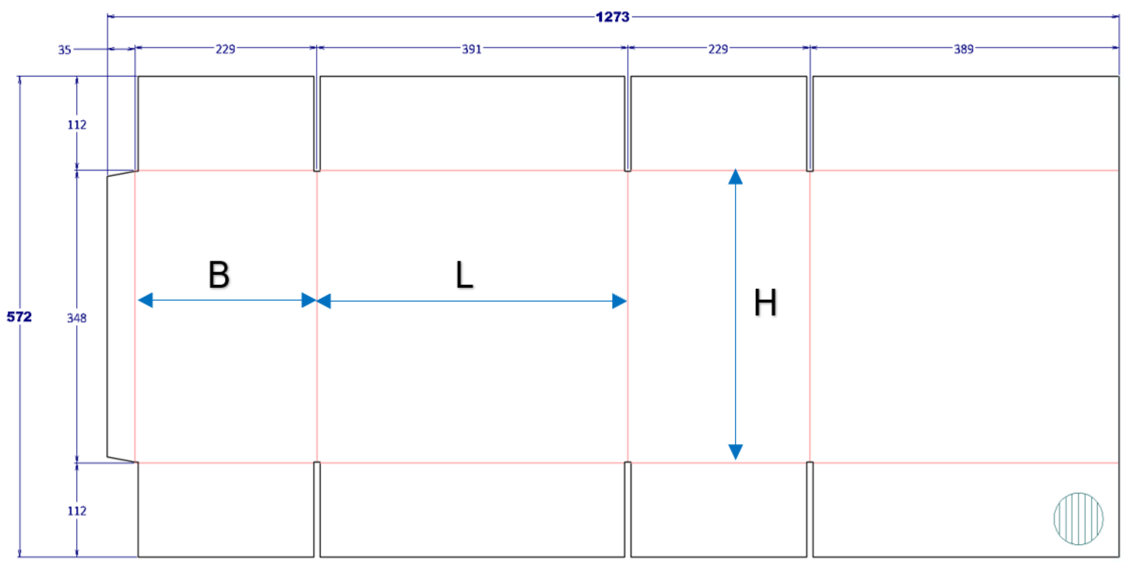


Fig. 1. Construction of the tested box

Table 1. Properties and Raw Material Composition of Corrugated Board

Type of corrugated board	Type of flute	Thickness (mm)	Weight (g/m^2)	ECT (kN/m)	Outer layer	Corrugated layer	Inner layer
Three-layer corrugated board	C	3.9	584	8.4	KI03-186	WBFL-150	KI03-186

Note: KI03-186 – testliner with a weight of 186 g/m² with enhanced barrier properties, used as a substitute for kraft papers; WBFL-150 – recycled fluting with a basis weight of 150 g/m² with enhanced strength properties.

Table 2. Internal and External Dimensions of the Box

Internal Dimensions of the Box			External Dimensions of the Box		
L (mm)	B (mm)	H (mm)	L1 (mm)	B1 (mm)	H1 (mm)
387	225	340	395	233	352

