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Influence of Stiffeners for Improving the Compressive Strength of Ventilated Corrugated Packages Using Finite Element Modelling Technique

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Abstract: The aim of this research is to optimize the corrugated fibreboard (CFB) boxes recommended by the Bureau of Indian Standards (BIS) for packaging apples and suggest improvements for the same with the help of finite element modelling technique. The motivation for the current study grew with the advent of the multipurpose use of corrugated fibreboard as a structural material, particularly for packaging boxes. A standard double walled (DW) panel box is considered for improvements in terms of ventilation slot configuration and reduction in material utilization for manufacturing through the implementation of a single walled (SW) panel box design. In order to maintain the structural integrity upon reduction in box construction material, the concept of stiffener has been introduced as a load-bearing enhancement feature. These enhancements will help establish a rationale and enable the corrugated fibreboard manufacturers and consumers to improve the understanding of the behaviour of such structures and help to check for the cost utilization, avoid overdesign and further mitigate the failures in practical applications. Full depth vertical rectangular slot was found to generate the least stresses and found to be suitable as ventilation slots. With the replacement with SW panel box, a saving in material consumption can be realized amounting to more than 34%. It was found that a 3-ply box configuration with a full-depth ventilation slot with panel stiffener can serve as a potential candidate for the replacement of the current box constituting of 5-ply panels recommended in the context of Indian standards.

Keywords: finite element analysis; corrugated fibreboard packaging; stiffeners; compression strength; ventilation slots; telescopic type box

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1. Introduction

Paper and its products such as paperboard have been reported to be used as a packaging medium as early as 1897 [1]. However, the development and rational use of corrugated paper began during World War II with the decrease in the conventional materials used in manufacturing packaging structures [2]. The advent of corrugated fibreboard (CFB) containers marked the revolution in packing of industrial products and shifted their outlook from traditional wooden crates. Further, the use drastically picked up after the war for commercial applications. Presently, the use of corrugated board has become ubiquitous, from the packaging of fresh agricultural products to its most recent utilization as a material to construct beds for use in COVID treatment centers and even in Olympic 2021 residential spaces.

The quest of raw agricultural produce from the cultivation plat all the way to the consumers consists of handling, storage, transport, and distribution, which requires cardboard packaging, wooden crates [3], jute bags, plastic pouches and crates, to name a few. The primary purpose of packaging is to provide a safe enclosure for the contents from the hazards encountered from the tasks involved during the transfer of the items from the producer to the end-user. In India, before 1987, wooden crates and cases have been the primary choice for transportation of apples in the country [4]. With depleting forest resources, an alternate from crude materials, a sustainable method for packaging was greatly sought after. As a consequence, the use of eco-friendly pulp products has gained importance particularly with corrugated fibreboard boxes for the packaging of apples [5,6]. This began to be practised widely and soon proved to be a healthy substitute for wooden crates. As per recent market trends, cardboard packaging or corrugated fibreboard boxes provide an affordable and versatile means for packaging and have become the most widely acceptable option for use in the packaging industries, particularly for transporting manufactured goods and fresh agricultural items. The popularity and widespread use can be attributed to the large-scale recyclability, economic aspects, appropriate cushioning and high stiffness as well as strength to weight ratios. Their low cost also has an added advantage and are preferred to transport contents that have value several times higher than the former.

The CFB boxes are one of the most crucial structural applications of CFB panels and are fabricated using panels of suitable dimensions. The package should maintain its structural integrity and support the display of artistic graphical details over the body. Corrugated board panels are manufactured using virgin wood or plant fibres that have been formed into a pulp [7] (kraft paper: paper with high mechanical strength and prepared from unbleached sulphate pulp) or fibres from recycled paper. Due to its recyclable properties, fibreboard containers have helped with the conservation of precious forest raw materials and its associated transportation [8]. The recycling capacity usually varies from five to seven times [5]. Beyond the recyclable life, paper products can be disposed-off at landfills which has little to no impact on the environment as compared to non-biodegradable counterparts such as plastics [9]. The panels form a structure that is commonly known as sandwich structure or monolithic material [1,10]. There are several variations available for the panels in terms of thickness of each layer, number of layers (ply), take-up factor of flutes, etc. For a widely used 3-ply system panel board, each panel consists of two liners (or facings) and a corrugated medium (or core). The corrugated medium is formed by passing a sheet through corrugation profile rollers after being preheated and steamed to enhance the formability of the flutes [11]. Further, an organic starch-based adhesive derived from potato, corn or wheat is applied upon the crests and troughs of the corrugated medium and secured with the liners to form a panel with pressure from rollers [12]. The liners provide bending stiffness whereas the corrugating medium forms a lightweight separating medium for the liners and provides shear stiffness to the panel [1,13]. It has been found that good combination of the flutes and the liners will provide superior compressive strength to withstand stacking and resist buckling [1,10]. Figure 1 depicts a simple process flow for the manufacturing of CFB boxes.

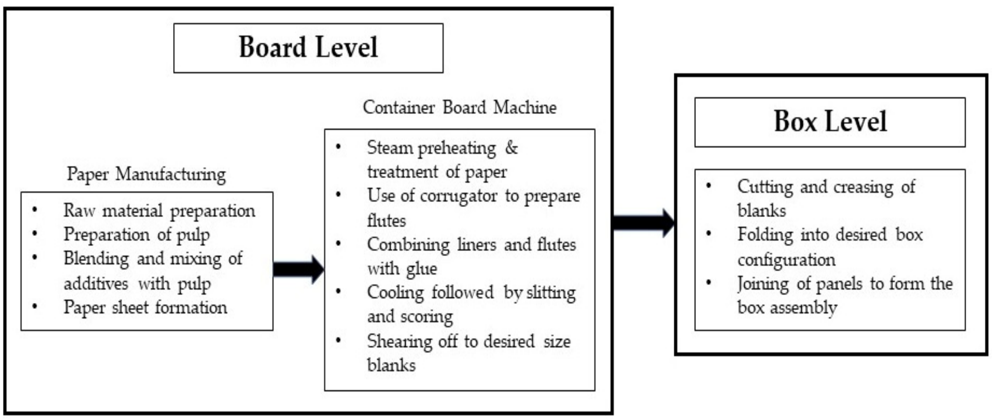


Figure 1. Process flow for CFB box manufacturing.

