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Virtual Drop Test Analysis of Corrugated Box Packaging for Material Handling

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Abstract

This research paper investigates the impact behaviour of corrugated boxes through drop tests, employing the 3D Experience platform for modelling and simulation. Various thicknesses of corrugated boxes (1 mm, 2 mm, 4 mm, and 6 mm) are analysed by dropping them from a height of 1 m. The structural package app is utilized for model creation, while pre-processing is conducted using structural model creation and mechanical scenario creation apps. The study incorporates wood and aluminium blocks within the box for testing, considering their respective yield strengths. Additionally, to accurately represent the material properties, composite modelling techniques are employed. This study aims to enrich our understanding of corrugated board behaviour under impact conditions and optimize its design for enhanced mechanical performance. Adding thickness to a component can indeed help reduce stress during a drop test, but it is not the only factor to consider. Increasing thickness can distribute forces more evenly and provide greater structural integrity, thereby reducing stress concentrations. However, other design features, such as changing material properties, can also play a significant role in stress reduction. It is essential to analyse the specific requirements and constraints of the drop test scenario to determine the most effective design modifications. The maximum Von Mises stress for corrugated cardboard box drops from 4×10^6 Pa in Case I to 1.41×10^6 Pa in Case IV, reflecting a reduction of 64.75 %. This highlights the significant stress reduction achieved with increasing thickness. The observed decrease in stress levels with thickness underscores the importance of considering material properties, stress concentrations, impact response, structural integrity, and design optimization strategies in developing robust and reliable components for drop test applications.

Major Findings: *The primary discovery is that augmenting the material's thickness markedly reduces Von Mises stress, thereby improving load-bearing capacity and structural integrity. Furthermore, employing sophisticated simulations such as virtual drop tests enhance design precision by detecting potential failure points.*

Keywords: Composite Modeling, Corrugated Box Design, Drop Test, FEA, Material Handling

1.0 Introduction

Corrugated cardboard boxes play a crucial role in protecting products during distribution, transportation, and storage, guaranteeing their safe arrival to consumers[1–3]. Throughout the transportation process, packaged goods may experience a range of dynamic occurrences, such as drops, impacts, compressions, and vibrations, which have the potential to result in damage. Corrugated cardboard is gaining recognition as a sustainable packaging alternative because of its ability to be recycled. Manufacturers are increasingly implementing sustainable production methods, minimizing energy usage, and incorporating renewable materials to comply with escalating environmental regulations. The increasing consumer interest in sustainable packaging is evident, as a significant number are prepared to invest more in eco-friendly products[4,5]. Shocks have been identified

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as a significant threat to product integrity[6–9]. Transport tools like conveyor belts and forklifts, positioning tools like lift tables, and storage systems like racks and bins are all types of material handling equipment. These increase output, cut down on manual labor, and lower the risk of damage from handling. The impact on the product during handling is simulated by a virtual drop test that uses Computer-Aided Engineering (CAE) tools. It helps find weak spots, improve design, and cut costs by reducing the number of physical prototypes needed[10]. CAE software has revolutionized the way engineers analyze and optimize various products and processes, including packaging design[11]. This case study focuses on conducting a drop test simulation of corrugated box packaging using CAE software to assess its structural integrity and performance under impact conditions. Since its patenting in 1856, corrugated paper has emerged as a fundamental material, spurring rapid advancements in manufacturing techniques[12].

The process commences with the breakdown of wood fibers from wood chips, achieved through either mechanical or chemical means. This initial stage, known as pulping, disrupts bonds within the wood fibers, yielding a substance referred to as pulp. Following refinement, the pulp is directed into the paper machine, where it undergoes a transformation into structured paper sheets. As the material traverses through heated rollers within the paper machine, moisture is expelled, and the orientation of wood fibers is shaped. Post-roller forming and drying, kraft paper is produced, notable for its increased stiffness in the Machine Direction (MD) relative to the Cross-Machine Direction (CD), with the through-thickness direction (ZD) exhibiting the least stiffness[13–15]. An integral phase of the manufacturing process involves assembling kraft papers into corrugated boards. This entails bonding two outer layers, known as liners, with a wavy middle layer called fluting. Before this fusion occurs, the paper intended for fluting undergoes treatment in corrugating rolls, where it is preheated and mechanically processed to adopt a wave-like profile. Only then can the fluting be adhered to the liners using an adhesive, resulting in the formation of a corrugated board. The efficacy of corrugated board hinges on various factors, including humidity, impact and static forces, and the design of the corrugated board itself[16–18]bellows are used widely in various engineering fields, especially in storage and transportation of floating liquefied natural gas (FLNG.

