

Printing stiffeners on corrugated board boxes: a bio-inspired strategy to lighten packaging

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Short abstract

Reducing the environmental impact of packaging requires both replacing plastics and optimizing the use of bio-based materials such as paper and cardboard. Although corrugated board is recyclable and biodegradable, its production remains resource-intensive, motivating strategies to reduce material usage without compromising mechanical performance. This study explores a bio-inspired approach based on printing rib-like stiffening patterns on corrugated board using fused deposition modelling (FDM) of poly(lactic acid) (PLA) as a proof of concept, with the objective of ultimately replacing it with an extruded cellulose-based paste. Box compression tests coupled with stereo digital image correlation (DIC) were used to analyze deformation mechanisms and map full-field strain distributions. Failure is governed by panel buckling followed by crease initiation, with strain concentrations mainly located in the corner regions. Reinforcement patterns were designed by exploiting these findings. Printed stiffeners delay crease formation and allow larger deformations before collapse, resulting in a compression strength increase of up to 50% for a mass increase below 30%. These findings highlight the potential of strain-driven, bio-inspired design to enhance the mechanical efficiency of corrugated board packaging.

Keywords: Corrugated board, compression strength, FDM printing, strain-driven design

1. Introduction and background

Plastic packaging accounts for approximately 40% of global plastic production and is a major contributor to greenhouse gas emissions and environmental pollution. In response, European regulations aim to progressively reduce single-use plastic packaging. Paper-based materials, including corrugated board, represent promising alternatives due to their bio-based, recyclable, and biodegradable nature. However, their production still involves significant consumption of water, energy, and raw materials. Therefore, reducing the mass of paper-based packaging while maintaining its mechanical integrity is a key challenge. During storage and transport, packaging boxes are subjected primarily to vertical compression loads, often under varying humidity conditions that can accelerate creep, Frank, 2014. Failure typically occurs through buckling of the panels, followed by crease formation and structural collapse, Viguié et al., 2010. The resistance to buckling is strongly governed by the bending stiffness of the panels, which depends on both material properties and geometry. Buckling induces a heterogeneous stress distribution, with the highest stresses concentrated in the corner regions. Crease formation in these areas is a direct consequence of this stress concentration. A well-known strategy to enhance stiffness without significantly increasing weight is to increase the second moment of area through structural design. Ribbed or stiffened surfaces are widely observed in nature, for example in leaves or insect wings, where they provide high stiffness-to-weight ratios. Inspired by these biological systems, engineered rib networks can be introduced to improve the mechanical performance of thin structures. Previous studies have demonstrated the potential of this approach for folding board packaging, where thin grids of poly(lactic acid) (PLA) printed by fused deposition modelling (FDM) increased compression strength by up to 60% under humid conditions with minimal mass increase (7%), Bonnet et al. 2023. The present study investigates the applicability of this strategy to corrugated board boxes to improve compression behaviour. Particular attention is given to optimizing pattern design by accounting for the heterogeneous stress distribution that develops in the panels after buckling. This distribution is characterized experimentally through strain field measurements using stereo image correlation, Viguié et al. 2011.

2. Materials and methods

Commercial e-flute corrugated board sheets ($1300 \times 800 \text{ mm}^2$) were used. The material had a thickness of $1.48 \pm 0.14 \text{ mm}$, a grammage of $379.9 \pm 4.4 \text{ g/m}^2$, and a flute pitch of approximately 3.5 mm. The structure consisted of a single fluted medium sandwiched between two liners. Boxes ($150 \times 150 \times 150 \text{ mm}^3$) were designed using ArtiosCAD and cut using a Kongsberg XL22 cutting table. The flutes were oriented parallel to the compression axis. Boxes were assembled using PVAc glue and conditioned for 24 h at 23 °C and 50% relative humidity (RH) prior to testing. PLA filaments (1.75 mm diameter) were deposited using a Mingda A128 FDM printer equipped with a 0.8 mm nozzle resulting in a final stiffener thickness of approximately 750 μm thickness. Printing parameters were optimized to ensure adhesion to the corrugated board, including nozzle temperature, speed, nozzle height, and extrusion flow rate. Stiffeners were printed on all four panels of the boxes.

