Formability and load-bearing capacity of multilayered paperboard in three-dimensional forming

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ABSTRACT: The forming of paper-based products presents significant challenges, including maintaining geometric integrity, managing springback, and overcoming instability limits. These arise from the material properties of paper, with its high anisotropy, inhomogeneity, and limited strain. Multilayered paperboard, formed without adhesives, offers a promising solution. By customizing layer composition and orientation, this approach leverages mutual fiber support to enhance forming properties.

Experimental and numerical analyses reveal that adhesive-free bonding during deep drawing enhances the material's formability and load-bearing capacity and reduces anisotropic springback. These innovations enable superior product protection compared to conventional industrial single-layered paperboard of similar thickness.

This study demonstrates the advantages of tailored layer configurations for improved geometric precision and stability, providing a pathway for sustainable, high-performance packaging solutions.

Application: This study researches the formability and robustness of multilayered paperboard in three-dimensional forming processes, achieving superior results to single-layer materials without additional adhesives or process steps. Manufacturers can enhance packaging quality and reduce environmental impact, offering sustainable, high-performing alternatives to plastic packaging. These findings align with global demands for eco-friendly solutions, meeting industry needs for cost efficiency, robust product protection, and adaptability to complex geometries.

The global packaging market is projected to grow 3.16% between 2025 and 2034, reaching an overall market volume of $1.69 trillion U.S. dollars [1]. This growth is being viewed critically from an environmental perspective, which has raised awareness of the need for sustainable packaging alternatives to replace plastics. Legislative measures, including the European Union's Single-Use Plastics Directive, are driving a shift to more sustainable packaging [2].

This development has brought paperboard into focus as a packaging material because of its recyclability, its origin in renewable resources, and high availability. However, the manufacturing of sustainable packaging must address not only environmental goals but also economic and functional requirements. These include cost-effective production, product protection during transport and handling, and the ability to form complex geometries [3]. Traditional three-dimensional forming techniques, such as deep drawing, offer short process times, geometric flexibility, and high surface quality, making them a useful process for research and advanced development of paperboard packaging applications [4]. Nevertheless, the industrial use of processes such as thermoforming and molding is currently limited by the inherent properties of paperboard. Its low elongation capacity and pronounced anisotropy, due to the fibrous structure, restrict forming depth and lead to varying degrees of springback, depending on fiber orientation. To expand paperboard's applicability in packaging, improvements in controlling anisotropy and enhancing formability are essential. Additionally, the diverse requirements of packaging for different products necessitate adaptable materials and processes [5].

Studies have demonstrated that moisture content exerts a significant influence on paperboard's mechanical properties. Increased moisture generally reduces stiffness while improving deformability, thereby enabling high forming depths. However, excessive moisture has the potential to compromise the material's structural integrity. Therefore, precise control of moisture levels during forming is critical [6].

In recent years, adaptation of metal forming techniques have been explored to expand formability of paperboard [5]. Hydroforming, for example, applies uniform pressure via a fluid medium and has shown potential to enhance the forming limits of paperboard [7]. In addition to hydroforming, other metal forming strategies, such as the use of preforming steps like creasing [8], draw beads [9], and thermoforming [10], have also been investigated for their transferability to paperboard. These approaches aim to control material flow more precisely and distribute strain more uniformly, thereby reducing or controlling wrinkling and enabling more complex shapes. For example, draw beads introduce localized resistance to help stabilize flange areas during forming, whereas creasing controls material overflow. Another important aspect is the significant impact of process parameters, particularly the blank holder force trajectory, on fiber-to-fiber movement. Consequently, there are consequences for wrinkle formation, rupture, and visual quality [11]. Such techniques show promise in improving process stability and product quality for paperboard-based forming applications.

Alongside process adaptation, the use of numerical modeling in paperboard forming has gained importance. While the complex anisotropic and inhomogeneous nature of paper challenges conventional simulation methods, simplified models can still provide valuable insights into material deformation, wrinkling behavior, and tool-material interaction. Previous work by the authors has established a simplified anisotropic model for forming simulations [12]. Additionally, Lindberg and Kulachenko used implicit finite element analysis to study tray forming operations, offering valuable insight into deformation behavior and blank control in press-forming setups [13]. Additionally, further studies such as the work by Wallmeier et al. [14] and Leng et al. [15] demonstrate the potential of explicit finite element methods for modeling deep drawing of paperboard, accounting for anisotropic and nonlinear material behavior with high fidelity.

In summary, while paperboard presents a promising sustainable alternative to plastic in packaging, challenges related to its formability and anisotropic behavior are still very limiting. Ongoing research into moisture control, advanced forming techniques, and modeling is essential to enhance the adaptability and performance of paperboard in diverse packaging applications. In addition, the need to adapt the packaging to the packaged product cannot be overlooked. Previous studies have shown that fiber networks can be mutually reinforcing, enhancing stiffness and extensibility [16]. Building on this, multilayered board forming processes may offer a solution, as discussed in this paper. This approach has the potential to improve both stiffness and formability while allowing for the tailored material combinations required for different products.

MATERIALS AND METHODS

The analysis is performed both numerically and experimentally. Numerical analyses of paperboard forming still face many challenges. On the one hand, the natural fiber network and material inhomogeneities result in highly complex simulations that have not yet been fully resolved. On the other hand, this complexity, combined with issues like wrinkling, leads to time- and resource-intensive simulations. To provide conclusive results, experimental findings were compared against each other, as well as with material characterization data and previous findings. The experimental apparatus must exhibit a high degree of flexibility to facilitate the investigation of diverse geometries and drawing gap adaptations in response to variations in material thickness.

Numerical results were validated against the experimental results before using the data scientifically and further qualifying the model. The utilization of a qualified numerical model has the potential to engender significant time and cost savings in subsequent investigations.

The material used in the experimental setup and the numerical simulations is a bleached virgin fiber material from the manufacturer Stora Enso, known as their trademarked Trayforma, which is well established in the packaging industry. It consists of three plies: a middle layer of chemithermomechanical pulp, with outer layers of sulfate pulp. The material is available in several thicknesses, and the layers are firmly combined in the material production process. For the research outlined in this paper, Trayforma with a grammage of 190 g/m^2 and a thickness of 255 µm is used for the multilayered purpose and 420 g/m^2, 610 µm Trayforma for the single-layered reference. [17]. Different material grammages are used to ensure that the overall formed material has a similar grammage, whether it is multilayered or not. This rules out differences in forming performance based on different grammages, attributing them instead to the multilayered approach.