The use of paper for the manufacturing of packaging containers is an important application. By 2018, paper and paperboard as a packaging medium represented 40% in the global market, which is the major contributor compared to other materials such as plastic, glass, metal, etc. [1]. CFB boxes are considered a secondary or transport packaging medium whose purpose is to store a primary item or a group [14]. A CFB package is subjected to a wide variety of loadings such as compression, impact and vibration during its life. These structures are susceptible to damage and reduction in its strength. Most research for corrugated paper mainly consists of investigations on compression loading and transport dynamics phenomenon [15]. Several factors affect the structural performance, including the mechanical properties of the panel combination, structural stability, the panel combination's mechanical properties, structural stability, and the quality of the input cellulose fibres [16]. The design and development of CFB boxes depends on the item that is required to be transported. This process usually includes estimation of mechanical forces, supply chain environment and several other factors [14]. The failure of the CFB panels and boxes are mainly estimated by the buckling of the structure under the applied compressive loading, particularly during stacking configuration. Therefore, the lowermost package should contain sufficient strength to avoid failure and damage to the products inside. Thus, the understanding of the buckling behaviour is of crucial concern.

The structural performance of a CFB box depends on several factors primarily defined by the structural shape and the process of preparing the box from panels [14]. Ventilated corrugated packages (VCP) are the most extensively used type of CFB boxes that facilitate the handling, storage and transportation of fresh agricultural products from the farmers to the consumers [17]. It has been found that the flutes in the sandwich CFB panels also serve to provide thermal insulation and facilitate airflow in the package, making it ideal for fresh produce industries [1]. Moreover, vent holes are provided in order to facilitate the uniform conditioning of the fresh products, particularly for agricultural produces, during their storage cycle [10]. It helps in maintaining the temperature, humidity and air velocity flow conditions as fresh produces respire even after their harvest [1]. In addition to the ventilation holes, additional holes are provided to facilitate the handling of the containers. The provision of slots in boxes results in the loss of material from the packaging and thus leads to a lowering in the strength. Good compression strength is an essential requirement for an ideal package. The loss in strength is a vital function of the shape, size and location of the handling/ventilation holes [3,17]. It was found that a linear relation exists linking the hand/ventilated hole area and the structural strength of the box [18]. Therefore, an optimum design has to be established to balance the ventilation and the strength of the packaging. Previous studies have been conducted to understand the phenomenon using the various experimental, analytical and numerical approaches.

The intensity of the bulge deformation of the panels depends on the bending stiffness and box panel dimensions [14]. Bulging of the boxes is undesirable as it damages the filled contents and may also affect the integrity of the surrounding boxes, particularly in a stacking scenario. Thus, the top-to-bottom compressive strength of boxes that influence this phenomenon depends primarily on the stiffness of the panels. The stacking performance of CFB boxes can be improved by improving the ability of the panels to resist the applied loading and flexural stiffness can be defined as the panel's resistance to applied loading [19]. It has been reported that the flexural stiffness in MD is approximately 1.29 to 1.48 times higher than that in CD but the maximum bending force and deflection are higher in CD than in MD [19].

Globally, there is a wide range of packaging standards for transporting items from the producer to the end-users. Bureau of Indian Standards (BIS), under the Government of India, adopted IS 6481 (1971) standard on 29th November 1971 which states the guidelines for the principal uses and styles of CFB containers to benefit the manufacturers and end-users for the Indian market. It considers various intricacies involved in the development of fibreboard packaging and provides the factors for the correct use and design. The different construction varieties of containers that have been listed in this standard are accepted by the European Federation of Corrugated Board Manufacturers (FEFCO), which is well-known globally.

However, concerning the Indian market scenario, the mass manufacturing of the conventional CFB boxes is based on empirical relations, subjected to structural strength tests to suit the application and usually overdesigned. Moreover, there are poorly set standards or the standards are not usually followed for the design of boxes by the mass manufacturers and/or usage of these boxes at various stages of the supply chain. These shortcomings need to be addressed to optimize the material consumption in manufacturing of the package without compromising the intended usage. The current research problem is on modelling CFB boxes used to pack apples recommended by the Bureau of Indian Standards. Through this study, the authors aim to understand the behaviour of such a structure which would facilitate the process of design and development of an optimal box structure to satisfy the requirements and improve the performance of the currently utilized packaging with the frugal utilization of material without compromising the strength requirements. Further, the concept of stiffener will be introduced as a load-bearing enhancement feature. This will help establish a rationale and enable the corrugated fibreboard manufacturers and consumers to improve the understanding of the behaviour of such structures and help to check for the cost utilization, avoid overdesign and further mitigate the failures in practical applications. For this study, Indian Standard IS 2771-1 (1990) was taken as the baseline for incorporating improvements to the packaging currently used for the packaging of apples in the Indian market. The terms used in this text adheres to the IS 4261 (2001) standards and can be referred to for detailed information [20]. The objective of this research is to optimize the corrugated fibreboard (CFB) boxes recommended by the Bureau of Indian Standards (BIS) for packaging apples and suggest improvements for the same with respect to the scope of reduction in material utilization for manufacturing the boxes has been looked upon without compromising the basic requirements. The novelty of the present study is displayed by considering a CFB box recommended by BIS for packaging of apples and looking into the possibilities of design modifications in order to reduce the material utilization for manufacturing a box. Through this study, the authors have attempted to display measures for a sustainable approach to manufacture a CFB box for packaging and transport of fresh agricultural produce by minimization and frugal utilization of raw materials. This will promote a responsible frame of mind with respect to its manufacturing which will amalgamate its application and environmental impact.

2. Materials and Methods

CFB boxes are commonly used to transport perishable items such as fresh agricultural produce, particularly for pome fruits such as apples, in the context of the Indian market and also on a global level [1]. Thus, the integrity of the packaging is an important criterion to ensure the safekeeping of the packed items. This study involves the modelling of a package recommended as per Indian standard for the transport of apples. The package will further be subjected to design variables with respect to the ventilation slots and venture into the possibilities of reduction in terms of material utilization during the manufacturing of each box without compromising the desired mechanical features. A mathematical model via the method of FE will be proposed to represent the actual packaging behaviour with highest degree of accuracy. In general, the FEM procedure can be classified into three main stages: pre-processing, solution and post-processing. After verification of the model, it can be utilized further to study the desired parameters.