This study aims to utilize virtual simulation techniques with CAE software to analyze the behaviour of corrugated box packaging under drop-test conditions. The focus is on employing advanced technology to gain insights into the performance of the packaging. Simulations are used to predict plastic strain and stress distribution in the packaging material. Additionally, the impact of different box thicknesses on stress distribution and overall structural integrity is investigated in detail. The ultimate objective is to optimize corrugated box design for improved mechanical performance during handling and transit.

2.0 Model Creation

The Structural Packaging app on the 3D experience platform is utilized to create a parametric model of the corrugated box. This app is designed to streamline the process of creating box models efficiently, saving time and effort. Key features of the app include the ability to quickly input dimensions and structural parameters, such as thickness variations and material properties. Enhanced options, such as fold or unfold geometry, provide detailed insights into the assembly and construction of the packaging. The app facilitates a detailed understanding of how the cardboard material will be pierced and folded during manufacturing.

After creating the parametric model, a detailed 3D CAD model of the corrugated box is developed within

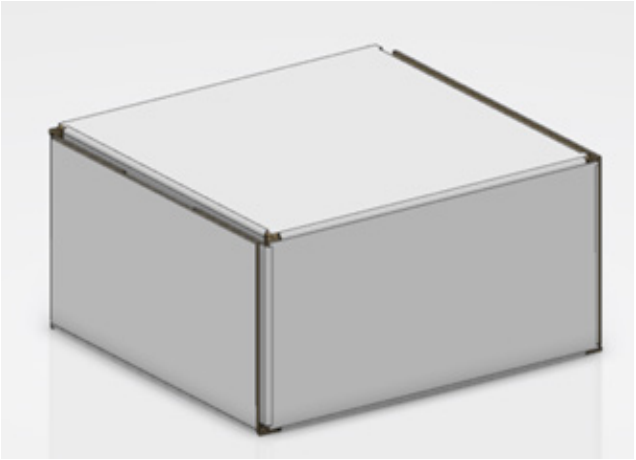


Figure 1. Corrugated box.

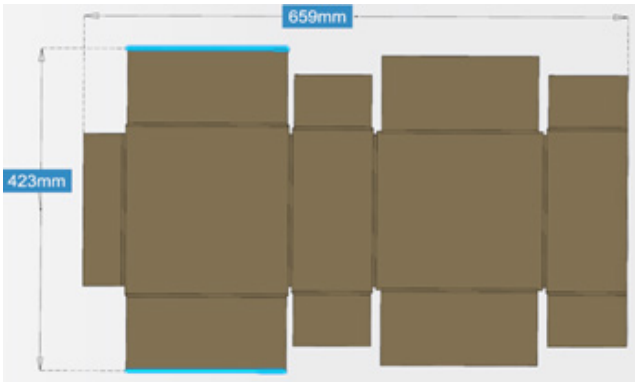


Figure 2. Unfold corrugated box.

a CAE software environment. Figure 1 illustrates the corrugated box used in the study. This CAD model accurately represents the geometry and construction of the packaging, incorporating specific dimensions (e.g., 200 mm × 200 mm × 100 mm) and thickness variations (1 mm, 2 mm, 4 mm, and 6 mm). Figure 2 shows the unfolded view of the corrugated box. The CAD model detail for the box and the material inside the box is given in Table 1.

Table 1. Specifications of the corrugated box for drop test simulation

Sr. No.	Description	Dimension
1	Box size	200 mm × 200 mm × 100 mm
2	Corrugated cardboard thickness	1 mm, 2 mm, 4 mm, and 6 mm
3	Box drop height	1000 mm

Material properties of the corrugated fiberboard are incorporated into the CAD model to ensure accurate simulation and analysis. Corrugated fiberboard is known for its orthotropic nature, meaning its mechanical properties vary depending on the direction of applied loads. To account for this orthotropic behaviour, the corrugated fiberboard is partially homogenized and modeled as a composite layup structure within the CAD environment. Linear boards are modeled without homogenization using orthotropic elasticity and anisotropic plasticity, while fluted layers are homogenized, and their mechanical behaviour is described using equivalent material properties. The process involves leveraging advanced software tools to create both a parametric model for initial design exploration and a detailed 3D CAD model for simulation and analysis, considering the intricate material properties and structural complexities of corrugated fiberboard packaging.

