# An Experimental-Numerical Framework for Evaluating the Elastic Properties of Laminated Papers

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**Keywords:** *laminated paper composites; elastic properties; experimental methodology*

## 1 ABSTRACT

Paper packaging, like cardboard angles or tube cores, are usually made from laminated paper. These laminates are composed of staking sheets of paper glued together by an adhesive. The choice of raw material can be made on different imperatives: availability, price, mechanical performance, usability and even aesthetics. Although, the choice of raw material is not as critical as in other composite domains, the misunderstanding of the effect of raw material makes it difficult to guarantee minimal mechanical performance of the end product.

This study investigates the in-plane and out-of-plane elastic mechanical properties of laminates made with different commercially available raw material. In-plane moduli were obtained with tensile testing. In addition, tensile tests on a ±45° stacking sequence, combined with classical laminate theory, were used to estimate in-plane shear modulus. Out-of-plane properties are known to be difficult to evaluate, particularly for thick laminate. Moreover, manufacturing paper laminates with sufficient thickness to apply standardized methods commonly used on conventional composites is difficult. Instead, we propose a simple methodology to estimate transverse shear moduli by combining three-point bending and finite element modeling. The order of magnitude of the results was comparable to those reported in the literature for single sheets of paper.

## 2 INTRODUCTION

The paper packaging sector in Canada occupies a predominant place in the economy. According to the Food and Agricultural Organization, Canada is among the 10 largest manufacturers of paper products in the world with a production estimated to 7,9 metric tonnes in 2023 [1]. Due to its abundant forestry ressources of great quality, Canada is a supplier of choice for the United States and Mexico. In the past decades, attention was brough to more eco-friendly packaging. Following the rapid increase of ecommerce in Canada since 2019 [2], the need for more optimized packaging, in terms of mass, geometry, recyclability and mechanical performance, became clear.

Paper packages can be made from a wide variety of paper and adhesive. The choice of raw material dictates the performance of the product. As for any material, mechanical performances are often measured by standardized tests. In the case of packaging products, composed of laminates from paper and adhesive, like cardboard angles and tube cores, there is a lack of standardized mechanical tests. Furthermore, few data exist to guide manufacturers in the choice of raw material, and thus, there is a misunderstanding of the effect of raw materials on the end product.

Paper is an anisotropic material composed mainly of wood fibers. At a macroscale level, paper can be considered as orthotropic [3]. Many authors have used this assumption to simplify the finite element modeling of packaging products [4]. Finite element modeling can be very effective at optimizing packaging product regarding, for instance, their buckling strength and folding capability. Due to the manufacturing process of paper, out-of-plane properties, such as shear moduli and Poisson's ratios, are generally very low compared to the in-plane properties. This large discrepancy generally results in a bending behavior that is very sensitive to the out-of-plane properties. Thus, many finite element studies on packaging products have in common the use of shell elements that required the out-of-plane shear moduli.

There are some standards to evaluate in-plane properties of a single sheet of paper [5] that are similar to those used for laminated composites [6]. But one of the difficulties that arises is the determination of the out-of-plane properties. There is some suggested methodologies to obtain out-of-plane properties of paper listed in [7], but these require a special fixture and can't be applied to laminated structures due to their high thickness. Furthermore, standardised tests designed for laminated composites, like ASTM D5379 [8], used to obtain transverse shear moduli, are not practical to use on laminated paper due to the high number of plies required.

The objective of this project is to investigate the properties of laminates composed of paper and adhesive used in the packaging industry. To do so, five different combinations of paper and adhesive were investigated. In-plane properties were estimated through tensile testing, while out-of-plane properties were estimated by combining three-point bending and finite element modeling. The in-plane properties of single sheets of paper were also investigated to serve as a reference and help to understand the effect of raw materials on the laminated properties. This project is done in collaboration with Abzac Canada Inc., a manufacturer of packaging products.