Virtual modelling of the CFB panels and boxes is difficult as it is composed of a planar network of cellulose fibres bonded together by fillers, the presence of additives, and the large randomness in the fibre orientations resulting from the fabrication process results in anisotropy in the material properties [11]. Fibres typically have high length to diameter ratio. In addition, length, orientation and concentration of fibre, and the quality of raw material used [7] affect the strength of the structure. It is considered as a composite structure and consists of a non-linear stress-strain relationship [11]. A reasonable and convenient way for modelling a CFB material is by assuming it as an orthotropic material because the fibre orientations are nearly symmetric [1,21], that is by approximating the material to have stiffness properties different in the three orthotropic directions [14]. The principal directions serve as the directions for elastic symmetry. Several analytical and numerical techniques have been developed to analyze CFB panels and boxes with detailed or equivalent corrugated board models. For CFB panels to be treated as an orthotropic material [1,15,22], it can be discretized in three principal directions on the macroscopic level as and pictorially described (Figure 2):

(1) Machine direction (MD);
(2) Cross-machine direction (CD);
(3) Out-of-panel direction (ZD).

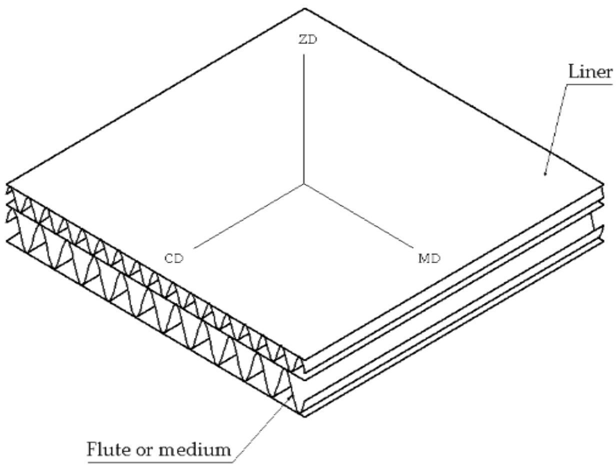


Figure 2. Nomenclature for scientific representation of a CFB panel. It has been described as an isometric view of a double wall (DW) corrugated fibreboard.

The MD is the direction along which the panels are usually flowing during the manufacturing process. It comprises superior material properties when compared to the other two directions as the longitudinal axis of the paper fibres becomes parallel to this direction. The CD direction, which is parallel to the flutings, represents the transverse direction to MD in the same plane, and ZD represents the direction of the MD-CD plane or the thickness direction [7,22]. As a result, of the orthotropic character of the material, the mechanical behaviour would differ in different loading directions.

The structural performance of a CFB box is administered by the mechanical properties of the paper constituents and dimensions of the container itself [14]. The characterization of paper performed by Biancolini, Brutti and Porziani consists of the following parameters [23]:

(a) E_x: Young's modulus in MD;
(b) E_y: Young's modulus in CD;
(c) E_z: Young's modulus in ZD;
(d) ν_{xy}, ν_{xz}, ν_{yz}: Poisson's ratios;
(e) G_{xy}, G_{xz}, G_{yz}: Shear moduli.

The subscripts x, y and z represent the MD, CD and ZD directions, respectively. This nomenclature will be adhered to in the following text.

The elastic constants help us to establish a relationship between stresses and strains in the material within the linear elastic behaviour (i.e., independent of loading rate and reversible), and their components can be represented with the help of elastic compliance tensor as [14]:

$$\in = S\sigma \tag{1}$$

$$\left\{\begin{array}{c}\in_x\\ \in_y\\ \in_z\\ \gamma_{xy}\\ \gamma_{xz}\\ \gamma_{yz}\end{array}\right\}=\begin{bmatrix}\frac{1}{E_x} & \frac{-\nu_{yx}}{E_y} & \frac{-\nu_{zx}}{E_z} & 0 & 0 & 0\\ \frac{-\nu_{xy}}{E_x} & \frac{1}{E_y} & \frac{-\nu_{zy}}{E_z} & 0 & 0 & 0\\ \frac{-\nu_{xz}}{E_x} & \frac{-\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{yz}}\end{bmatrix}\left\{\begin{array}{c}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{xz}\\ \tau_{yz}\end{array}\right\} \quad (2)$$

A widely used method to estimate the 3-D state of stress in a system is to evaluate the equivalent stress (σ_e) or commonly known as Von Mises stress with the Equation (3) as below [24,25]:

$$\sigma_e = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2}{2}\right]^{1/2} \quad (3)$$

where, σ_1, σ_2, σ_3 = principal stress ($\sigma_1 > \sigma_2 > \sigma_3$).

The deformation for the system is described by resultant or total deformation (U) given by [26]:

$$U = \left[U_x{}^2 + U_y{}^2 + U_z{}^2\right]^{1/2} \quad (4)$$

where, U_x, U_y, U_z = three component deformations.

2.1. Box Properties

Some of the general features of the Indian standard recommended package are:

- Type of box: Telescopic type box;
- Box dimensions (Length, L × Width, B × Height, H): 504 × 303 × 290 mm;
- These are internal box dimensions of the inner box as specified to the manufacturer by the purchaser with a net content weight of 16–20 kg [4]. The maximum combined internal dimension of the box (L + B + H) → 1575 mm [27];
- Number of plies: 5-ply or double-wall for maximum mass content of 16–20 kg as per Table 2 in IS 2771-1 (1990);
- Flute type: A > C > B
- Type-A flutes provide the best stacking strength and cushioning among all. Type-B has superior folding property and executes better strength along score lines. Type-C flutes consist of properties intermediate to Type-A and Type-B [27];
- Ventilation slot dimensions:
    - Inner box → 70 × 15 mm
    - Outer box → 60 × 15 mm
- Average compression strength: 500 kgf (~4903.32 N) with deflection less than 20 mm. This criterion has been benchmarked and considered for the failure of the packaging box in this study.