Conditioning of Samples, Climatic Conditions during Testing

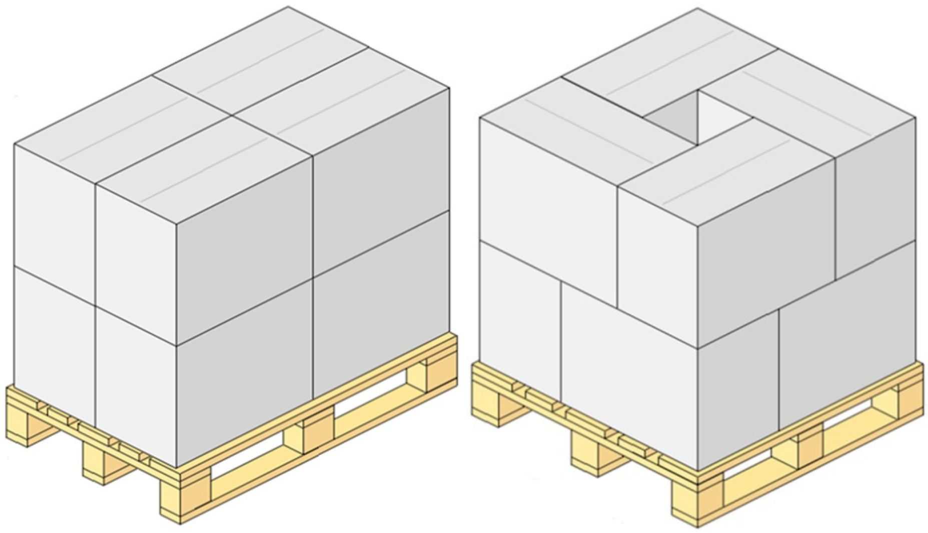
The boxes were conditioned in accordance with ISO 2233 (2000) in a room where the temperature was maintained at 23 ± 1 ºC and the relative humidity at 50 ± 2 %. The measurements were taken in a room with the same climatic conditions as during air conditioning.

Measurement Methodology

The tests were carried out on a Techlab Systems Validator strength press (Fig. 2). The press had two rigidly mounted plates measuring 800 mm x 800 mm with a maximum height between the plates of 950 mm. The load measurement range was from 0 kN to 25 kN.

Fig. 2. Box strength testing press

The tests were conducted on a single box and eight stacked boxes arranged in two different ways. The first arrangement consisted of stacking the boxes on top of each other in columns. The method of stacking packages in columns is often used due to the modular dimensions of the manufactured packages, which are adjusted so that their multiples fill the pallet as efficiently as possible. The simulation of the arrangement of packages is shown in Fig. 3a: two packages along the length of the pallet, two packages across the width of the pallet, and two layers stacked on top of each other.



(a) (b)

Fig. 3. Arranging boxes: a) in columns, b) in a blocking arrangement with overlapping edges was determined

In the next stage, packages stacked in a blocking arrangement with overlapping edges were determined to be examined. The simulation of the package arrangement is shown in Fig. 3b. There were four packages on each layer, which were arranged so that they interlocked, and the point of contact between two adjacent boxes on each layer was located along the length of the box in the lower or upper layer. This method is characterized by the fact that the boxes partially overlap each other. The blocking arrangement method allows for greater stability of the packed pallet by creating a "brick wall" effect. Filling the pallet space in this type of arrangement usually requires an analysis of the dimensions of the packages.

Static pressure resistance BCT measurements of a single box were performed in accordance with ISO 12048 (2022). In the case of stacked boxes, the above-mentioned standard was also used.

In accordance with the standard, in the first phase of the measurements, a test measurement was performed without preloading in order to determine it for a single box and for eight boxes stacked in two different ways. The tests were carried out on empty boxes in which the outer bottom and top flaps were glued with adhesive tape. The speed of the plates during the test was 10 mm/min.

The destructive force for a single box and stacked boxes ranged from 3000 N to 10000 N in accordance with the guidelines in Table 3 (ISO 12048 2022), a preload force of 250 N was adopted for all cases tested.

Table 3. Initial Load Values

Average Expected Pressure Force (N)	Initial Load Value (N)
201-200	10
201-1000	25
1001-2000	100
2001-10000	250
10001-20000	1000
20001-100000	2500
etc.	*etc.*

After determining the initial force value, measurements were taken to record the relationship between force and deformation, as well as the maximum destructive force and deformation during the application of the destructive force. In the case of BCT measurement of a single box, 10 measurements were taken, and the result was given as the average value of the ten measurements (Fig. 4). In the case of stacks of boxes (see Figs. 5a and 5b), 4 measurements were taken, and the result was given as the average value of the four measurements.