2.1 Analysis Steps

2.1.1 Mesh Generation

Generated a mesh for all the component geometry using the meshing tools provided by 3D experience software. Ensure the mesh is sufficiently refined to capture the structural details and geometry complexities of the component, especially in regions of interest such as areas expected to experience high stress or deformation during the drop test.

Meshing involves dividing the 3D model into smaller elements, which can be tetrahedral or hexahedral for solid elements and quadrilateral or triangular for surface elements. The purpose of meshing is to discretize the geometry into smaller, manageable elements that can be analyzed computationally. Meshing plays a crucial role in the accuracy and efficiency of simulations, as it determines how well the model captures the physical behaviour of the system being analyzed. Different mesh sizes and element types may be chosen based on the material and structural characteristics of the components being modeled. The corrugated box is meshed with a 2.5 mm mesh size using surface quad mesh elements. A 2.5 mm mesh size refers to the size of the individual elements used to discretize the surfaces of the box. Surface quad mesh elements are quadrilateral elements used to discretize the surfaces of the box, providing a more accurate representation of its geometry compared to other element types. For other materials such as wood and aluminum, hex mesh elements are used. Hex mesh elements are hexahedral elements that provide a more efficient mesh for solid structures like wood and aluminum.

The mesh is refined to ensure it captures the intricate details and geometrical complexities of the components accurately. In areas expected to experience high stress or deformation during the drop test, such as corners and edges of the corrugated box, the mesh is further refined. By refining the mesh in these critical areas, the simulation

Table 2. Specifications of the corrugated box for drop test simulation

Sr. No.	Contain part material	Mesh type	Density (kg/m^3)	Young's Modulus (N/m^2)	Poisson's ratio	Mesh Size (mm)
1	Corrugated box	Surface Quad	240	6×10^8	0.3	2.5
2	Particle Board	Solid Hex Mesh	621	2.5×10^9	0.2	5
3	Aluminum	Surface Quad	2700	7×10^{10}	0.33	5

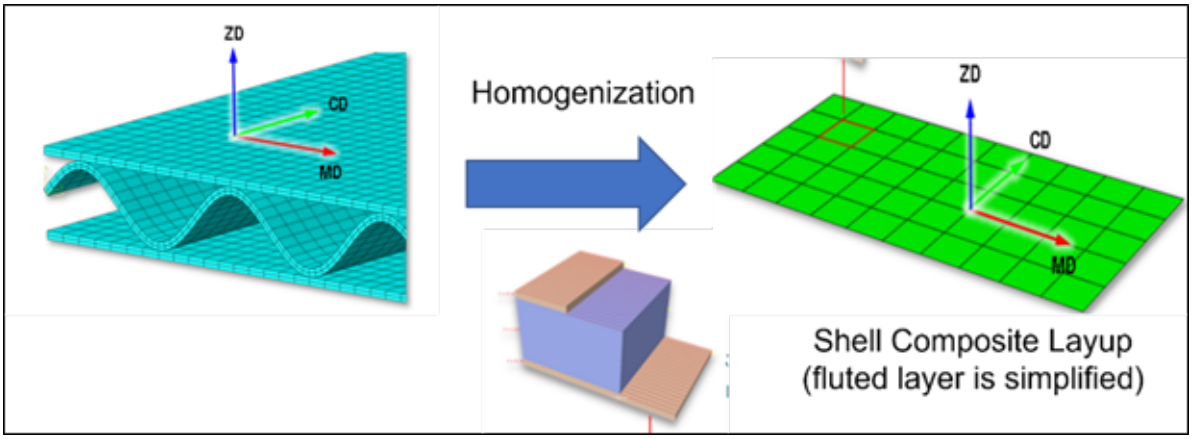


Figure 3. Initial prototype design.

can provide more accurate predictions of how the box will behave under loading conditions, such as during a drop test. Material properties were assigned to each component of the model based on real-world data for corrugated cardboard, wood, and aluminum, as shown in Table 2, Figure 3 shows the initial prototype design used in the study.