Mechanical Properties of Panel Constituents

The elastic moduli have been estimated with the help of the mathematical Equation (5) using flexural stiffness of specimen (S_b), specimen width (ω) and the moment of inertia of the panel (I) as depicted by Han et al. [28]. Since nine material properties are required to prepare the virtual model, apart from E_x, E_y, ν_{xy} and ν_{yz}, remaining properties have been approximated from relations as depicted in Equation (6) [28]:

$$E = S_b \frac{\omega}{I} \quad (5)$$

$$E_z = \frac{E_x}{200} \quad G_{xy} = 0.387\sqrt{E_x E_y} \quad G_{xz} = \frac{E_x}{55} \quad G_{yz} = \frac{E_y}{35} \quad (6)$$

The values of the properties for DW panels have been referred from along with the remaining properties estimated using Equation (5) and has been tabulated below in Table 1 [28].

Table 1. Material properties of CFB DW and SW panels components used for modelling.

Property	Values for DW Panels	Values for SW Panels
E_x (MPa)	3690.00	3114.7
E_y (MPa)	1560.00	1611.2
E_z (MPa)	18.45	15.574
ν_{xy}	0.28	0.28
ν_{xz}	0.12	0.12
ν_{yz}	0.12	0.12
G_{xy} (MPa)	928.51	866.95
G_{xz} (MPa)	67.09	46.034
G_{yz} (MPa)	44.57	56.631

The above properties have been modified using Equation (5) to perform a similar analysis on the SW panel box using analytical and experimental values by Lee et al. [19].

In practice, the standard dimensions for individual flutes may vary from one production facility to another. For the current study, geometrical data for the modelling of corrugated board panels for the boxes have been referred from the journal by Lee et al., and mentioned in Table 2 [19].

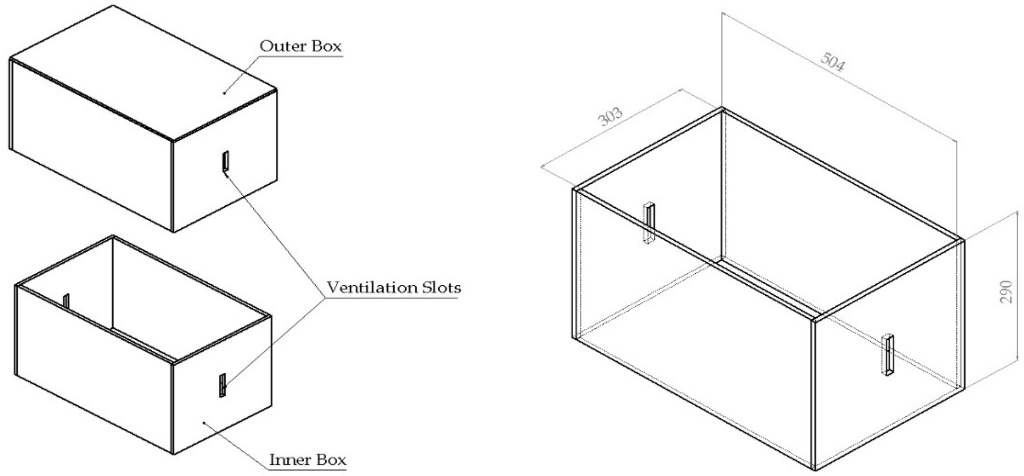
Table 2. Thickness of individual plies and flute dimensions of CFB panels.

Parameter	DW with AB/F (Flutes)	SW with A/F (Flutes)
Thickness of liners (mm)	0.253	0.253
Height of A flute (mm)	5.161	5.422
Height of B flute (mm)	2.911	-
Number of corrugations (Per 300 mm)	A flute: 35 B flute: 54	35

2.2. Finite Element Simulation

To materialize the objective of this study, finite element modelling was utilized to understand the structural features of a CFB container [22]. Stress and displacement fields are of primary importance with regard to a structural mechanics problem. The validation conceived FE modelling of similar models from the journal by Han et al. [28]. The authors, in their work have established superior FEA models that confirmed experimental results with sufficient accuracy. By utilizing a similar methodology, the authors have extended the philosophy to study the packaging containers for transporting apples specified as per Indian Standards. IS 11844 (1987) states the standards for usage of corrugated fibreboard boxes for the transport packaging of apples in the Indian market scenario. It was published in March 1987 and was reaffirmed in October 2019.

For the virtual modelling and analysis, a standard FEFCO (European Federation of Corrugated Board Manufacturers) 0320 telescopic type box recommended as per IS 11844 (1987) has been considered. A telescopic box consists of two or more pieces, typically with a lid engulfing the body of the inside box. Figure 3 depicts a virtual model of the container recommended by the said standard. According to Lee et al. [19], the compressive strength of packages with flutes perpendicular to the length was 20% higher than for configuration with parallel flutes apparently due to the flutes acting as vertical columns. The predominant failure mechanism was however confirmed to be due to the local failure of the flutes. A similar philosophy was used to model the boxes for analysis which will help us to optimize the current design. Optimizing the design will improve the protection and reliability of the package in which the products are placed and thus reduce the cost associated with failure. In addition, this will support the proper design of such packages without any overdesigning, ultimately leading to savings in material cost.



(a) (b)

Figure 3. Virtual representation of a telescopic type box used for transportation of apples recommended as per IS 11844 (1987) as: (**a**) Inner box and outer box of the telescopic type box configuration; (**b**) Dimensions of the inner box as per standard specification.

2.2.1. Modelling

For a body under equilibrium, the net forces and moments acting on the system must be zero and should satisfy the equations of equilibrium. With the help of index notations, the equilibrium equation with stress 'σ' and body forces 'F' can be stated as in Equation (7) [29]:

$$\sigma_{ji,j} + F_i = 0 \tag{7}$$

From finite element formulation, the system is discretized into a number of smaller sized elements called elements. The corner points of these elements are called nodes and the unknown parameters (displacements) in the form of trail functions are defined on these nodes. Further, strains ($\in$) and stresses are related with the displacements (U) as given by Equations (8) and (9) [25].