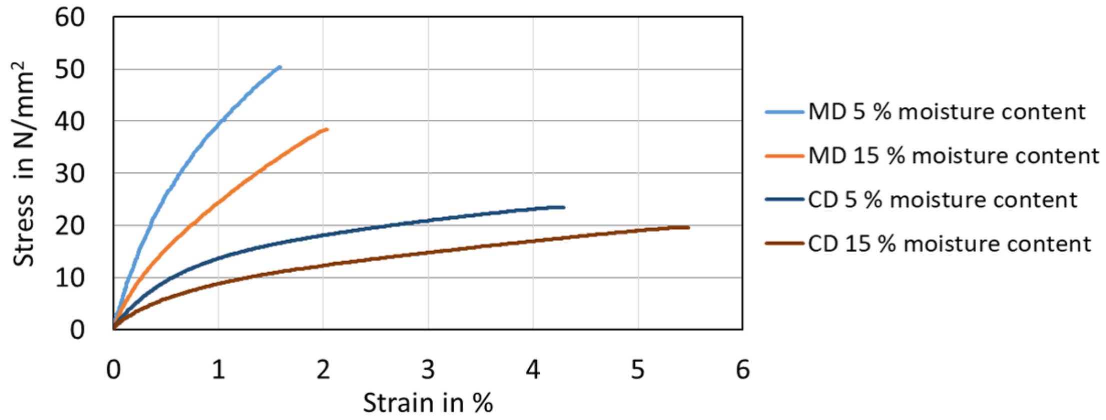
Layering was performed by stacking the different paper probes according to the required setup. The layers were distributed in either the machine direction (MD) or the cross direction (CD). The glue was applied manually, and the amount used was carefully measured and evenly spread using adhesive rollers. Stacking the layers manually ensures the approach's high flexibility, while also allowing the layers to form individually and making the formed bonds easily accessible for research.

The stress-strain graph in **Fig. 1** depicts the tensile test results with Trayforma. The curves represent the stress-strain behavior in MD and CD at 5% and 15% moisture content, respectively. The curve progression is typical for paper, which has a minimal elastic strain and no constriction prior to breakage. The higher elongation exhibited by CD and the enhanced tensile strength observed in MD, as well as the influence of moisture content, are consistent with current research and can be attributed to the fiber orientations [5].

All experiments in the following research were carried out at 15% moisture content of the paperboard. This was achieved by storing the probes in a climate chamber at all times, except during the experiments themselves. The loss of moisture to the surroundings was monitored by weighing the probes. If this loss was sufficient to change the relative humidity, the probe was returned to the climate chamber until the required moisture content was achieved.

Numerical setup

The modeling of paperboard presents many challenges due to natural fibers with different lengths and curvatures, pores, and additives, and their distribution throughout the paperboard. The development of an appropriate model is the current state of research. To use numerical modeling of



1. Stress-strain graph for Stora Enso's Trayforma paperboard material (MD: machine direction; CD: cross direction).

deep drawing of paperboard in the research at hand, an explicit model specifically for Trayforma was used to represent both wrinkling areas and breakage. The material model has been simplified to be homogeneous for efficiency while still representing anisotropic material behavior. Further information on the numerical model can be found in previous publications by the author [12].

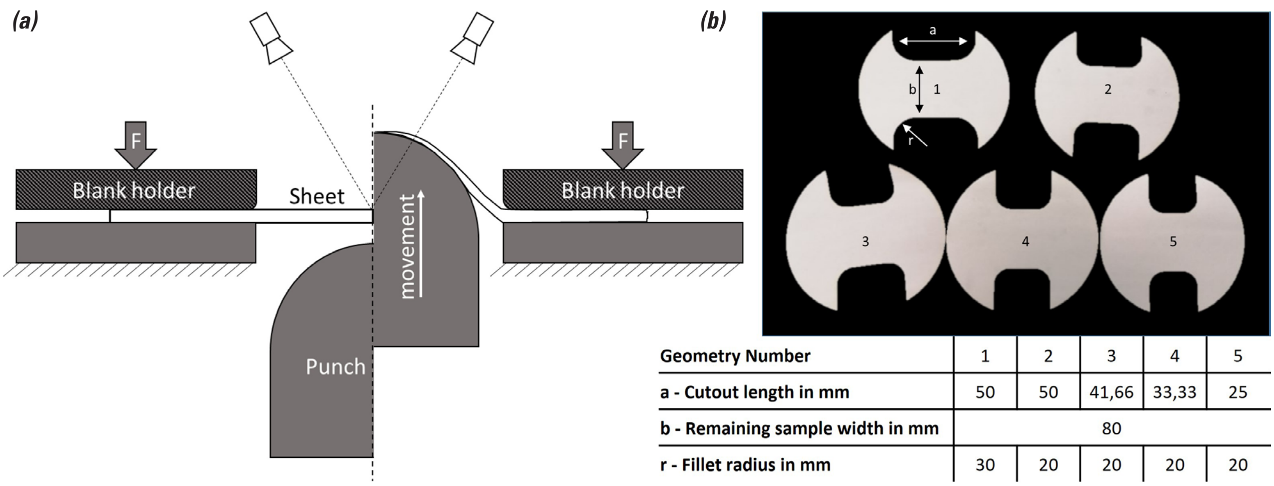
Necessary adjustments to the model were made regarding the layered setup. All contacts in the numerical model were implemented as surface-to-surface penalty contacts. The normal behavior was defined as hard contact, allowing for separation in the normal direction. In the tangential direction, Coulomb friction was applied with constant coefficients: μ = 0.10 between tool and blank and μ = 0.50 between individual blank layers. These friction values were selected to represent typical contact behavior between paperboard and polymer-based tooling surfaces, as well as internal layer friction. To evaluate the influence of these assumptions, a parameter variation was conducted. The results showed no significant impact on the draw depth, strain distribution, or wrinkling. This confirms that the simulation results are robust with respect to the chosen friction coefficients.