2.1.2 Boundary Conditions and Constraints

Boundary conditions were defined to simulate the physical environment of the drop test, including gravitational effects and any external constraints. In this case, fixed clamping was applied to the bottom surface of the model to represent the ground. General contact was specified between all contacting parts of the model (box, wood block, aluminum block) to accurately simulate interactions during impact. The box is dropped from a height of 1 m, resulting in a velocity of 4.42 m/s now of contact with the floor.

2.1.3 Drop Test Setup

The drop test simulation was configured with specific parameters: the drop height was set to 1 meter, the drop orientation was in the Z-direction (vertical drop), and the impact surface considered was the bottom surface of the corrugated box. Initial conditions for the components were defined at the beginning of the simulation, including any initial velocity if the component was dropped from a specific initial position.

2.1.4 Simulation

An explicit dynamic simulation was chosen for this analysis. This type of simulation is suitable for problems involving large deformations and nonlinear material behavior, which are expected during a drop test. The time step for the simulation was set to 2.26×10^{-4} seconds, and geometric non-linearity was maintained to account for the large deformations that might occur.

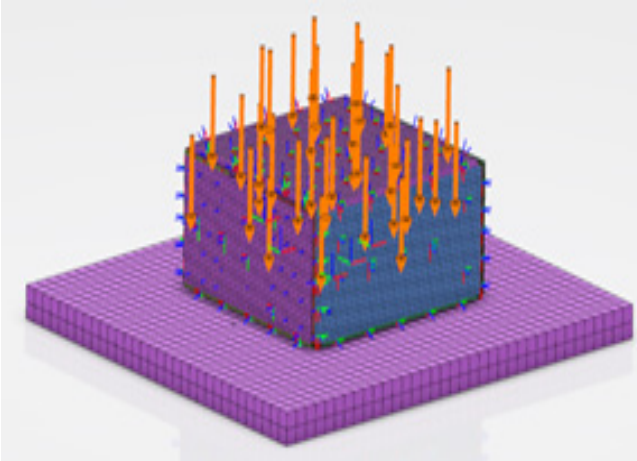


Figure 4. Corrugated boxes drop test simulation setup.

3.0 Post Processing

Once the simulation was complete, post-processing tools within the CAE software were utilized to visualize and analyze the results. Key output parameters examined to evaluate the corrugated box's performance under drop test conditions included:

Von Mises Stress: This is a failure criterion used in engineering to predict the onset of yielding within a material. It considers the combined effects of normal and shear stresses acting on a point. Areas with high Von Mises stress values are more susceptible to failure.

Plastic Strain: This parameter represents the permanent deformation experienced by the material after a stress event. Higher plastic strain values indicate more significant material deformation.

Deformation Contours: These visual representations depict the extent of deformation experienced by the box and its contents (wood and aluminum blocks) during the drop test.

4.0 Results and Discussion

The drop test simulations were conducted for each variation of the corrugated box thickness (1 mm, 2 mm, and 4 mm, and 6 mm). The following observations were made based on the analysis of Von Mises stress, plastic strain, and deformation contours:

4.1 Von Mises Stress Analysis for Corrugated Cardboard Box, Wood Blocks and Aluminum Blocks

The results showed a general decrease in stress levels within the corrugated box as the thickness increased from 1 mm to 6 mm. This observation highlights the significance of thickness optimization as a strategy to enhance the structural integrity and resilience of the packaging material.