$$\{\in\} = [B]\{U\} \tag{8}$$

where, [B] is the matrix for strain-displacement;

$$\{\sigma\} = [D]\{\in\} = [D][B]\{U\} \tag{9}$$

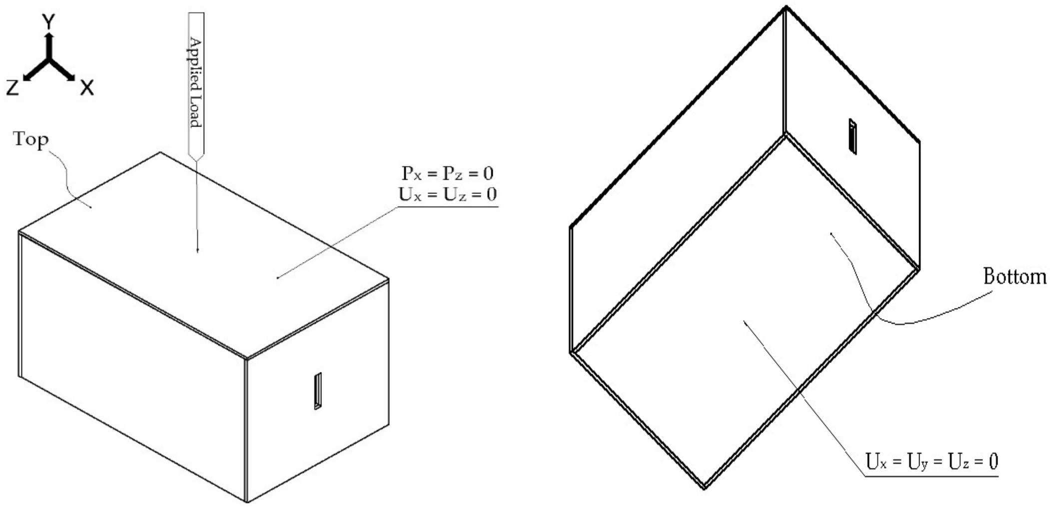
where, [D] is the material matrix.

For the finite element modelling, the panels were individually modelled and assembled to prepare the box structure. Further, the 3-D model was interfaced with suitable specifications onto ANSYS 18.1 to study the physics associated. ANSYS 18.1 Mechanical analysis system was further used to implement the necessary boundary conditions and extract the study results.

2.2.2. Boundary and Loading Conditions

The CFB containers are exposed to a variety of loading conditions in the practical field under various constraints. For this study, the current problem has been considered as a displacement problem. The base of the box was assumed to remain in a constrained configuration, similar to an actual practical scenario. The base nodes were assigned accordingly to have no displacements in the x, y and z directions. The authors have considered the top of the box to subjected uniform loading over the edges. This is true when the box withstands the compressive loads alone, and the stored items do not provide any bearing surface to share the loading. Further to accompany this condition, adopting the philosophy of Han et al. to simulate compression situations, the authors have assigned a 4% top-to-bottom compressive displacement on the nodes at the top of the box [28]. The panels for the inner and outer boxes, respectively, were assumed to have perfectly bonded interfaces with each other having continuous displacement and traction fields, whereas the interaction between the outer and inner boxes was allowed such that motion was permitted without any resistance along the plane of the panels specifying a displacement discontinuity between the inner and outer boxes.

For studying the application of stiffeners on a package, an evenly distributed load was applied over the top panel of the box. This replicated the compressive loading nature under stacking configuration. In addition to the above-mentioned boundary conditions, the top features of the box were constrained to have only in the direction of loading. Figure 4 depicts a description of the boundary conditions as described above with displacements represented by ‘U_i’ and loads with ‘P_i’, where ‘i’ is the direction with respect to the global coordinate system.



(**a**) (**b**)

Figure 4. Visual description of boundary conditions used for simulating the package as: (**a**) Boundary constraints applied over the top of the package; (**b**) Boundary constraints applied at the bottom of the package.

2.2.3. Mesh Sensitivity Analysis

The domain of the models was discretized by using the ANSYS Mechanical meshing toolbox. A conformal mesh was ensured between the interacting elements of the inner and outer boxes, respectively. To select a mesh size suitable to be used in the current study, a mesh convergence study in terms of element spacing (h-convergence) was performed concerning the maximum and minimum equivalent stresses generated in the FE analysis. Figure 5 depicts the variation of stresses with a decrease in the mesh size. A convergence criterion was set at <±2% deviation between the stress for consecutive mesh sizes. A global mesh size of 4.9 mm was found to satisfy the convergence criterion stated above with respect to both the maximum and minimum stress generation. Beyond this value, the deviation was greater than to be acceptable for this study. Thus, this mesh size was chosen for further iterations in the design problem. It will help to ensure that the FE models are neither computationally expensive nor possessing discretization errors.

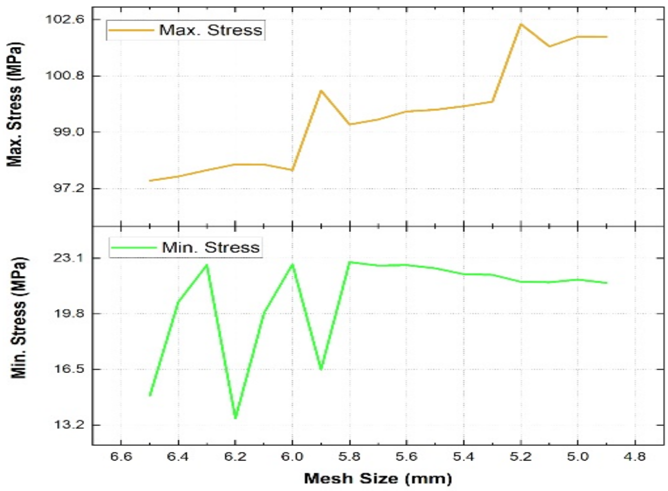


Figure 5. Graph depicting the mesh convergence study performed to establish a constant global mesh size.

3. Results and Discussions

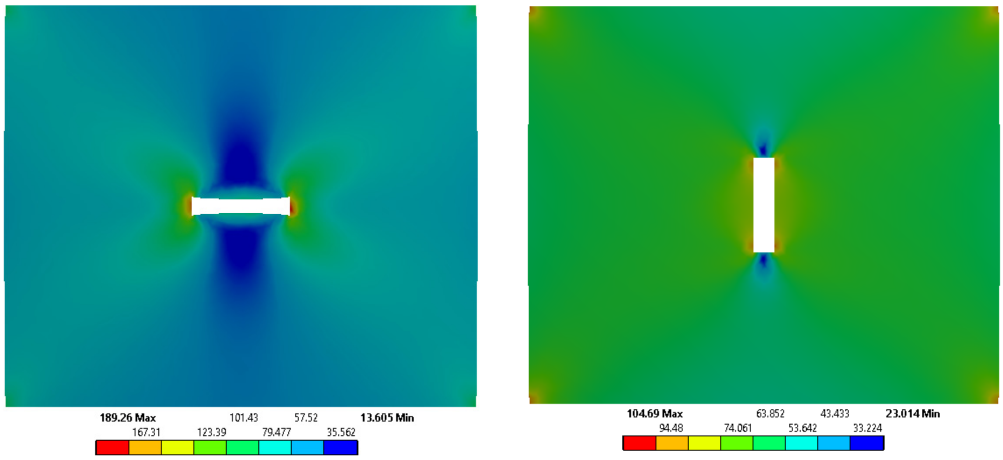
The results of this study have been divided into three subheadings and are discussed below.