## 3 MATERIALS AND METHODOLOGY

### *1.1. Materials*

In this study, two types of commercial recycled papers were used along with three types of adhesives. These materials are commonly used to manufacture paper packaging products. Some properties of these materials are shown in Table 1 and Table 2.

Liner papers are usually used for facing in packaging products like cardboard angles and corrugated boxes. Chipboard is often used as a core in cardboard angles due to its high thickness.

The first adhesive is a polyvinyl alcohol (PVA) based on Dry bond 636 powder. To achieve a liquid form, the powder is mixed with other substances such as water and an antifoaming agent. The second adhesive is Dural 3114, which is a polyvinyl acetate (PVAc) that comes directly in a liquid form. Finally, the last adhesive is a dextrin based on Clintose® maltodextrine CR10 powder, mixed with other agents that are diluted in water. All these adhesives are designed to be used at ambient temperature.

*Table 1. Properties of the papers.*

| | Grammage ($g/m^2$) | Thickness (mm) |
|---|---|---|
| Liner | 165 ± 2 | 0,269 ± 0,004 |
| Chipboard | 575 ± 20 | 0,884 ± 0,013 |

Data are taken after conditioning

*Table 2. Properties of the adhesives.*

| | Solid content (%) | Viscosity (cps at 23°C) |
|---|---|---|
| PVA | 19,4 | 1440 |
| PVAc | 18-23 | 1600-2000 |
| Dextrin | 24,5 | |

Properties are given by Abzac except for PVAc that are given by the manufacturer

### *1.2. Manufacturing and conditioning of specimens*

Liner laminates are composed of 16 sheets, and chipboard laminates are composed of eight sheets. The manufacturing starts by cutting rectangular pieces of paper directly from the roll. A film of adhesive of 200 µm is applied on these pieces using a motorized film applicator Elcometer 4340. The glued papers are then pressed together using a manual press roller, where excess of adhesive is also removed. The laminate obtained is then slightly pressed between two perforated polypropylene plates of 6 mm thickness for a full week in a room where the relative humidity is about 30 % and the temperature is 22°C. This step serves as a preconditioning where excess of water evaporates and also ensures that the laminate remains straight.

After preconditioning, rectangular specimens are cut from the laminates using a CNC table Shapeoko Pro. The table is equipped with a router bit #251 from Cardbide 3D, which is a downcut flat cutter of 0.25 inches in diameter. The rotation and displacement speed of the bit are set to 18 000 rpm and 12,7 mm/s respectively. The cutting quality can be seen in Figure 1.

a)
b)

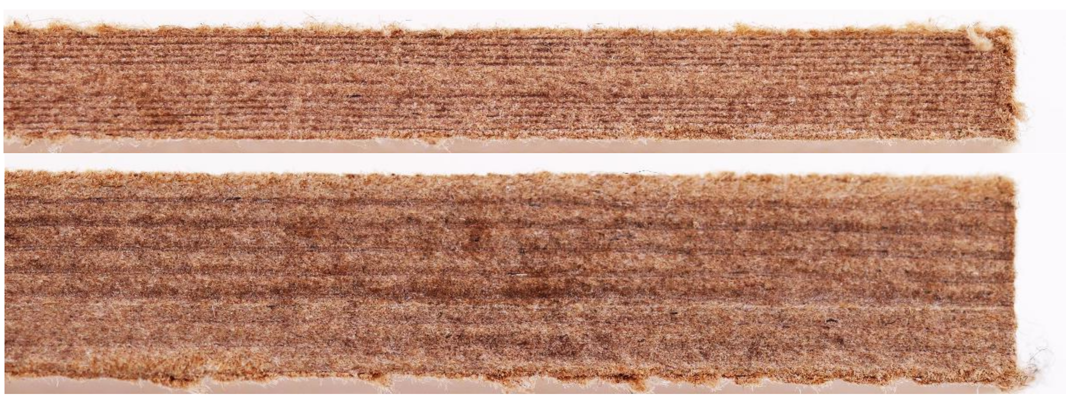


*Figure 1. Cutting quality of the router bit on laminate made with a) liner and b) chipboard.*

For single sheets of paper, specimens are simply cut at their final dimensions directly from the roll with a precision cutter designed for paper material. Preconditioning is also performed on these specimens in the same conditions as for the laminates.