Experimental setup

For the experimental research on deep drawing and material characterization, tools consisting of a stamp, die, and blank holder were set up on a pneumatic press. Tool movement is controlled by force. Internal research has found that additively manufactured tools from polylactic acid (PLA) can be used in paperboard forming if the process is not heated, and the surface quality of the tools is controlled. For the purpose of this research, additively manufactured tools were used in deep drawing as well as Nakajima testing (ISO 12004-2:2021 "Metallic materials — Determination of forming-limit curves for sheet and strip — Part 2: Determination of forming-limit curves in the laboratory"). The deep drawn geometry is rectangular and measures 225 mm x 185 mm with corner radii of 40 mm. The punch is inclined by 1° on all sides, meaning that the drawing gap increases with the drawing depth, providing space for the formed wrinkles. The drawing gap is set at 1.1 times the thickness of the paper, as paper thickens due to hygroscopicity when used in moist conditions. The blank holder force is 1000 N, decreasing to 600 N throughout the process to account for the indrawn material. The punch is path-controlled. The drawing depth is at least 40 mm and goes up to 55 mm, depending on the formability of the probes.

Deep drawn geometries were analyzed using laser-based 3D measurements with the Absolute Arm by Hexagon (Stockholm), allowing for digitalization of geometrical cross-section measurements. Nakajima tests, which determine formability limits, were conducted using five distinct geometries, as shown in **Fig. 2b**, while the elongation and breakage during the tests were optically measured using the GOM Aramis system by Carl Zeiss AG (Oberkochen, Germany). The optical data acquisition conducted at a frequency of 12 Hz in combination with the associated software is used to generate the forming limit curves. Figure 2a illustrates the setup with the camera system and the punch movement. The blank holder force is set to assure that no flange draw-in or blank movement occurs in the Nakajima test.

Geometry 1 results in a predominantly unidirectional strain, while Geometry 5 exhibits a more biaxial strain pattern. While three data points are the minimum required to derive a forming limit curve, a higher number provides a continuously more accurate and meaningful curve. Considering the evaluation and experimental effort compared to the necessary data points, five geometries and five repetitions each were assumed to be sufficient to compare the layered approaches. The curve itself defines the formability of each material and aids in setting up suitable forming tools and processes. Additionally, comparing the curves and analyzing data point deviations allows hypotheses to be made about the influence of thickness, layers, and layer bonding.



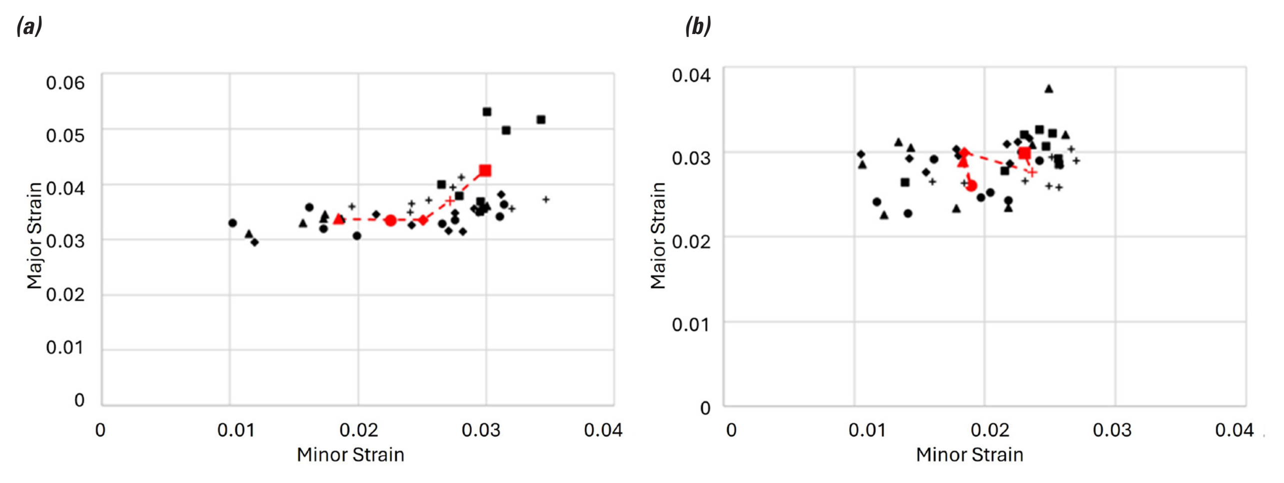
Geometry Number	1	2	3	4	5
a - Cutout length in mm	50	50	41,66	33,33	25
b - Remaining sample width in mm	80				
r - Fillet radius in mm	30	20	20	20	20

2. (a) Schematic of Nakajima test, and (b) the geometries used.