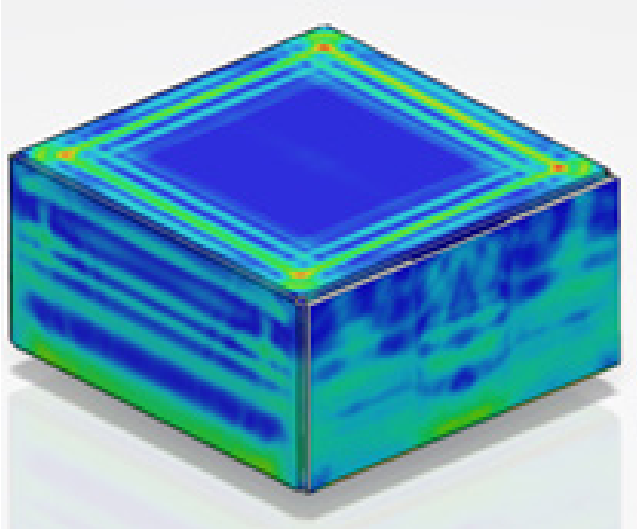


Figure 5. Case I: Von Mises stress in a corrugated cardboard box.

Table 3. Von Mises stress values for different thicknesses of corrugated cardboard boxes under drop test conditions

Von Mises Stress (Pa)	Case I: 1 mm thick	Case II: 2 mm thick	Case III: 4 mm thick	Case IV: 6 mm thick
Minimum	2.1×10^5	1.7×10^5	1.52×10^5	1.35×10^5
Maximum	4×10^6	1.86×10^6	1.52×10^6	1.41×10^6

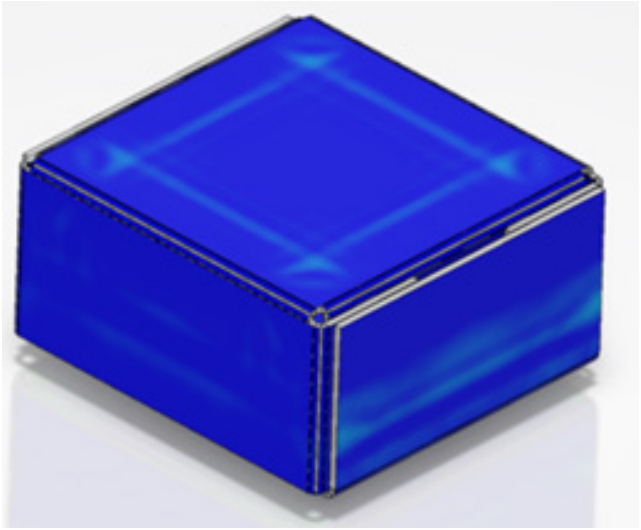


Figure 6. Case IV: Von Mises stress in a corrugated cardboard box.

Table 3 shows Von Mises stress values for drop-tested corrugated cardboard boxes of thicknesses 1 mm, 2 mm, 4 mm, and 6 mm. The distribution of Von Mises stress in a corrugated cardboard box for Case I and Case IV is shown in Figures 5 and 6, respectively. The maximum Von Mises stress for corrugated cardboard box drops from 4×10^6 Pa in Case I to 1.41×10^6 Pa in Case IV, reflecting a reduction of 64.75 %. The maximum stress levels vary across different thicknesses, with the 1 mm thick box experiencing the highest stress levels and the 6 mm thick box showing slightly lower maximum stresses. This indicates that the stress distribution is not uniform and is influenced by the thickness of the box. Thicker boxes provide enhanced protection as they can withstand more stress, which may result in higher manufacturing and transportation expenses.

Table 4 presents the Von Mises stress values observed for wood blocks. The distribution of Von Mises stress in wood blocks for Case I and Case IV is depicted in Figures 7 and 8, respectively. The maximum and minimum Von Mises stress remains consistent at 4×10^5 Pa and 4×10^6, respectively across all thicknesses (Cases I, II, III, and IV) of the corrugated box.

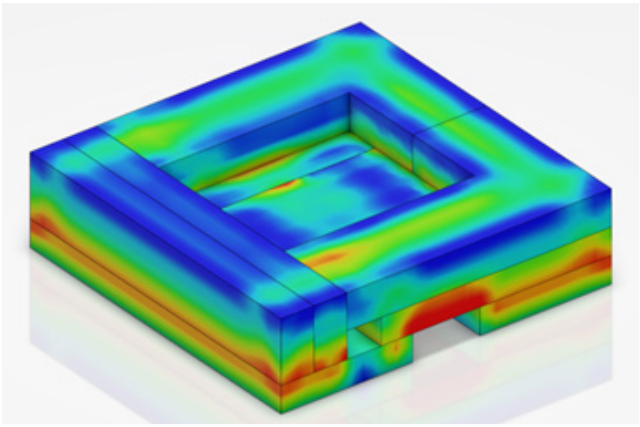


Figure 7. Case I: Von Mises stress in wood blocks.