Specimens are then conditioned in a controlled room where relative humidity and temperature are set to 50 % and 23°C respectively. Usually, conditioning standards for paper products recommend a conditioning time of 48 hours [9]. Due to the high thickness of the laminate specimens, conditioning is performed for a minimum of one month to ensure specimens reach equilibrium. Single sheet specimens are also conditioned for the same duration as laminates for convenience, even though a duration of 48 hours would have been enough from our observation. Specimen are weighed 24 hours before testing and just before testing to ensure that the weight is stable.

Finally, since specimens are not tested in the same room as the one used for conditioning, a desiccator with a Boveda B49 kit placed inside is used for transportation. This kit is a two-way humidity control pack usually used for music instruments in closed cases. It allows humidity to stay at 50 % during transportation.

### *1.3. Determination of in-plane and out-of-plane elastic properties*

All tests are performed on a universal testing machine in conjunction with an Aramis digital image correlation (DIC) system to measure deformation and displacement. For laminate specimens and single sheet specimens, a 50 kN and a 10 kN load cell are used respectively.

Tensile testing, based on ASTM D828 [5] for single sheets and ASTM D3039 [6] for laminates, is performed to evaluate in-plane properties, such as moduli ($E_1$ and $E_2$) and Poisson's ratio $v_{12}$. The testing speed is set to 2 mm/min for all tensile tests. For the in-plane shear modulus $G_{12}$ of laminates, a similar methodology is employed on specimens with plies oriented at plus and minus 45°. An equivalent modulus $E_x$ is first measured and then, by using equation 1, based on the classical laminate theory (CLT) [10], the in-plane shear modulus $G_{12}$ is estimated. The terms $Q_{ij}$ represent the components of the reduced stiffness matrix. Average values of $E_1$, $E_2$ and $v_{12}$ are used to calculate these terms. For single sheets of paper, equation 1 is also used to determine $G_{12}$, where $E_x$ is obtained from a tensile test on a single sheet oriented at 45°.

$$G_{12} = \frac{E_x a}{4a - E_x} \quad \text{with} \quad a = \frac{1}{4}(Q_{11} + Q_{22}) + \frac{1}{2}Q_{12} \tag{1}$$

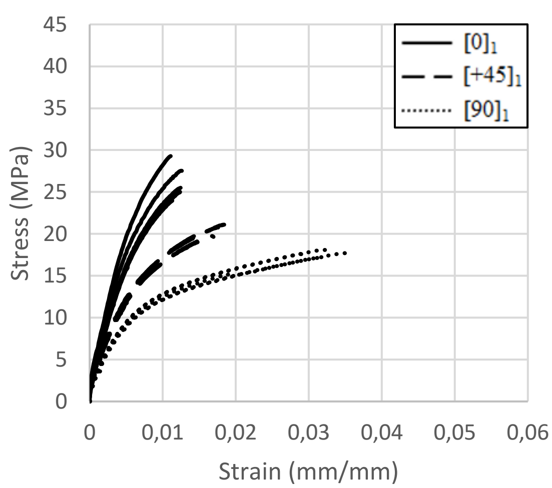
Out-of-plane shear modulus $G_{13}$ and $G_{23}$ of laminates are obtained through reverse engineering by using experimental testing and finite element modeling. Inspired by ISO 14130 [11], three-point bending tests are performed on short rectangular specimens. The width and length of the specimens are respectively five times and 10 times their thickness. The radius of the supports and the loading nose is 5 mm. The span length is fixed at five times the thickness of the laminate. The short span length ensures that out-of-plane shear stress is important during testing. The testing speed is set to 1 mm/min. The displacement of the loading nose is obtained using DIC. Data for the experimental force-displacement curves are recorded and the average slope of the elastic part of the curve is calculated.