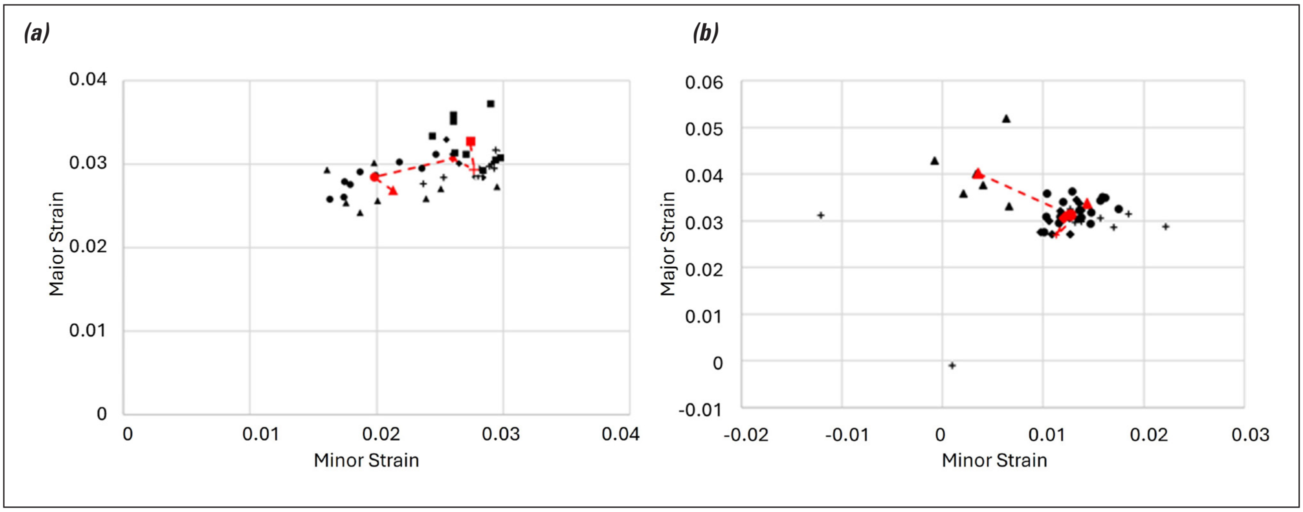
NAKAJIMA TEST RESULTS

In the context of forming limit curves (FLCs), the major strain is defined as the highest strain experienced by a sheet material along its principal axis during deformation, while the minor strain corresponds to the strain along the perpendicular axis. For each of the five geometries tested in the Nakajima test, the major and minor strain are plotted as a black data point, and the average of each geometry out of five repetitions is depicted as a red data point in the following curves. The same data point shape attributes to the same Nakajima test geometry. The utilization of major and minor strains facilitates the evaluation of material formability under diverse strain states. The curve delineates regions where material deformation occurs without failure (below the curve) and where localized necking or failure occurs (above the curve). These regions are influenced by material properties, thickness, and loading conditions, thereby providing insights into the limits of its deformation capabilities. By comparing the values and position of the points in relation to each other, statements can be made about the reproducibility and the maximum elongation that can be reached [18].

In a preliminary step, the thickness influence was studied. **Figure 3** shows FLCs for Trayforma with different material grammage. The FLC of the thinner material (Fig. 3a) demonstrates a higher robustness to different strain states, as shown by the longer curve, while the thicker material (Fig. 3b) exhibits a more stable deformation, as shown by the more compact curve. The thicker material was used for comparison with the multilayered material, although it comprises only about 73% of the thickness of the multilayered material, which contains three layers of the thinner sheets. Since the thicker material in Fig. 3 shows a trend of reduced minor and major strains, it is expected that the multilayered material will continue to decrease both further while exhibiting a more stable formability, i.e., the black points will be less distributed.



3. Comparison of the forming limit curves of (a) one-layer material (190 g/m²), and (b) one-layer material (420 g/m²). Note the different scales for better readability.



4. Comparison of the forming limit curves of three-layer materials: (a) unbonded, and (b) bonded. Note the different scales for better readability.

The significant spread in the data points is attributed to the inhomogeneity of the natural fiber material. However, with five or more repetitions conducted for each experiment, the comparison of the FLCs remains reliable. The distribution of points is an important aspect of the analysis, providing insights into the material's variability. Furthermore, the results were validated through additional experiments and numerical simulations, enhancing their credibility.

The forming limit curves for the three-layered paperboard (**Fig. 4a**) and the single paperboard with 420 g/m² grammage (Fig. 3a) were compared. Contrary to the initial hypothesis regarding the effect of thickness, the maximum major and minor strain increased in the multilayered material, despite its higher overall thickness. Additionally, no significant decrease in reproducibility is expected, as the spread of data points did not increase substantially. This result may be attributed to the relative movement between the unbonded layers, which likely allows for better distribution of strain and accommodates deformation. To further confirm this hypothesis, the layers were bonded together by using a one-component polyurethane adhesive and letting the glue fully dry before forming. A comparison of Fig. 4a and Fig. 4b shows that the paper with bonded layers exhibits reduced maximum minor strain and enhanced maximum major strain, mostly regarding Geometry 1, exhibiting a close-to-uniaxial deformation. Additionally, the bonded material shows a higher spread in data points. This supports the hypothesis that a restriction of the layer, and consequently the fiber movement, has a negative effect on the forming capacity.

However, the robustness to different forming states of the bonded multilayer material did not diminish compared to the thicker single-layer material, despite its greater overall thickness. This indicates that the multilayer structure, whether bonded or unbonded, demonstrates a higher overall formability. Furthermore, the reduced relative movement between layers in the bonded configuration contributes to improved reproducibility.

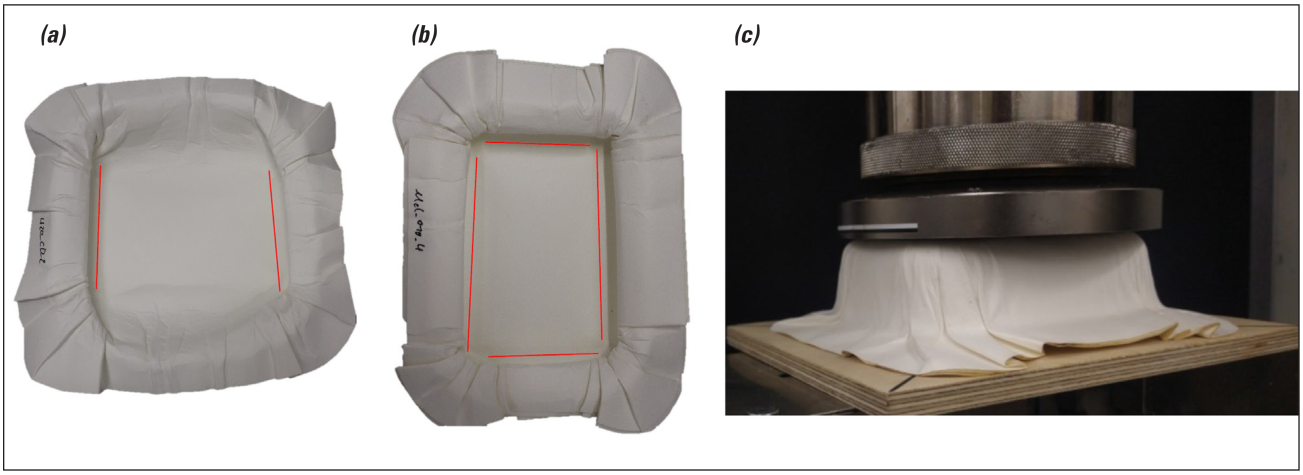
Discussion of Nakajima test results

The Nakajima test results reveal three key findings:

1. Thicker paper exhibited more uniform forming capabilities, albeit with slightly reduced strain values and distribution.
2. Multilayered paper, whether bonded or unbonded, demonstrated improved formability, exceeding the limitations typically associated with increased thickness.
3. Leaving the layers unbonded further enhanced biaxial forming behavior compared to the bonded configuration, likely due to greater relative movement between the layers.