3.1. Effect of Change in Configuration of Ventilations Slots

Table 3 shows a comparison in terms of stress generated in the vicinity of the slots for various configurations placed on the box's shorter side panels. Horizontal ventilation slots generate more stresses as compared to vertically placed slots as shown Figure 6. The loading pattern over the top panel of the box generates compressive stresses in the vertical panels. The ventilation slots are a source of discontinuity in the panel and provides obstruction to the uniform stress distribution around it. The horizontal slot configuration issues a more severe obstruction to the generated stresses as compared to the vertical slot configuration. As the loading progresses, the shape of the hole distorts with the horizontal edges of the slots coming closer to each other which further leads to increase in the stress intensity and concentration near the corners of the ventilation slot. As a result, the intensity of generated stresses is greater in horizontally located slots as compared to its vertical counterpart under a given magnitude of loading. This was found to be true for both rectangular and oblong-shaped horizontally located slots. Regarding vertical configuration slots, rectangular slots show lower stress generation than the oblong-shaped slots though the increase is limited to +1.37%. This result can be supported with a similar conclusion found by Singh et al. from their experimental study [18]. Further, it was observed that a full depth ventilation slot hole of the larger size could help reduce the maximum stress generation by 4.1%.

Table 3. Equivalent stresses (in MPa) for different slot configurations.

Slot Configuration	Maximum Stress	Minimum Stress
IS box	104.510	22.952
Full depth slot	100.220	35.901
Vertical oblong shape	105.940	25.452



(**a**) (**b**)

Figure 6. Contour plot for equivalent stress (in MPa) generated around the slot of the same area as: (**a**) Horizontal ventilation slot; (**b**) Vertical ventilation slot.

Concerning this argument, the authors have realized the following advantages of the mentioned slot configuration:

- The increase in the dimensions of the slot on the outer box from 60 × 15 mm to 70 × 15 mm, similar to the inner box corresponding to an increase of 16.667% in slot area, will lead to a decrease in the volume of a box by ~0.08% and thus a reduction in resource utilization, item cost and net weight per box. This material saving can be realized with the high magnitude of boxes manufactured per year;
- A single die can be incorporated to fabricate the ventilation slots in the panels instead of two different in the present scenario;
- The abrupt change in the ventilation slot dimensions can lead to an increase in pressure drop across the slot interfaces resulting in inferior fluid flow characteristics and thus poor ventilation performance.

However, a more detailed study in terms of fluid flow analysis would be required to determine whether the increase in stress for horizontal slots is beneficial in enhancing the ventilation characteristics for the flow of fluid to condition the stored items.

3.2. Effect on Box Performance on Replacement of Double-Ply Panels with Single-Ply Panels

As per IS 2771-1 (1990), the use of DW or 5-ply corrugated board has been recommended for boxes used for mass content of 20 kg. Through this sub-section, the authors have tried to estimate the effect on box performance on replacing DW corrugated boards with SW or 3-ply boards w.r.t the box's structural integrity.

From a general perspective, it can be implied that as less material is available to resist the applied load, the deformation will tend to increase. In general, under the application of a fixed load and same boundary conditions, the reason for the above statement can be attributed to the use of lower number of plies in the system. Table 4 displays the total deformation values for different box configuration systems. It is observed that there is an increase in the magnitude of the stress with the decrease in the number of plies. However, the pattern of stress generation is the same as the former DW system with maximum stress generated at the corners of the packaging. These observations confirm with the findings by Han et al. [28].

Table 4. Comparison of total deformation for different box configuration systems.

S. No.	Box Configuration	Total Deformation (mm)	Percentage Increase w.r.t IS 5-Ply System (%)	Equivalent Stress (MPa)
1.	DW system	9.389	-	8.485
2.	SW system	17.252	83.747	16.611
3.	SW system with full-depth slot	17.252	83.747	16.611

To realize the reduction in the volume of material required to manufacture a box with 3-ply system w.r.t a 5-ply system, the authors have introduced a factor which is defined as:

$$\text{Material Savings Factor (MSF)} = \frac{\text{Volume of Indian Standard box}}{\text{Volume of altered system box}} \tag{10}$$

MSF will provide an idea to the designer to interpret the effectiveness of a similar alteration methodology. A factor greater than one will indicate an improvement to the standard box design with a reduction in material utilization for manufacturing the box. The percentage change in material consumption can be found out by using Equation (11) given below.

$$\text{\% change in material utilization} = \left(1 - \frac{1}{\text{MSF}}\right) \times 100 \tag{11}$$

SW corrugated board contributes to about 80% of the total corrugated board [1], among different types of corrugated boards produced globally. Its use can significantly reduce the dependency among the niche manufacturers producing DW or TW boards. By altering the current Indian Standard DW system box with a SW system box configuration, a reduction of 34.558% can be expected in material consumption with an MSF of 1.5281. Further, with a full-depth slot, the material utilization can be reduced to 34.573% (MSF = 1.5284). It means a large amount of savings in raw material and reduce the cost of manufacturing a box for our intended use. Due to the less structural material volume content of the containers, the total weight can also to brought down, which would further result in an appreciable reduction in transportation cost and encourage more efficient utilization of space.

However, as per the design requirements, the total deformation needs to be contained to ensure the structural integrity. An innovative methodology to address the same has been conceptualized in the following sub-section.