Box compression tests were conducted using an IDM BC100/20 testing machine at a crosshead speed of 12.5 mm/min. Tests were performed under controlled conditions (23 °C, 50% RH). Stereo digital image correlation (DIC) was performed using two Canon EOS 2000D cameras (Fig. 1a) to have access to the stress distribution on the panels. Images were captured every second during compression. This allowed reconstruction of full-field strain maps on the box panels. From these maps, principal strain fields and their orientations were extracted. The corresponding principal stress fields were then estimated using the elastic stress-strain relationship (Fig. 1b). Based on this information, optimal stiffener geometries can be identified by aligning reinforcement patterns with the principal stress directions (picture on Fig. 1c), thereby maximizing their mechanical efficiency while minimizing added material.

3. Results and discussion

Figure 1c depicts typical load displacement curve for the reference (unprinted) box. The load-displacement response revealed distinct deformation stages. Initially, a linear region corresponds to flap flattening. This is followed by a transition marking the onset of panel buckling. Finally, a peak stress is reached, after which collapse occurs through crease propagation. Full-field observations revealed that failure is governed by panel buckling followed by crease formation. Creases typically initiate near the box edges and propagate across panels, leading to collapse. The principal stress fields and their orientations, estimated from stereo digital image correlation (DIC) measurements prior to collapse (Fig. 1b), indicate that regions near the corners experience the highest constraints. These areas exhibit a combination of compressive stresses oriented approximately 30° relative to the vertical (e_y) and horizontal (e_x) axes. In contrast, the central regions of the panels are only weakly stressed. Along the vertical edges, the principal stress directions tend to be predominantly aligned with the vertical and horizontal axes, with stress levels lower than those observed in the corner regions and tensile stresses appearing along the horizontal axis. Based on this analysis, an optimized reinforcement pattern was designed, printed on all four panels, and tested under vertical compression. The corresponding load-displacement curve is presented in Fig. 1c. The introduction of printed grids delays creases initiation during buckling and thus enables the structure to sustain larger deformations prior to collapse. As a result, the compression strength increases by nearly 50%, while the box mass increases by less than 30%.