These results highlight the importance of strain-based characterization when evaluating forming behavior, particularly in anisotropic and layered materials such as paper. Although wrinkling contributes significantly to the overall deformation in deep drawing, Nakajima tests and the resulting FLCs remain a valuable method for assessing in-plane forming limits. Forming limit curves enable the quantification of strain thresholds under controlled loading conditions and allow systematic comparisons between different material configurations — such as fiber orientation, moisture content, and layering — independent of geometry-induced instabilities. While wrinkling reflects out-of-plane and instability-driven deformation, it is strongly influenced by in-plane stress states, which are captured by FLC measurements. Therefore, FLCs provide critical insight into the forming potential.

An analysis of the three key findings shows that the first observation aligns with tensile test results. While thinner paperboard exhibits higher strain at breakage, its increased anisotropy may lead to reduced reproducibility during form-



5. Compression tests: (a) inner side single layer, and (b) inner side multilayer. (c) Compression test setup.

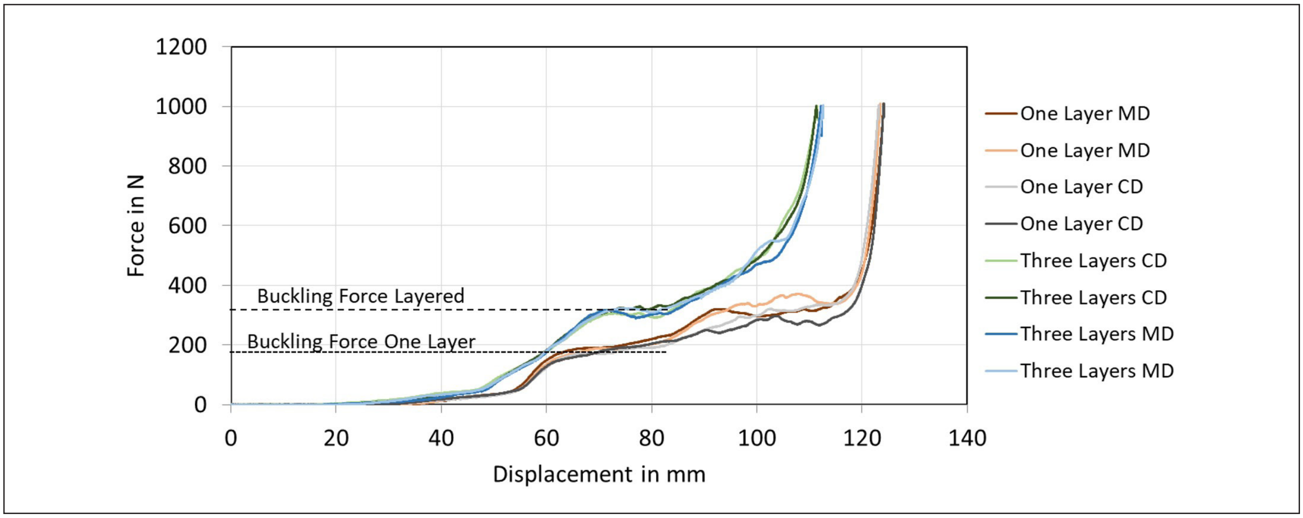
ing. The lower strain tolerance observed with thicker paperboard is probably due to a change in material distribution. It has already been investigated in the past that elongation at break increases with density [19]. When considering grammage and material thickness, the Trayforma with a grammage of 190 g/m² shows a 1.08 times higher density than the Trayforma with a grammage of 420 g/m² [17].

The second and third findings are explained by the mutual reinforcement provided within fiber networks. It has been shown that nonwoven materials composed of fiber layers exhibit greater elongation at failure due to the progressive alignment and sliding of the fibers [20]. These networks distribute stress more effectively, enhancing formability. In multilayered materials, stress can be spread across several layers rather than being concentrated in a single point. While this principle applies to both bonded and unbonded configurations, unbonded layers have greater freedom of movement, allowing them to adapt more effectively to varying strain conditions. In contrast, bonding layers restrict this movement, reducing the elasticity of individual fibers and limiting the overall flexibility of the network.

Based on these findings, additional tests were conducted to further validate the use of unbonded multilayered materials in terms of layer bonding, forming, and dimensional stability. Importantly, forming-based bonding without adhesives has shown no reduction in sustainability, making it a promising approach for future applications.

LOAD CARRYING CAPACITY

Beyond formability, an individual package's capacity to carry load is critical for ensuring product protection during handling and transportation. This capacity was evaluated using compression tests, as depicted in Fig. 5c, on deep drawn multi- and single-layered paperboard products. Figure 5a shows a single-layer package, which exhibits significant deformation, indicating that the load-bearing capacity has been exceeded. In contrast, the multilayer package, Fig. 5b, retains its original rectangular shape, demonstrating a higher load capacity. It has been demonstrated that the discrepancy between single-layer and mul-



6. Force-displacement curves in pressure tests.

tilayer samples is consistent across all pressure tests. Each test was repeated a minimum of five times.

To further quantify these findings, force-displacement measurements were conducted five times for each setup, showing characteristic progressions (**Fig. 6**): an initial flat phase represents the tool closure, followed by a slight force increase as the flange flattens (Fig. 5c). The steeper rise in force, commencing at approximately 50 mm displacement, corresponds to edge compression, which ultimately leads to buckling of the edges. Up to a displacement of 105 mm or 120 mm, complete buckling or unbuckling of the edges can be observed. The subsequent increase in force demonstrates the compression of the failed package. The four curves (green and blue) correspond to multilayered packaging, with the green curves representing the CD parallel to the longer edge and the blue curves representing the perpendicular configuration. Similarly, the other four curves represent single-layered tests, again two with CD parallel and two with CD perpendicular to the long edge. The high repeatability of the curve, represented by two out of five replicates in each case, shows that the results are representative. This outcome is consistent with expectations, as the applied pressure is distributed evenly across the surface. The highest resistance occurs at the corners, where the MD and CD intersect, creating areas of enhanced structural support.

It is evident that the single-layer packaging reaches its buckling strength at lower forces and displacements, but at the same time, the total displacement until complete failure is higher. This can be attributed to the fact that the sample allows a higher compression due to the loss of geometric integrity, as can also be seen in Fig. 5.

Both the force data and optical observations indicate that multilayered packaging significantly outperforms single-layer packaging in terms of load-carrying capacities. Although the deep-drawn samples exhibit different wrinkling and geometric variations, these are independent of the layering, as in five repetitions for each setup different variations were tested. Consequently, the observed and repeatable changes in load-bearing force and deformation under load can confidently be attributed to fiber orientation.