Abaqus software is used to replicate the three-point bending test with the finite element method. The average elastic in-plane properties, obtained by experimental testing, are implemented in the model along with a representative value of a 100 MPa, obtained from the literature [3], for $G_{13}$ and $G_{23}$. The specimen is modeled as a laminated orthotropic unidirectional plate. S8R shell elements with 1 x 1 mm dimensions are used to mesh the plate. Dimensions of the plate are based on the average dimension of their real counterparts. The fixed supports and loading nose are modeled as rigid elements. A displacement of 1 mm is imposed on the loading nose. The slope of the force-displacement curve on the loading nose is then compared to the average elastic slope of the experimental curves. Out-of-plane shear moduli are varied in the model until a good agreement is found between the two slopes.

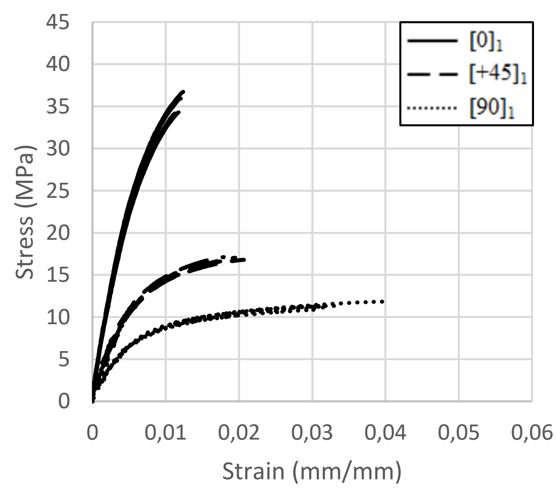
## 4 RESULTS AND DISCUSSION

Tensile curves for single sheets of paper are presented in Figure 2. Tensile curves for all five different laminate constructions are presented in Figure 3. In these figures, the effect of the stacking sequence is clear. Specimens with a stacking sequence of $[0]_n$ have higher elastic slopes and tensile strength. Specimens with a stacking sequence of $[90]_n$ show the lowest slope and tensile strength. This is due to the manufacturing process of the papers where fibers have a tendency to align in the direction of the flow of pulp, called the *machine direction* [12]. Also, the more perpendicular the fibers are to the tensile direction, the more the specimen can sustain stretch before failure. These observations are common for paper products [3].

By comparing the reference liners to the laminate made with the same paper, we observe that the presence of adhesives increases the strain before failure for each stacking sequence. Laminates also have a higher tensile strength than single liner sheets. In the case of the laminates made with chipboards, the increase in strain before failure is not as significant as for the laminates made with liners. Also, their tensile strength with $[0]_8$ stacking sequence decreases while there is no significant change for the other stacking sequences.




a)




b)

*Figure 2. Tensile stress-strain for single sheets of paper: a) liner and b) chipboard.*

The in-plane and out-of-plane elastic properties of each laminate and single sheet of paper are presented in Table 3. For samples made with chipboard, including single sheets of chipboard, the discrepancies on in-plane properties between machine direction and other orientations are more pronounced than for samples of liner. In other words, chipboard shows higher orthotropy than liner. An indication that chipboard fibers are more aligned in the machine direction than liner fibers.