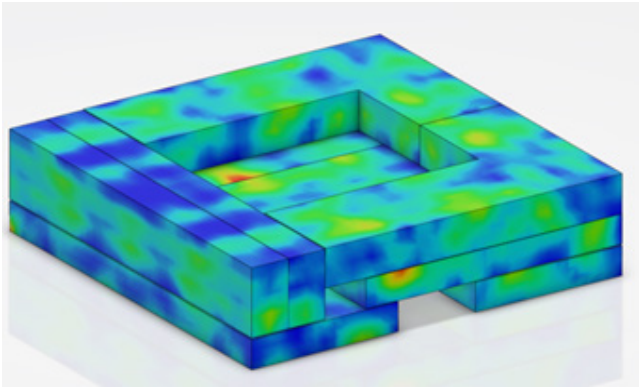


Figure 8. Case IV: Von Mises stress in wood blocks.

Table 5 presents the Von Mises stress values for aluminum blocks for different thicknesses of corrugated cardboard boxes under drop-test conditions. These values

Table 4. Von Mises stress values for wood blocks for different thicknesses of corrugated cardboard boxes under drop test conditions

Von Mises Stress (Pa)	Case I: 1 mm thick	Case II: 2 mm thick	Case III: 4 mm thick	Case IV: 6 mm thick
Minimum	4×10^5	4×10^5	4×10^5	4×10^5
Maximum	4×10^6	4×10^6	4×10^6	4×10^6

Table 5. Von Mises Stress values for aluminum blocks for different thicknesses of corrugated cardboard boxes under drop test conditions

Von Mises Stress (Pa)	Case I: 1mm thick	Case II: 2mm thick	Case III: 4mm thick	Case IV: 6mm thick
Minimum	3.99×10^6	3.7×10^6	3.7×10^6	3.7×10^6
Maximum	3.99×10^7	3.7×10^7	3.7×10^7	3.7×10^7

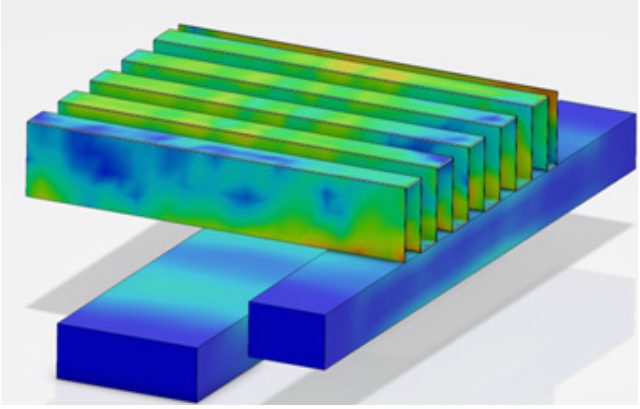


Figure 9. Case I: Von Mises stress in aluminum blocks.

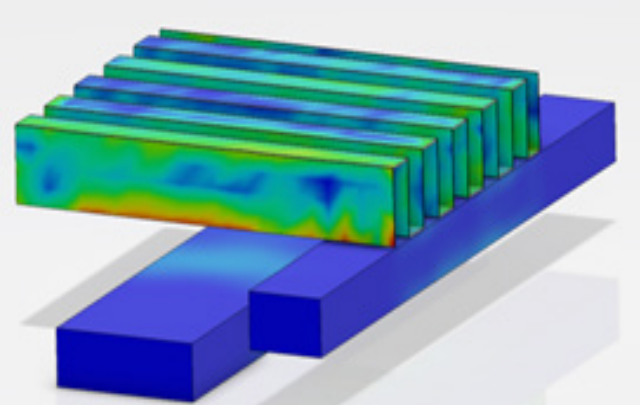


Figure 10. Case IV: Von Mises stress in aluminum blocks.

depict the range of Von Mises stress experienced by aluminum blocks during the drop tests, showing both the minimum and maximum stress levels observed under the specified conditions. The distribution of Von Mises stress in aluminum blocks for Case I and Case IV is depicted in Figures 9 and 10, respectively.