Fig. 4. BCT measurement of the box

(a) (b)

Fig. 5. Arrangement of packages on the press during testing: a) in columns, b) in a blocking arrangement with overlapping edges was determined

RESULTS AND DISCUSSION

The individual results of the destructive force and deflection measurements at the moment of loss of load-bearing capacity of the single box are presented in Fig. 6.

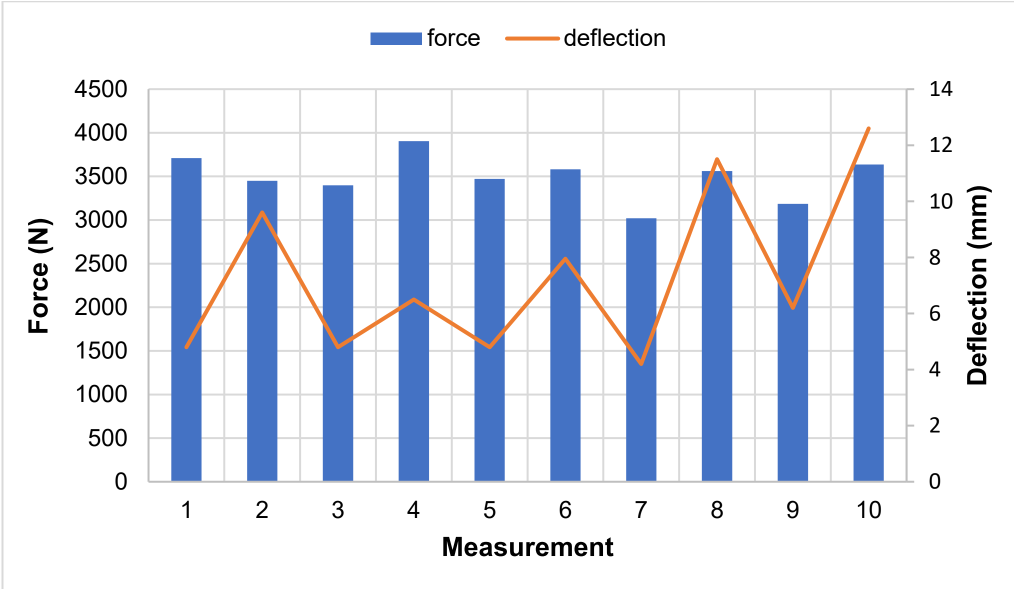


Fig. 6. Results of destructive force and deflection measurements for a single box

During tests on individual boxes, buckling of the box walls was observed across their entire width boxes. This is caused by the large dimensions of the box height in relation to its width (Fig. 7). In the case of the single box tested, the external height H1 of the box was 352 mm and the width B of the box was 233 mm, which contributed to the destruction of the box as a result of buckling of the wall across the width of the box.

Fig. 7. Destruction of a single box

Table 4 shows the average value of destructive force and deflection, standard deviation, and maximum and minimum values obtained during single box measurements. For boxes arranged in columns and stacked in an overlapping manner, four measurements were taken, which yielded repeatable results for the destructive force. During the measurements, a graph of force versus deflection was recorded, which allows for analysis of the material's characteristics under load and determination of the maximum values of destructive force and deflection at the moment of loss of load-bearing capacity of the boxes. Such information is crucial for assessing the strength and behavior of the material under load, as well as for determining its strength and safety limits in engineering applications.

Table 4. Average Value of Destructive Force and Deflection for a Single Box

	Force (N)	Deflection (mm)
Average value	3491.7	7.3
Standard deviation	253.4	3.0
Maximum	3904.0	12.6
Minimum	3020.5	4.2

Figure 8 compares the values of destructive force and deflection during the loss of load-bearing capacity of boxes for individual measurements for boxes arranged in columns. Table 5 shows the average value of destructive force and deflection, together with the standard deviation, maximum, and minimum values obtained during measurements for boxes arranged in columns.