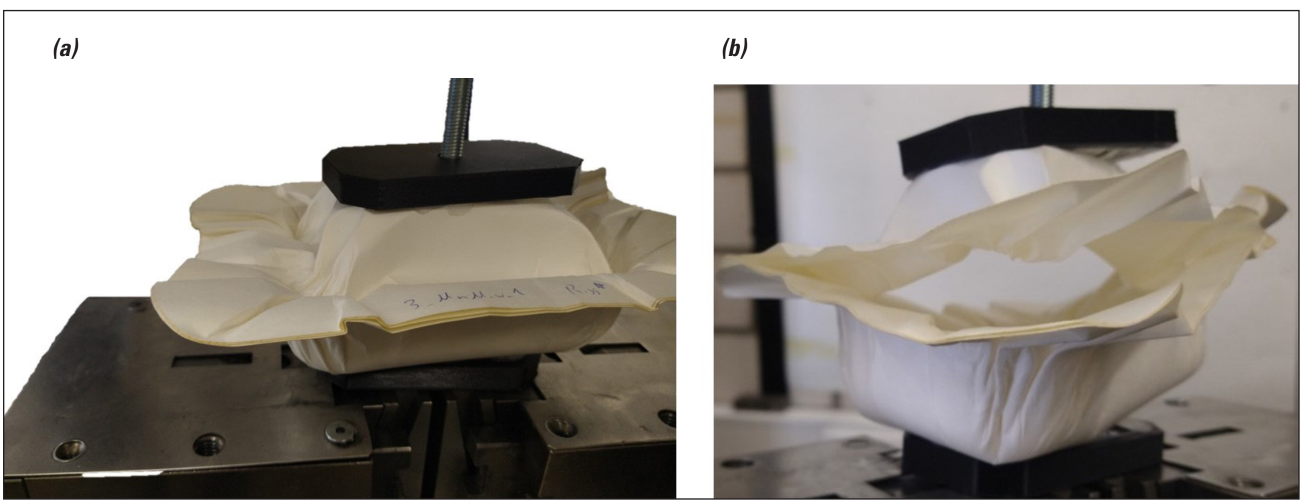
The enhanced performance of multilayered packaging is attributed to the unique behavior of the fiber network. At the microscopic level, the fibers within the network can interlock and slide relative to one another, distributing stress more evenly and allowing the layers to absorb and adapt to applied pressure. The sliding mechanism reduces localized strain concentrations, while the interlocking fibers provide additional reinforcement, collectively enhancing the overall stability of the structure. Additionally, the overlapping and interlocking fiber networks reinforce each other, increasing resistance to strain and improving adaptability to varying pressure levels.

It is worth noting that all the multilayer samples were unbonded and were held together only by the wrinkles created by the forming process.

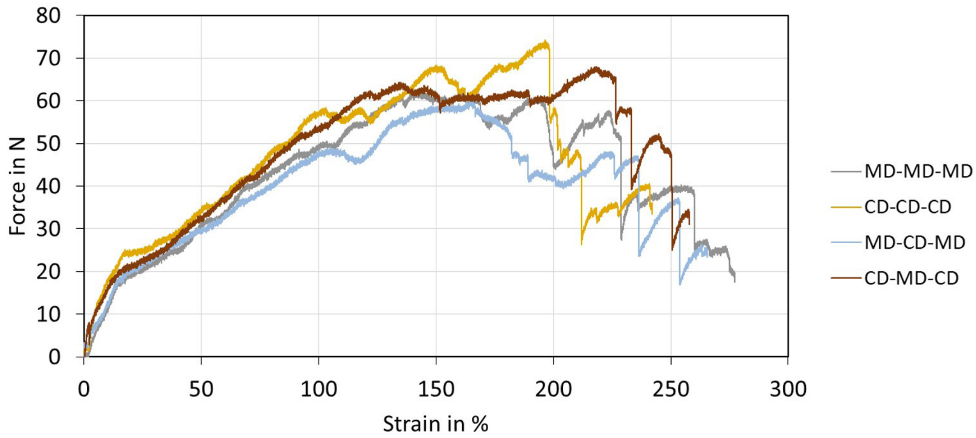
PEELING TESTS

The objective of the peeling test is to assess the functional relevance of wrinkle-induced cohesion between unbonded layers in a formed multilayered structure. While the structural performance under compressive load was evaluated previously, this test isolates interlayer interaction by applying a controlled tensile load to examine resistance against delamination. To investigate whether this mechanical interlocking is robust under varying conditions, the fiber orientation of the outer layers was systematically varied. The test thus helps verify that the wrinkle-based connection provides sufficient integrity independently of fiber direction, supporting the feasibility of adhesive-free, multilayer forming for practical packaging applications.

During the deep drawing process, wrinkling connects the layers. To research this connection, the innermost and outermost layers were pulled apart, as shown in **Fig. 7**. Although geometric deviation changes the layer bonds and



7. In the peeling test, the innermost and outermost layers are pulled apart and (a) wrinkles connecting layers separate, causing (b) fold cohesion that results in tearing.



8. Forces in peeling test.

outcome of the results, by testing each variation five times, the influence of the material and forming deviations was carried out and the reproducibility ensured.

In Fig. 7a, the wrinkles begin to separate under tension; however, at a certain point, the fold cohesion exceeds the material's resistance. This results in tearing of the innermost layer, as illustrated in Fig. 7b. The tests show that the mechanical layer connection withstands higher forces than the material resistance, as the material itself will break before resulting in a full layer separation.

Figure 8 shows the forces during the peeling. The first part of the graphs, up to about 20% strain, shows the cupping of the base, followed by the peeling of the wrinkles in the frame up to about 150% strain. It ends with the rupture of a single layer of material, separating it from the rest of the packaging.