4.2 Plastic Strain Analysis for Wood Blocks and Aluminum Blocks

The plastic strain values for wood blocks in various thicknesses of corrugated cardboard boxes under drop-test conditions can be found in Table 6. Figures 11 and 12 display the deformation contours of plastic strain for wood blocks in Case I (1 mm thick) and Case IV (6 mm thick), respectively. According to the data presented in Table 6, there is a significant decrease in the maximum plastic strain when comparing the 1 mm thick box (0.0656) to the 6 mm thick box (0.0027). The findings of this study indicate that as the thickness of corrugated cardboard boxes increases, there is a corresponding decrease in plastic strain. This suggests that thicker boxes are more effective in absorbing impact energy, resulting

Table 6. Plastic strain values for wood blocks for different thicknesses of corrugated cardboard boxes under drop test conditions

Plastic Strain	Case I: 1 mm thick	Case II: 2 mm thick	Case III: 4 mm thick	Case IV: 6 mm thick
Minimum	0.0065	0.0047	0.00103	0.0009
Maximum	0.0656	0.054	0.0103	0.0027

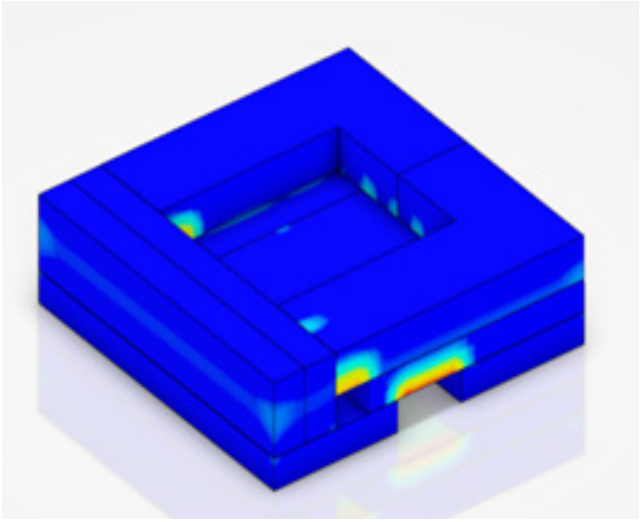


Figure 11. Case I: Plastic strain in wood blocks.

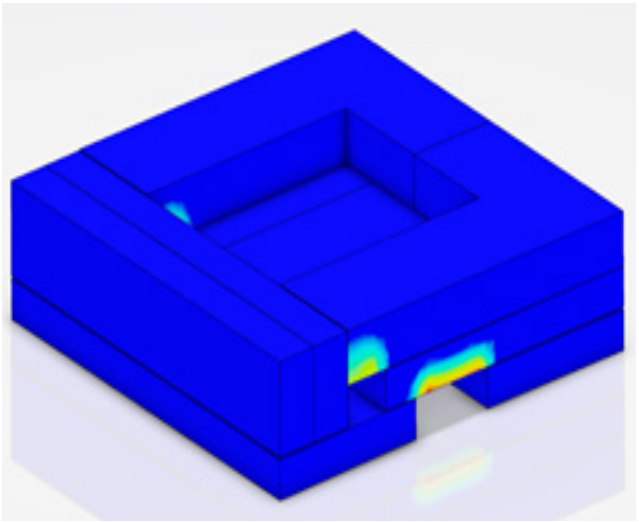


Figure 12. Case IV: Plastic strain in wood blocks.

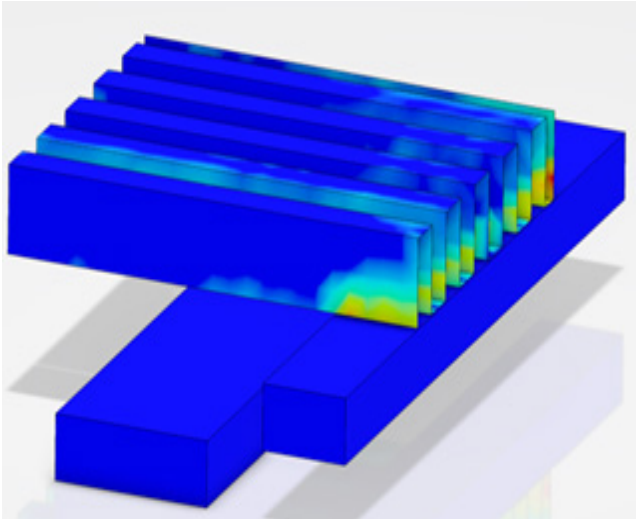


Figure 13. Case I: Plastic strain in aluminum blocks.