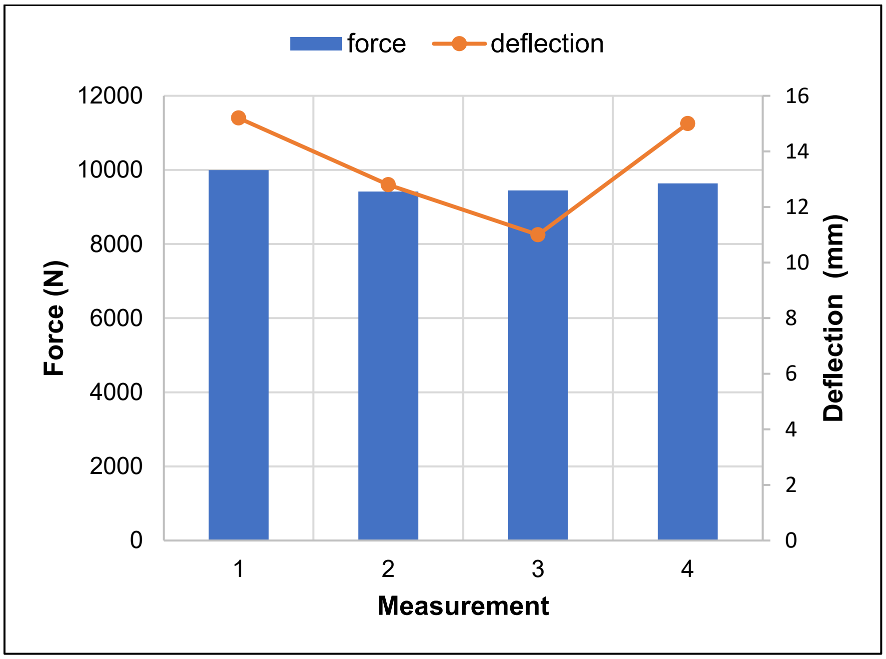


Fig. 8. Graph showing destructive forces and deflection of packaging arranged in columns

Table 5. Average Value of Destructive Force and Deflection for Boxes Arranged in Columns

	Force (N)	Deflection (mm)
Average value	9 625.4	13.5
Standard deviation	265.9	2.0
Maximum	9 996.5	15.2
Minimum	9 418.5	11.0

In the case of the destructive force of boxes arranged in columns, there were no significant variations in the results, as evidenced by the low standard deviation of 266 N, which represents 2.8% of the average force obtained during the measurements (Table 5). In the case of deformation values during the loss of stability of the packaging, significant variations were observed in the measurement results, which were characterized by a high standard deviation of 2 mm, which was approximately 15% of the average deformation value (Table 5).

During the measurements, it was observed that the accuracy of the box arrangement had a significant impact on the destructive force value. Higher destructive force values were obtained for boxes arranged in columns when the axes of symmetry of the corners of the boxes in the bottom and top layers coincided (Fig. 9a). In the case of non-coinciding axes of symmetry of the corners, the destructive force value obtained during the measurements was lower (Fig. 9b). This confirms the proven principle observed in the measurement of the destructive force of individual boxes, that the greatest load during the measurement is transferred through the corners of the box.

(a) (b)

Fig. 9. Arrangement of boxes in columns: a) the axes of symmetry of the corners of the boxes coincide, b) the axes of symmetry of the corners are shifted relative to each other

During the measurements of boxes stacked in columns, two types of damage were observed. In the first case, the corner at half height was damaged (global buckling) (Fig. 10a) in one of the boxes located in the bottom layer. The reason for this type of damage could have been the different heights of the boxes caused by the large dimensional tolerance of the packaging manufactured using board creasing on a corrugated board production machine. The difference in height between the box corners caused uneven load distribution during the measurement, and the higher corner of the box carried a greater load and failed more quickly. In the second case, the boxes in the bottom layer lost their load-bearing capacity due to buckling of the walls along the length of the box, a typical deformation of the box walls known as telescoping (Fig. 10b). In the case of corner buckling for the tested stack of boxes arranged in columns, higher destructive force values were also obtained in relation to stacks of boxes in which wall buckling occurred.