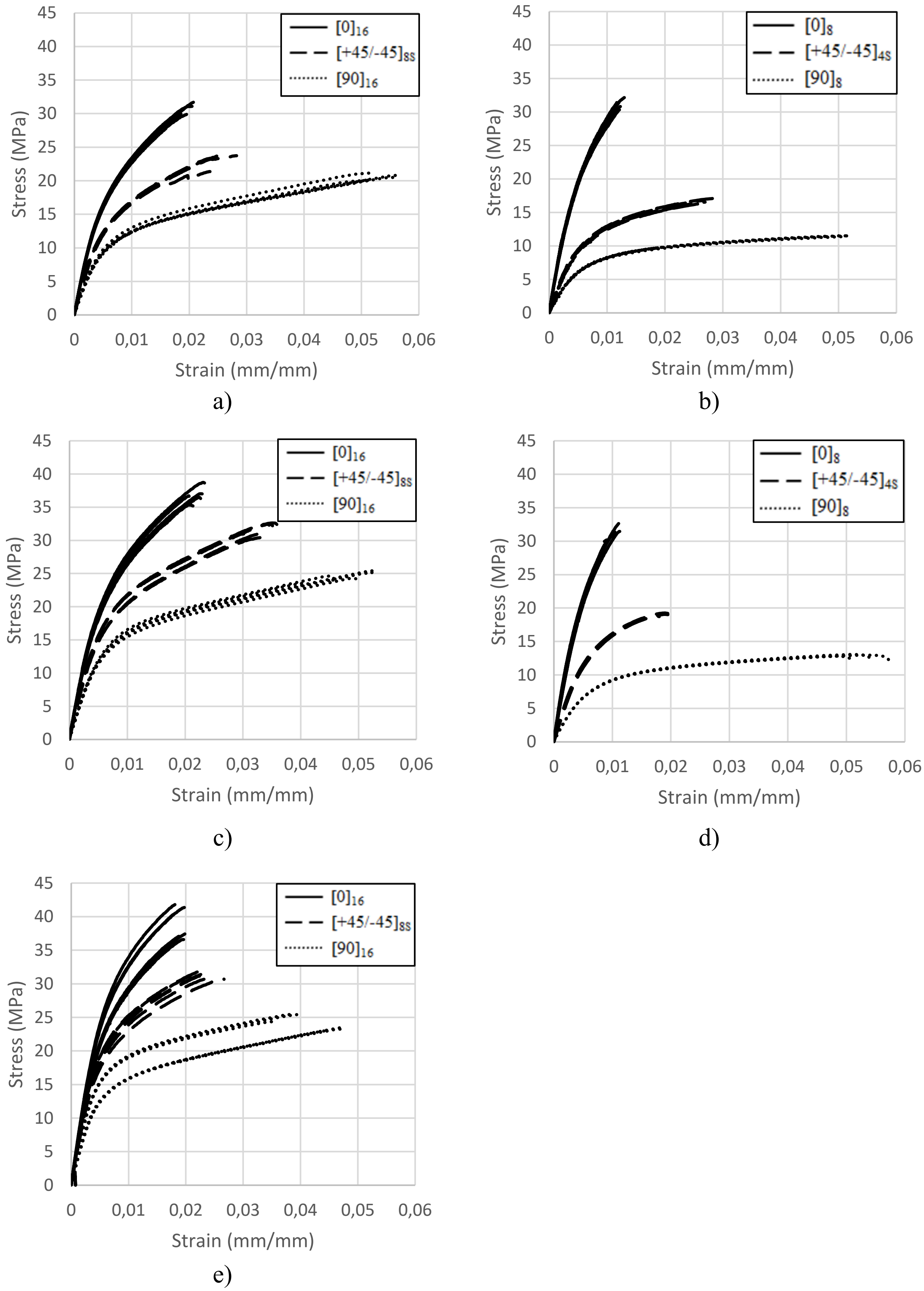



*Figure 3. Tensile stress-strain curves for laminates: a) liner-PVA, b) Chipboard-PVA, c) Liner-PVAc, d) Chipboard-PVAc and e) Liner-Dextrin. The stacking sequence for each curve is shown in legend.*

*Table 3. Elastic mechanical properties of laminates and single sheets of paper.*