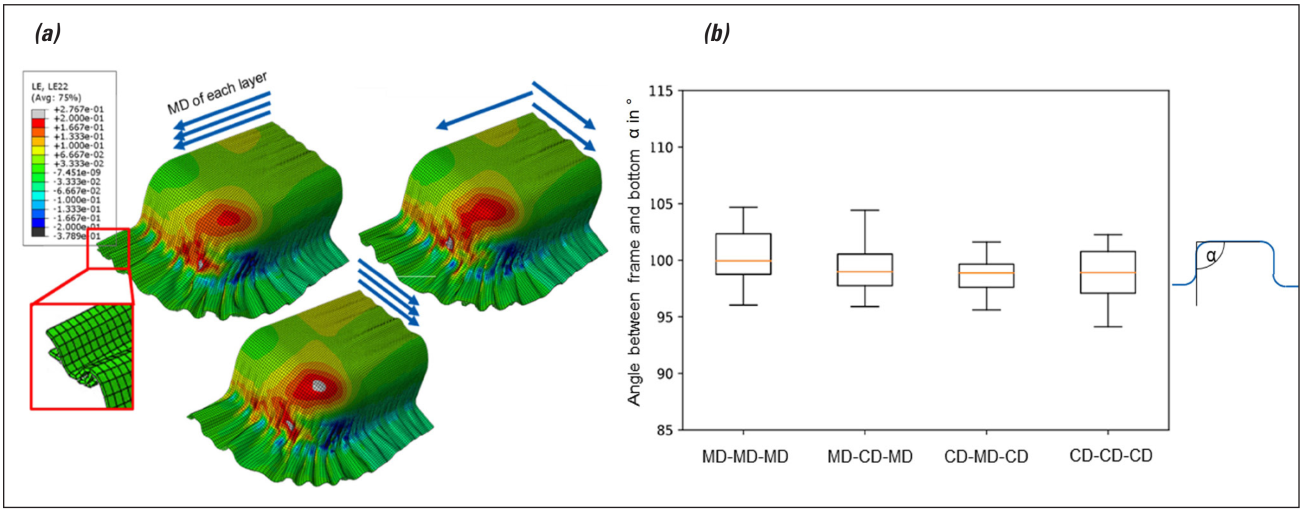
The Fig. 8 graphs illustrate the fiber orientations aligned parallel to the long side of the geometry, configured as outer layer–middle layer–outer layer. Across five repetitions for each fiber orientation, no significant differences were observed in the peeling behavior, indicating that the material's performance is not dependent on orientation. Consistently, all deep-drawn samples exhibit a nearly identical wrinkle pattern, which solely drives the bond cohesion. The observed independence from fiber orientation aligns with expectations, as the wrinkles effectively maintain the connection between layers. Furthermore, the consistent peak forces and overall curve progression confirm reliable performance without the need for adhesives and highlight the robustness of this wrinkle-driven design. The material composition shows a high peeling resistance due to wrinkles and without using glue while being reproducible.

LAYER ORIENTATION

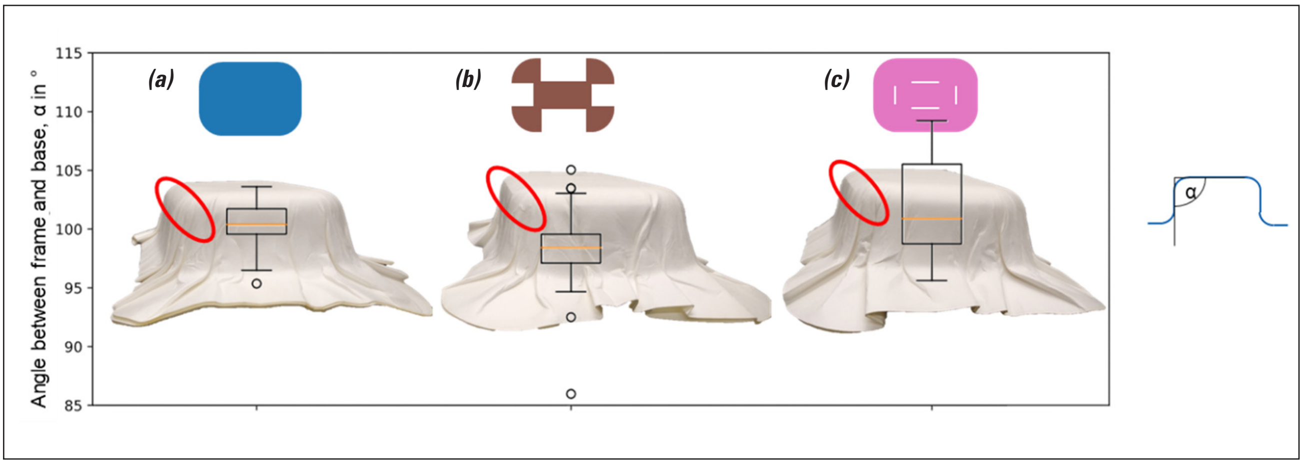
While multilayered paperboard products exhibit numerous advantages in terms of formability and load-bearing, fiber orientation has a significant impact on springback and achievable drawing depth in paperboard, largely due to its inherent anisotropy. Numerical simulations helped to investigate the impact of layer orientations on drawing depth and load distribution. The maximum achievable drawing depth before material failure was investigated by adjusting layer directions. Failure was modeled by ductile damage, considering fracture strain, stress triaxiality, strain rate, and displacement at failure (**Fig. 9a**). The results showed that aligning all layers in MD, parallel to the short side, led to the earliest breakage. Conversely, orienting the layers perpendicularly resulted not only in a greater drawing depth but also in extended wrinkle-free areas. The most favorable results were achieved by orienting the two outer layers in the same direction and the middle layer perpendicular to them. These numerical findings were validated through experimental testing.

Springback, which often degrades geometric accuracy, is difficult to control and has not been well modeled numerically. Compared to single-layer paperboard, multilayer configurations showed consistently lower springback in experiments, supporting previous findings regarding the shape-stabilizing effect of the fiber network.

No significant difference was observed between the two variants with varying layer orientations, which is consistent with the numerical modeling results (Fig. 9b). However, the configuration with the two outer layers aligned parallel to CD exhibited marginally lower springback than the perpendicular variant, with the desired geometry having a 90° angle between frame and bottom. Compared to single-layer and uniformly oriented multilayer samples, this alternating configuration clearly improved springback reduction and decreased variation. The underlying cause of this improvement lies in the counteracting anisotropic effects across alternating layers and the tensile and shear loads they exert on one another. This residual stress enhances material resistance and decreases elastic deformability, necessitating plastic deformation to achieve the desired shape.



9. (a) Logarithmic expansion in numerical models, depending on the layer orientation, and (b) experimental springback angle depending on layer orientation.