Figure 11 compares the values of destructive force and deflection during loss of load-bearing capacity for individual measurements for the blocking arrangement with overlapping edges.

(a) (b)

Fig. 10. Damage to boxes stacked in columns: a) global buckling of the corner, b) buckling of the box wall along its length

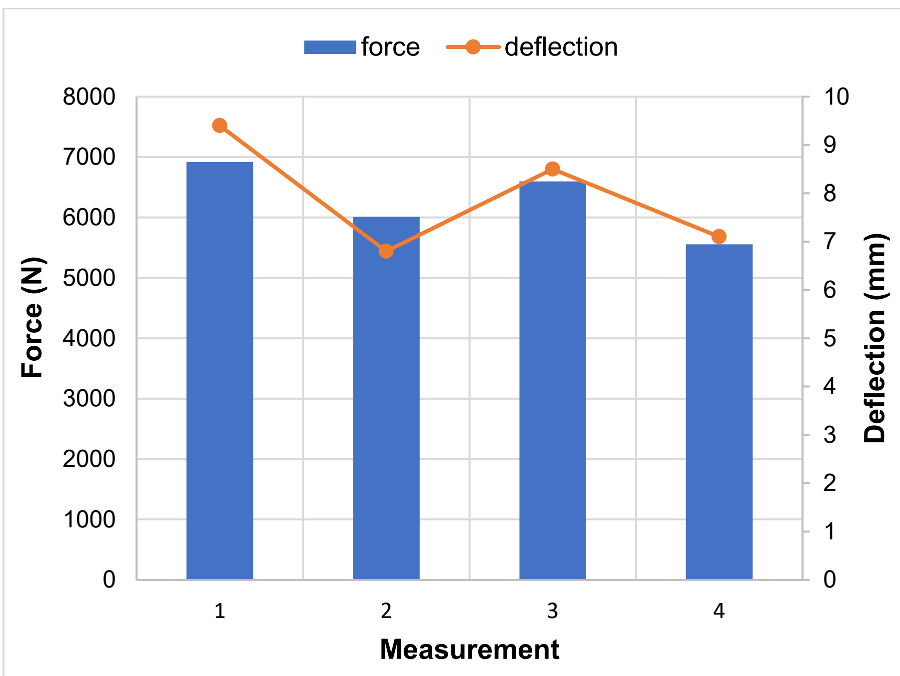


Fig. 11. Graph of forces and deflections measured for boxes arranged in a blocking arrangement

Table 6. Average Value of Destructive Force and Deformation for Boxes Arranged in a Blocking Arrangement

	Force (N)	Deflection (mm)
Average value	6 269.4	8.0
Standard deviation	606.2	1.2
Maximum	6 916.0	9.4
Minimum	5 554.5	6.8

Table 6 shows the average value of destructive force and deflection, together with standard deviation, maximum, and minimum values obtained during measurements for boxes arranged in a blocking arrangement. In the case of destructive force, there were significantly greater variations in the results than in the case of boxes arranged in columns, as evidenced by the higher standard deviation value of 606.2 N, which represents approximately 10% of the average force obtained during measurements (Table 6). In the case of deflection values during the loss of stability of the packaging, there was a similar dispersion of measurement results as in the case of stacking in columns, where the standard deviation was 1.2 mm, *i.e.*, approximately 15% of the average deflection value (Table 6).

During tests on boxes stacked in a blocking arrangement, a different type of deformation was observed than in the case of stacking in columns. The walls of both the upper and lower layers of the boxes buckled locally in length. The upper boxes buckled at the bottom of the box along the entire length of the wall, while the walls of the box in the lower layer buckled locally along a specific length extending from the corner to the point of contact with the corner of the upper layer box (Fig. 12).