| Construction | $E_1$ (MPa) | $E_2$ (MPa) | $G_{12}$ (MPa) | $G_{13}$ (MPa) | $G_{23}$ (MPa) | $\nu_{12}$ |
|---|---|---|---|---|---|---|
| Liner-PVA | 4144 ± 62 | 2430 ± 82 | 1221 | 14,4 | 16,7 | 0,33 ± 0,04 |
| Liner-PVAc | 4399 ± 148 | 2594 ± 131 | 1443 | 26,3 | 23,5 | 0,32 ± 0,01 |
| Liner-Dextrin | 5316 ± 314 | 3461 ± 430 | 1862 | 31,8 | 50,0 | 0,31 ± 0,03 |
| Chipboard-PVA | 4758 ± 96 | 1535 ± 45 | 810 | 13,5 | 13,0 | 0,40 ± 0,06 |
| Chipboard-PVAc | 5079 ± 391 | 1464 ± 7 | 953 | 17,5 | 23,5 | 0,47 ± 0,02 |
| Liner | 3535 ± 280 | 1912 ± 68 | 893 | | | 0,37 ± 0,02 |
| Chipboard | 4869 ± 139 | 1305 ± 73 | 786 | | | 0,44 ± 0,02 |

The properties obtained for single sheets of paper and laminates are of the same order of magnitude as those listed in the literature [3]. As expected from the literature, the out-of-plane shear moduli of laminates are much lower than their in-plane properties.

The results obtained from tensile curves and elastic properties seem to indicate that the liner is more sensitive to the adhesives than the chipboard. However, the adhesive was applied with a constant thickness of about 200 µm with no regard to the type of paper. By knowing their average grammage and thickness, we estimate that the density of a single sheet of liner is 0,615 ± 0,010 g/cm$^3$ and 0,650 ± 0,021 g/cm$^3$ for chipboard. Thus, the fiber density for laminates made with chipboard is higher than for laminates made with liner. This can be a plausible explanation of the low effect of adhesive on the elastic properties of chipboard laminates.

The average thickness of the laminates, after conditioning, is shown in Table 4. It was noticed that the average ply thickness for liner laminates is 4 to 11% lower than the thickness of a single sheet of liner depending on the construction. For chipboard laminates, the average ply thickness is 1 to 4% lower than for a single sheet of chipboard.

*Table 4. Average thickness of the laminates*

| Construction | Thickness (mm) | Average plies thickness (mm) |
|---|---|---|
| Liner-PVA | 4,00 ± 0,05 | 0,25 |
| Liner-PVAc | 3,91 ± 0,04 | 0,24 |
| Liner-Dextrin | 4,13 ± 0,05 | 0,26 |
| Chipboard-PVA | 6,96 ± 0,09 | 0,87 |
| Chipboard-PVAc | 7,02 ± 0,02 | 0,88 |

The reduction of thickness can be attributed to compression occurring during manufacturing of laminates. Due to the way that in-plane moduli are calculated (based on the cross-section area), it becomes difficult to directly link the modulus of a single sheet of paper to the modulus of a laminate by isolating the effect of the adhesive. Furthermore, some questions persist about the dynamics of moisture absorption of paper with and without adhesive. In this project, raw materials were stored in a dry environment (≈30% relative humidity) before the manufacturing of laminates.

It is possible that the adhesive, after preconditioning, prevents partially paper from absorbing additional moisture, as the remaining hydroxyl groups of fibers have bonded to the adhesive. For future work, study of the dynamics of moisture absorption of laminates could be useful to have a better understanding of the effect of adhesive.

# 5 CONCLUSION

The objective of this project was to investigate in-plane and out-of-plane mechanical elastic properties of laminates used in the packaging industry. Tensile testing was used to evaluate the in-plane properties. Out-of-plane properties were estimated by combining three-point bending and finite element modeling. Five different laminate constructions, composed of paper and adhesive, were studied using the proposed methodology. Results for single sheets of paper were also presented for comparison. Depending on the paper used in the laminate and the stacking sequence, the adhesives have a varying degree of impact. Overall, properties obtained for laminates were still comparable, in order of magnitude, to the properties of single sheets of paper. The proposed methodology can be useful for future work regarding the optimization of packaging products in terms of geometry and the choice of raw materials.

# 6 ACKNOWLEGMENT

The authors wish to acknowledge the material and financial contribution of Abzac Canada Inc. as well as the financial support from the Natural Sciences and Engineering Research Council of Canada (NSERC).

# 7 CONFLICT OF INTEREST

All authors state that there is no conflict of interest of any kind.

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