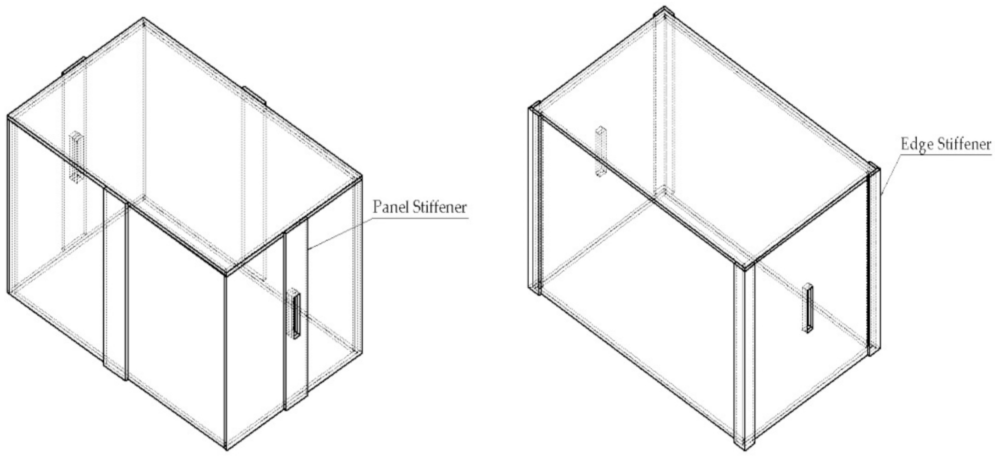
3.3. Effect of Stiffeners on the Box Compression Strength

The rationale behind introducing stiffeners is to reduce the deformation of a SW box to comply with the design requirements same as for DW boxes. Stiffeners are slender geometrical cut-outs that can arrest excessive deformation by providing extra stiffness to the box. For this study, stiffeners of the same SW cardboard panels have been considered to understand its effect. Two stiffener configurations have been studied, namely: vertical panel stiffener configuration and vertical edge stiffener configuration. The different iterations for each configuration considered for this study have been summarized via Table 5. The stiffener sizes have been considered a factor of the longer side of the box and the longer side of the box and a fixed width for a particular iteration. Configuration IX represents the limit for the panel stiffener when it covers the entire short vertical face.

Table 5. Summary of different iterations of each stiffener configuration.

Configuration	Description	Configuration	Description
I	IS 5-ply	IX	61.78% panel stiffener
II	3-ply	X	10% edge stiffener
III	Modified 3-ply	XI	20% edge stiffener
IV	10% panel stiffener	XII	30% edge stiffener
V	20% panel stiffener	XIII	40% edge stiffener
VI	30% panel stiffener	XIV	50% edge stiffener
VII	40% panel stiffener	XV	59.07% edge stiffener
VIII	50% panel stiffener		

Similarly, configuration XV represents the width limit for the stiffener at the short face without interference to the ventilation slot. The reason behind choosing the configurations mentioned above is due to the fact that vertical panels of a CFB tend to bulge inwards or outwards due to compressive loads under stacking [17]. In addition, it has been reported that 40–64% of the compressive load is sustained by the edges of the packaging and the panels sustain the remaining [1]. Figure 7 provides a visual overview for the incorporation of the stiffener with the package.



(**a**) (**b**)

Figure 7. Stiffener configurations as: (**a**) Modified 3-ply package with 10% panel stiffener; (**b**) Modified 3-ply with 10% edge stiffener.

The stiffeners have been placed in a vertical configuration to oppose the applied load over the top panel of the box. To assist with determining the effect of varying the stiffener widths, a factor of safety (FOS) has been defined as per Equation (12) satisfying the IS requirements. The maximum load corresponds to the absolute value of compressive load at which the package undergoes a deformation specified in the standard and has been reported with an accuracy of 20 ± 0.1 mm.

$$\text{FOS} = \frac{\text{Maximum Load}}{\text{Design Load}} \tag{12}$$

The FE simulations results have shown that the maximum deformation is observed at the top panel of the box subjected to the loading as shown in Figure 8. This phenomenon is characterized by a phenomenon which is characterized by lower stiffness of the top panel compared to the vertical panels. This observation is compliant with the findings of Fadiji et al. [1]. Figure 9 depicts the decrease in maximum deformation with an increase in the stiffener size.

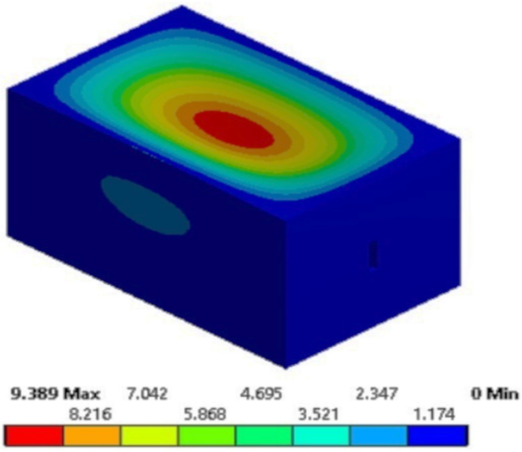


Figure 8. Deformation (in mm) over the top panel for configuration I.

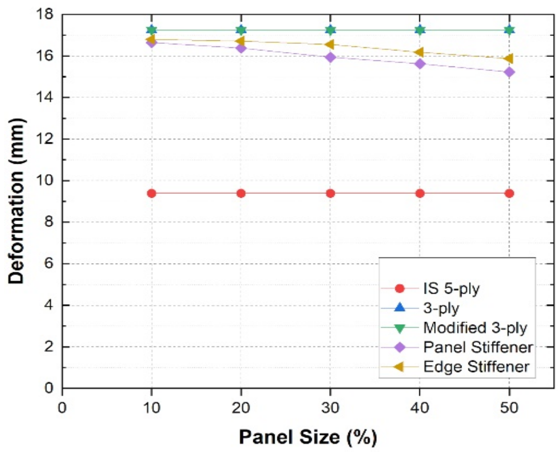


Figure 9. Comparison of deformations for different package configurations.

Referring to Figure 10, an increasing trend was observed w.r.t FOS. With the observations, it can be concluded that stiffeners can serve as additional load-bearing members for the structure and improve the capacity of withstanding external loadings of the package.