Fig. 12. Damage to boxes stacked in a blocking arrangement

Different types of packaging arrangements allowed for the observation of buckling and damage in other areas of the tested boxes and for obtaining different values of destructive force and deflection during the loss of load-bearing capacity of the box stack. Figure 13 compares the destructive force values obtained for a single box with the values obtained during the testing of eight boxes stacked in two different ways in column layout and boxes stacked in a blocking arrangement. The error bars shown in the graph represent the maximum and minimum values obtained during the measurements.

When comparing the destructive force values for stacks of eight boxes arranged in a columnar arrangement with boxes blocking arrangement, significantly higher destructive force values were observed when the boxes were arranged in columns. The difference in destructive force was 3356 N. The destructive force value for eight boxes arranged in a blocking arrangement reached 69% of the destructive force value obtained for boxes arranged in columns. This is due to the arrangement of the critical points of the boxes, *i.e.*, the corners, which carry the highest load during measurements. Measurements for boxes arranged in columns were characterized by a smaller spread of results compared to boxes arranged in a blocking pattern, as evidenced by the error bars (Fig. 13).

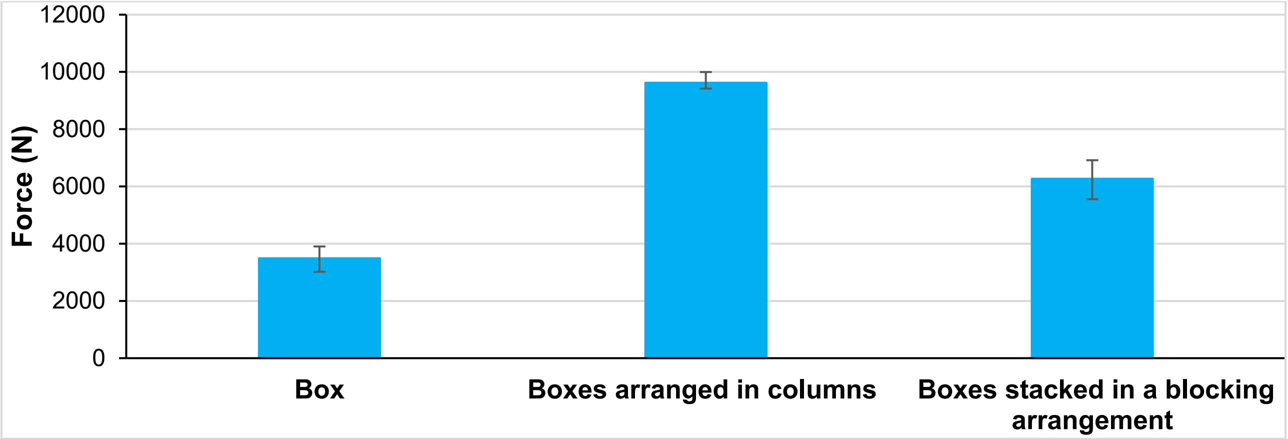


Fig. 13. Comparison of average destructive force values for a single box and boxes arranged in columns and boxes stacked in a blocking arrangement

Comparing the destructive force measurement results for eight boxes stacked in piles, there were almost three times higher destructive force values for boxes stacked in columns and approximately twice higher destructive force values for boxes stacked in a blocking arrangement compared to the destructive force obtained for a single box.

Figure 14 compares the average deformation values during the measurement for a single box and for eight boxes arranged in columns and in a blocking arrangement with overlapping boxes. The error bars shown in the graph represent the maximum and minimum values obtained during the measurements.