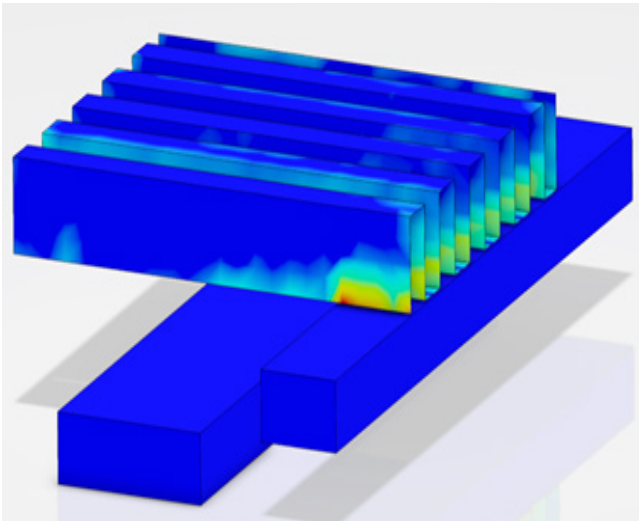


Figure 14. Case IV: Plastic strain in aluminum blocks.

Table 7. Plastic strain values for aluminum blocks for different thicknesses of corrugated cardboard boxes under drop test conditions

Plastic Strain	Case I: 1 mm thick	Case II: 2 mm thick	Case III: 4 mm thick	Case IV: 6 mm thick
Minimum	0.0065	0.000364	0.000210	0.0001
Maximum	0.0656	0.00325	0.00241	0.0015

in a reduction of permanent deformation in wood blocks.

Table 7 shows the plastic strain values for aluminum blocks in various thicknesses of corrugated cardboard boxes under drop-test conditions. Figures 13 and 14 show the deformation contours for plastic strain for aluminum blocks in Case I and Case IV. Table 7 shows that the maximum plastic strain drops from 0.0656 in the 1 mm

thick box to 0.0015 in the 6 mm thick box. The observed patterns highlight the importance of thicker corrugated cardboard boxes in providing better protection against the permanent deformation of aluminum cubes after impacts.

5.0 Conclusion

In conclusion, the findings of the drop test study indicate a reduction in stress levels within the corrugated box as thickness variations were introduced. The maximum Von Mises stress for corrugated cardboard box drops from 4 $\times 10^6$ Pa in Case I to 1.41 $\times 10^6$ Pa in Case IV, reflecting a reduction of 64.75 %. This highlights the significant stress reduction achieved with increasing thickness. This observation underscores the significance of thickness optimization to enhance the structural integrity and resilience of packaging materials. Notably, the plastic strain in sample parts, representative of wood and aluminum, also exhibited improvements with changes in thickness. This suggests that thickness variation can positively impact the overall mechanical performance of corrugated boxes across diverse material compositions. Furthermore, it is essential to emphasize the importance of proper design considerations in conjunction with thickness variations to mitigate stress concentrations, particularly in notch and fillet regions. These critical areas are prone to elevated stress levels during drop testing and can significantly affect the overall durability of the packaging. Therefore, incorporating robust design principles, such as smooth transitions and reinforcement features, is paramount to ensuring the integrity and reliability of corrugated box packaging. Overall, the results of the drop test study are highly satisfactory, demonstrating the effectiveness of thickness variation as a strategy to reduce stress levels and enhance the mechanical performance of corrugated boxes. Moving forward, continued research and development efforts should focus on refining design methodologies and material selection to further optimize packaging solutions for improved product protection and customer satisfaction. Additionally, ongoing advancements in simulation techniques and experimental validation will play a crucial role in advancing our understanding of packaging dynamics and driving continuous improvement in packaging design and performance. The future scope of corrugated cardboard boxes includes integrating advanced technologies such as AI-driven automation, smart sensors, and sustainable materials to enhance packaging efficiency and reduce environmental impact.

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