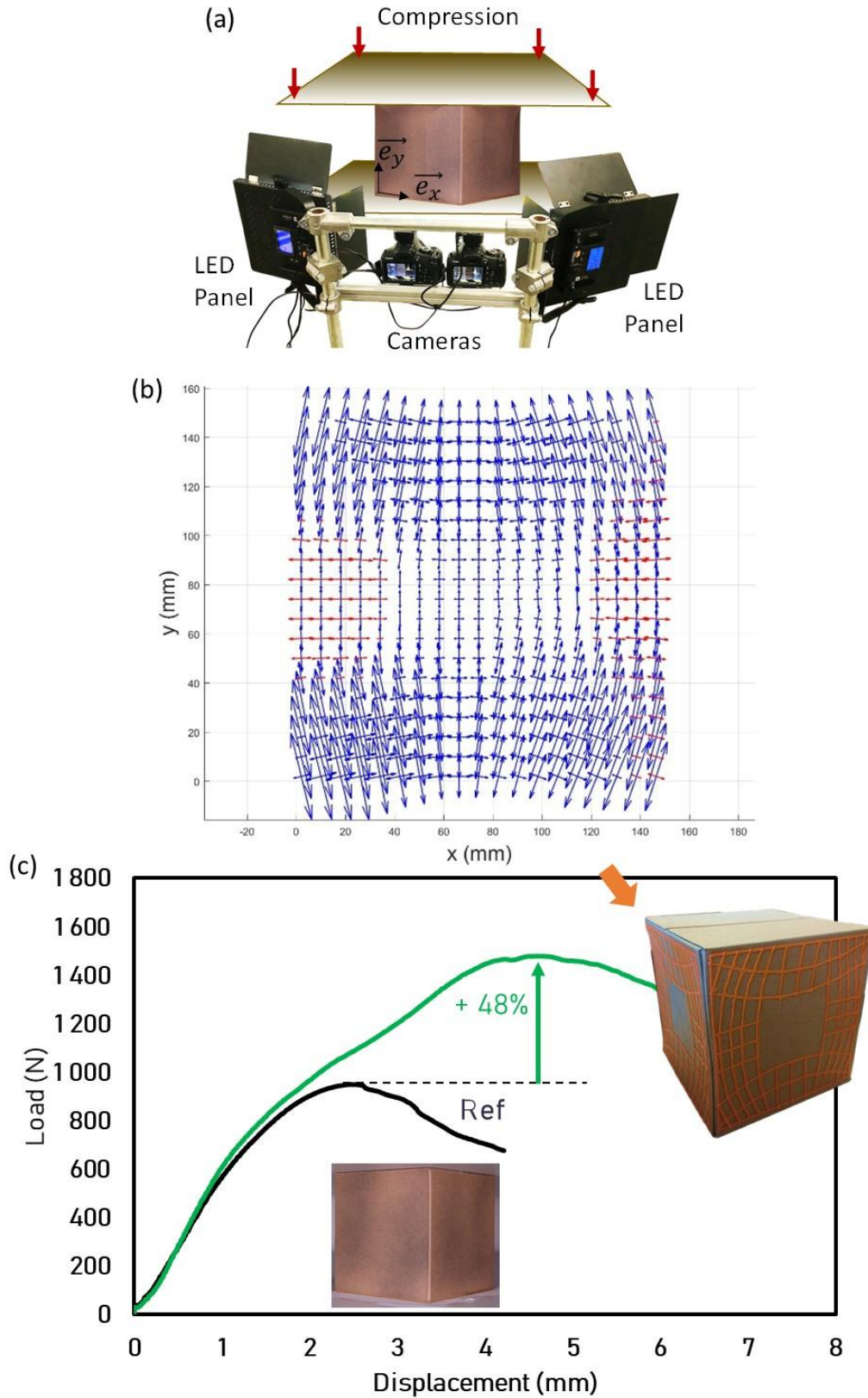


Figure 1: (a) Experimental setup for strain field measurement using stereo digital image correlation (DIC). (b) Principal stress map and orientations on a panel prior to box collapse (compression in blue, tension in red). (c) Load-displacement curves for the reference box and the box reinforced with the optimized printed stiffener pattern.

4. Conclusions

This study demonstrates the potential of additively manufactured stiffener networks to enhance the mechanical performance of corrugated board packaging under compressive loading. Strain field measurements obtained by stereo digital image correlation revealed that failure is governed by panel buckling followed by crease initiation, with the highest strain and stress concentrations located in the corner regions and oriented along preferential directions. Reinforcement patterns were designed by exploiting this heterogeneous distribution. The introduction of printed stiffeners significantly modified the mechanical behaviour by delaying crease initiation and allowing larger deformations prior to collapse. As a result, the compression strength of the boxes increased by nearly 50%, while the associated mass increase remained below 30%. These results confirm that bio-inspired structural design, combined with strain-field-driven optimization, is a promising approach for reducing material usage while maintaining or enhancing mechanical performance in paper-based packaging. As a perspective, future work will focus on evaluating the feasibility of replacing PLA with a cellulosic paste formulation.

References

- Bonnet, N., Viguié, J., Beneventi, D., and Chaussy, D. 2023. Reinforcing folding board boxes by printing a PLA patterned grid on their panels: A new approach for lightweighting stiff packaging. *Packaging Technology and Science* 36(3), pp. 211-218.
- Frank B. 2019. Corrugated Box Compression—A Literature Survey. *Packaging Technology and Science* 27(2), pp. 105-128. doi:10.1002/pts.2019
- Viguié, J., Dumont, P. J., Desloges, I., and Mauret, É. 2010. Some experimental aspects of the compression behaviour of boxes made up of G-flute corrugated boards. *Packaging Technology and Science: An International Journal*, 23(2), pp. 69-89.
- Viguié, J., Dumont, P. J., Orgéas, L., Vacher, P., Desloges, I., and Mauret, E. 2011. Surface stress and strain fields on compressed panels of corrugated board boxes. An experimental analysis by using Digital Image Stereocorrelation. *Composite Structures* 93(11), pp. 2861-2873.