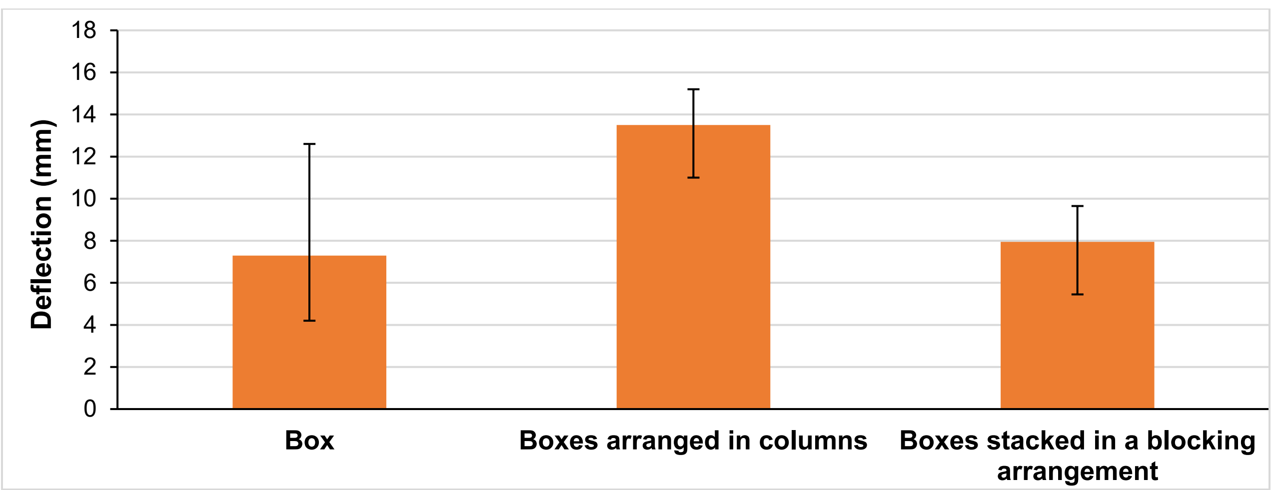


Fig. 14. Comparison of deflection for a single box and boxes arranged in columns and boxes stacked in a blocking arrangement

When analyzing the deflection values for stacks of eight boxes arranged in columns and boxes arranged in a blocking arrangement (Fig. 14), higher deformation values were observed during the loss of load-bearing capacity for boxes arranged in columns. The deformation value for boxes stacked in columns was 1.7 times higher than for boxes stacked in a blocking arrangement. Comparing the deflection results obtained for a single box and boxes stacked in columns, approximately twice as high deflection was obtained for boxes arranged in columns, and comparable deformation for boxes arranged in a blocking system, compared to the deformation results obtained for a single box.

CONCLUSIONS

1. Research has shown that the way boxes are stacked has a significant impact on the static pressure resistance of stacked boxes.
2. Higher destructive force values were obtained for eight boxes arranged in columns. The destructive force value for eight boxes stacked in a blocking arrangement with overlapping edges was determined to reach 69% of the destructive force value obtained for the arrangement of boxes arranged in columns.
3. The destructive force when eight boxes are arranged in columns and stacked in a blocking arrangement was approximately three times and twice as high, respectively, as the destructive force obtained for a single box.
4. Various effects of box destruction were observed during the loss of stack load capacity for eight boxes arranged in columns and stacked in a blocking arrangement.
5. The accuracy of the arrangement of eight boxes in columns affects the force value during the loss of load capacity.
6. Higher deformation values during the loss of load-bearing capacity were obtained for boxes arranged in columns compared to the deformations obtained for boxes arranged in a blocking arrangement.
7. Approximately twice as much deflection was obtained for boxes arranged in columns and comparable deformation for boxes arranged in a blocking arrangement, compared to the deformation values obtained for a single box.

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Article submitted: September 9, 2025; Peer review completed: September 29, 2025; Revised version received: October 1, 2025; Accepted: October 14, 2025; Published: October 27, 2025.
DOI: 10.15376/biores.20.4.10725-10740