10. Selection of middle layer geometry studied: (a) reference, and (b,c) strategic weakening in edge areas to encourage controlled bending.

To further optimize springback and enhance product appearance, adjustments were made to the blank geometry. Since the middle layer is not visible, its shape can be more customized, provided it continues to support the inner and outer layers sufficiently.

The blue, brown, and pink colored areas in **Fig. 10** represent some middle-layer geometries explored in the study. Figure 10a (blue) serves as the reference geometry, identical to the outer layers in all cases. The other two designs, Fig. 10b (brown) and Fig. 10c (pink), incorporate strategic weakening in the edge areas to encourage more controlled bending. In the Fig. 10c geometry, this weakening is achieved by thin cutouts along the bottom of each wall, whereas the Fig. 10b geometry includes larger cutouts in each wall section, both excluding the highly stressed radius area.

The hypothesis was that the removal of excess material would decrease springback by redistributing strain and preventing material overflow, which tends to concentrate in the corner areas and potentially leads to breakage. The forming results showed no early breakage or compromise in the formability.

The wrinkle formation pattern shifted with the cutouts. While the reference geometry (Fig. 10a) displayed horizontal wrinkles along the walls, the modified designs (Fig. 10b and Fig. 10c) exhibited diagonal wrinkle formations. This shift can be attributed to the redistribution of strain across the modified geometry. The absence of material in the cutout areas allowed localized deformation along more independent vectors, thereby altering the wrinkle orientation.

The results, as shown in Fig. 10, indicate visual differences in the edge angles of the geometries. The red circles highlight a pronounced edge in the adjusted geometries, which is rounded in the reference design. Despite this visual difference, there was no relevant measurable variation in the springback angle across the configurations. The modifications primarily affected the radius at the edges, but their impact on springback remained negligible, suggesting that the springback behavior is governed more by overall material properties and forming conditions than by local geometric changes.

CONCLUSION

This study presents significant advances in the formability and load-bearing capacities of paperboard using a multilayered approach. The research highlights the potential of multilayered paperboard materials to address the increasing demand for environmentally friendly packaging alternatives while enhancing essential performance characteristics. As sustainable packaging gains prominence, especially as a substitute for single-use plastics, the insights provided in this work may pave the way for more robust and adaptable applications in the packaging industry.

The experimental and numerical analyses conducted in this study underscore the distinct advantages of multilayered paperboards over single-layer materials. One of the key findings is the enhanced formability exhibited by multilayered structures, particularly when layers are unbonded. Unbonded layers allow relative movement between fiber layers, increasing flexibility and enabling higher tolerance to various strain states. This increased adaptability makes multilayered paperboards a promising choice for complex packaging geometries, where the material needs to withstand significant deformation without structural compromise. Additionally, the research shows that the anisotropic behavior of paperboard, which often limits its application in three-dimensional forming, can be mitigated through the appropriate orientation of layers. By aligning the outer layers perpendicular to the middle layer, the study demonstrates an effective way to reduce anisotropic springback, thus achieving fewer deviations in forming results.

The findings also reveal the influence of fiber orientation on the overall form stability of the paperboard. Pressure tests show that multilayered configurations exhibit greater load-bearing capacities compared to single-layered counterparts, even without adhesive bonding. This behavior is attributed to the mutual support provided by fiber networks across layers as well as the mechanical coupling of the wrinkles, which enhances resistance to external pressures. These improvements are particularly valuable in applications requiring robust protection for packaged goods, further increasing the competitiveness of paperboard as a viable packaging material. Additionally, the results suggest that the performance of multilayered paperboards in resisting deformation is independent of fiber alignment, which simplifies design considerations and broadens the range of potential applications.

Another noteworthy aspect of this study is the peeling tests confirming that, under certain forming conditions, the layers establish a sufficient mechanical bond through wrinkling, effectively holding the layers together without the need for adhesives. This adhesive-free approach not only aligns with the sustainability goals by reducing material inputs, but also enhances recyclability. By relying on the material's inherent properties rather than additional bonding agents, this innovation contributes to a more sustainable lifecycle for paperboard packaging, from production to end-of-life disposal.

The numerical modeling component of this research also provides valuable insight into the behavior of multilayered paperboards under different strain conditions. The model developed for this study effectively simulates wrinkle formation and failure, which are critical factors in forming processes. The alignment of simulation results with experimental findings validates a good enough accuracy and reliability of the numerical approach, providing a useful tool for preliminary approximations on forming outcomes and parameter optimization. The ability to simulate and predict material behavior in advance allows for tailored design and process adjustments, potentially reducing material waste and improving production efficiency, but it needs to be further developed in terms of springback and more accurate wrinkle mapping in the future.

Finally, this study's implications extend beyond the technical improvements in paperboard forming to broader industry applications. As global regulations and consumer expectations drive the shift towards sustainable packaging, the demonstrated capabilities of multilayered paperboards offer a compelling solution that balances sustainability with functionality. The potential to customize material composition, layer structure, and fiber orientation according to specific packaging needs positions multilayered paperboard as a versatile and scalable alternative for various sectors. Furthermore, the reduced dependence on adhesives and the improved structural integrity of multilayered configurations contribute to the overall sustainability and durability of the final product, making it a competitive choice in the market. **TJ**

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ABOUT THE AUTHORS

The main goal in my research (Jessen) has been using paperboard to its full capacity, making its application as flexible and customizable as possible in packaging solutions. The research here supports previous research on fiber movement and overall paperboard forming, as well as my own research regarding modeling of paperboard forming processes and utilizing its strain capacities.

The most difficult aspects of this study were related to the inherent inhomogeneities of paper and the data deviations due to the natural fiber network in paperboard. This was addressed by comparing paperboards with the same ply layering, as well as increasing the dataset by repeating experiments more frequently. In addition, numerical analysis helped a great deal in supporting key findings.

Through this work, I discovered how fiber interaction is a crucial part of paperboard forming and needs further research in many aspects, one of which is how it can be strategically influenced. The high repeatability and layer bonding without adhesives just by forming was really unexpected, as was how the load bearing capacity can provide big advances for many industries.

Mills might benefit from this information, because it highlights the importance of individual fibers and layers in each network. It may help them to choose developments that make fibers more available for different industries. In the next step of this research, the modeling processes will be advanced further, and the research will be taken to new levels by studying multilayered approaches with different functional materials.

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