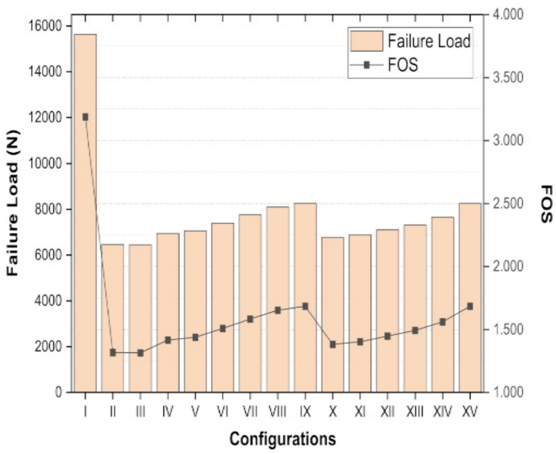
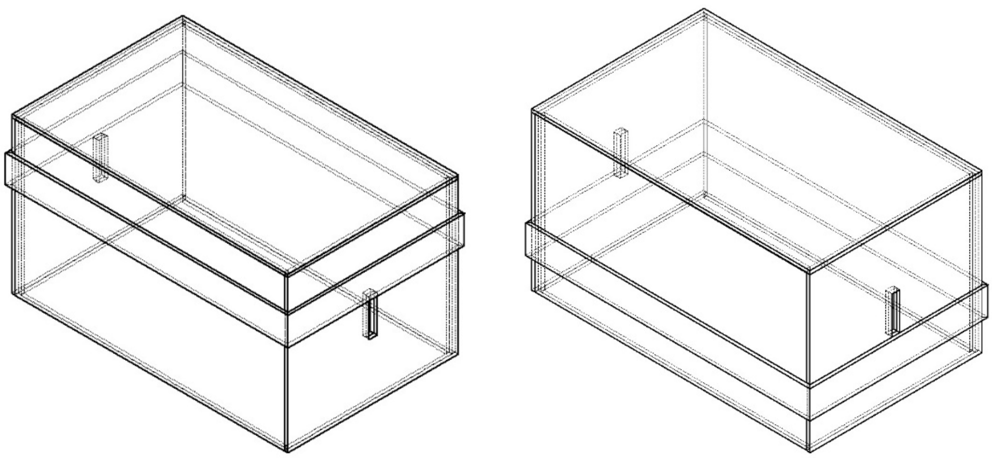


Figure 10. Failure loads and FOS for different package configurations.

From the data described in this subsection, it has been observed that the MSF for edge stiffener is higher than that of a comparable panel stiffener. However, the difference is less than 1% which might not be justified with the extra effort involved in preparing the edge stiffener. Moreover, panel stiffeners' performance is superior to their counterpart edge stiffener as its implementation results in lower deformation and higher FOS for the same width. For the stiffener configuration at the width limits, the difference was down to 0.422%.

Further, looking into another possible stiffener configuration, the authors have considered horizontal stiffeners. This configuration was integrated at two specific locations above and below the ventilation slot to look into its effectiveness, as depicted in Figure 11. The interpretation of the FE study showed that both the horizontal stiffener configuration resulted in reducing the total deformation with the stiffener above the ventilation slot showing greater reduction in deformation as compared to its counterpart. This is likely because placing the stiffener above the ventilation slot enabled to restrict the bulging out the side panels due to the top-to-bottom loading over the top panel of the box. In addition, it is observed that the equivalent stresses are higher for the configuration with the stiffener placed below the ventilation slot as compared to when placed above. However, the sole integration of the horizontal stiffener configuration displays an inferior performance in terms of total deformation and maximum loading capacity when compared to the vertical panel and edge stiffener configuration of the same width. In addition, the material utilization increases by more than 2.3%. The integration of the horizontal stiffeners was also analyzed in a combination of the same with vertical stiffener configurations. It was observed that introducing both the vertical and horizontal stiffener to the package helped in further reducing the total deformation and improving the stacking strength for a given width, but this increase will not be justifiable by the fact that the material utilization per box increases by a greater extent. Hence the horizontal stiffener integration may not be looked into further. Thus, it can be concluded that the panel stiffener can serve to be a superior configuration for the external stiffening of a CFB box.



(**a**) (**b**)

Figure 11. Horizontal stiffener configurations as: (**a**) Above ventilation slot; (**b**) Below ventilation slot.

From the fabrication point of view, the stiffeners can be used as an attachment with the container boxes with the help of procedures similar to standard enclosing guidelines for shipping containers as per IS 6481 (1971). A few notable are [8]:

- Staples and stitches: To fix the stiffeners to the panels of the container, wide crown staples can be used around the vertical edges of the stiffeners. Similarly, a portable stitching apparatus can be helpful to speed up this process and provide a uniform pattern attachment with the panels;
- Glue: Starch-based glue same as the one used for joining corrugating medium, and the liners can be utilized.

4. Conclusions

A detailed study was performed on CFB package for the transport and storage of apples by applying FEA to understand the various dimensional dependencies on the box's structural integrity. The authors have tried to look into the possibility of implementing a modified 3-ply box to replace the existing package to reduce the material utilization per box.

The following key points can be concluded from our study:

1. Vertically oriented ventilation slots result in lower stress generation as compared to its horizontal counterpart slots. With regard to the shape of the slots, rectangular slots show lower stress generation than the oblong-shaped slots with a full depth ventilation slot reducing the maximum stress generation along with benefits in terms of material utilization. Hence, it can be concluded that the use of a full-depth vertical ventilation slot can improve the current IS design with reductions in terms of material utilization and overall cost;
2. With the total deformation limited to below the standard recommendation, a 3-ply system can be proposed as a replacement for the current 5-ply IS package. This design modification can result in significant material saving of 34.558% and can help in mitigating the associated issues;
3. The use of stiffeners can lead to improvement in the stacking performance of a package. With the introduction of stiffeners to the package, the stiffness of the structure improved that resulted in lowering of deformation and an increase in the loading capacity. The panel stiffeners' performance was found to be superior when compared with the edge stiffeners as it resulted in lower deformation and higher FOS for the same width. The sole implementation of horizontal stiffener configuration displayed an inferior performance in terms of total deformation along with the increase in material utilization. The integration of the horizontal stiffeners as a combination with vertical stiffener configurations was not found be justifiable by the fact that the material utilization per box increased by a greater extent.

The ultimate aim of a package should be to provide sufficient protection to the content stored at the minimum cost possible. Through this study, the authors could also establish FEA as a potential method to be used for the optimization of CFB packaging. It will help designers to optimize their design in terms of strength and check material usage. Further, this enables the quick and effective designing of packages for new products and adds high value to the packaging industry.

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