Influence of Humidity and Temperature on Mechanical Properties of Corrugated Board - Numerical Investigation

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Paper is a material whose mechanical properties are highly dependent on humidity and temperature, naturally building the relationship between the stiffness and strength of corrugated board and changing weather conditions. In this paper, attention is focused on the dependence of the physical properties of the cardboard on changes in humidity and temperature, which undergo dynamic fluctuations both during the production of corrugated board and during its storage. Two techniques were used to test this effect, namely numerical homogenization and global sensitivity analysis. Both methods were implemented to determine the theoretical relationships between the change in humidity and/or temperature in each layer of corrugated board and its global bending, compression, and shear stiffness. The procedure was used to analyze different types of 5-ply and 3-ply cardboard. The obtained results allowed the authors to build a complete map of the relationship between the change in humidity of selected layers and the strength characteristics of the full assembly.

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INTRODUCTION

Papyrus, which dates to 3000 BCE, was the oldest material, resembling paper, used for writing by the Egyptians, Romans, and Greeks (Gaudet 2014). In terms of production, *i.e.* macerating and blending fibers, papyrus is not a true paper; the paper, as it is today, was developed in China in 105 C.E. (Tsien 1985) and then spread worldwide. The first European paper mill was built in the 1100s on the Mediterranean coast (Santos 2012), and in the U.S. – in 1690 (Harrison 1943). The papermaking machine, the wood pulping method, and lithographic printing were three significant technological advances made in the 1800s that helped pave the way for the mass production of paper packaging at the turn of the century (Twede 2005).

Technological progress and the needs of the packaging sector, which have been growing rapidly over the years and driving the industry, have resulted in the global pulp and paper market being valued at USD 351.5 billion in 2021, and is projected to exceed approximately USD 380.12 billion by 2030 (Precedence 2022). This has also been the rationale behind the paper industry's pursuit of efficient, profitable, and simple solutions, which has in turn sparked a vibrant growth of research in the area. A matter of strength evaluation of paperboard or corrugated cardboard containers is the subject of ongoing, comprehensive studies.

As early as the 1950s (Kellicutt and Landt 1952; Maltenfort 1956) and 1960s (McKee *et al*. 1963) analytical formulae were derived and used for the calculations of corrugated box compressive strength. They are still widely applied because they lead to quick and easy solutions, however, only for simple standard boxes. This fact has been an impulse for further development of the approach through the years (Allerby *et al*. 1985; Garbowski and Knitter-Piątkowska 2022). With the development of computer methods and the increase in computing power, numerical methods, such as finite element method (FEM) have become common for evaluating the load-bearing capacity of cardboard boxes (Park *et al*. 2020), as well as the material parameters of cardboard or paperboard itself (Domaneschi *et al*. 2017). When testing corrugated board, it is essential to know the material properties of each constituent layer, which is a demanding task due to anisotropy of the paper. The procedure that allows for facilitating one single layer, therefore, getting substantial savings in computational time while maintaining the accuracy of the results, is called homogenization. The application of this method is discussed, *e.g.*, in Nordstrand (2004); Suarez *et al*. (2021); and Garbowski and Gajewski (2021). The fundamental physical testing, *e.g*., box compression test (BCT), bending stiffness (BS), or the edge crush test (ECT), allows for assessment of the strength of the corrugated board or box itself (Jamsari *et al.* 2019; Czechowski *et al.* 2021). To assess the behavior of the corrugated board box during handling and transport, it can also be subjected, when tested, to an impact load, featuring different levels of kinetic energy (Johst *et al*. 2023), a vibration load (Paternoster *et al.* 2018), or a drop (Wang *et al.* 2021).

Molded pulp products, such as paperboard and corrugated board, offer an environmentally friendly alternative to diverse petroleum-based packaging systems. One of the most important advantages that make cardboard packaging superior to plastic is the possibility of its recycling for further various uses. The study (Sobotková *et al*. 2021) investigated the feasibility of using post-consumer recycled paper to produce paper plates for furniture design. The main materials used were cardboard and office paper. Multiple recycling leading to loss of quality of cellulose fibers from corrugated board, and consequently reducing the mechanical properties of paper can be partially offset by the addition of bamboo powder (Chen *et al*. 2022). Various methods are also being developed and enhanced to recover cellulose fibers from gloss art paper (Hafid *et al*. 2023) or food service waste, such as disposable coffee cups (Triantafillopoulos and Koukoulas 2020). However, it must be borne in mind that the poor mechanical strength of old corrugated container (OCC) paper limits its widespread use. To solve this problem, it has been proposed to construct a dense cross-linked network of carboxymethylcellulose inside OCC papers (Yang *et al*. 2023) to enable exceptional mechanical performance and water resistance. An algorithm that determines the best corrugated cardboard composition based on the packaging's geometry and the material utilized, allowing for more environmentally conscious corrugated cardboard production using components, *e.g*., from multiple recycling processes, was proposed in Mrówczyński *et al*. (2022). The effect of using recycled fibers on the thickness, modulus of elasticity, and bending stiffness of a handsheet was discussed in Ham *et al*. (2020). In the extensive literature on the subject, one can also find discussions on the main interactions and challenges affecting package design decisions

(Berry *et al*. 2022), the rapid prototyping and advances in tooling, providing future opportunities for more efficient molds and more effective packaging (Debnath *et al*. 2022) or the different types of molded fiber products in terms of natural fiber sources, manufacturing processes, current and emerging applications, and environmental sustainability of molded products (Zhang *et al*. 2022).

The factors that reduce the strength of cardboard packaging, such as different ventilation openings and holes or shifts on flaps (Mrówczyński *et al*. 2021), moisture, and temperature, cannot be overlooked. The impact of the last two factors will be discussed in detail in this paper. Contact with water or moisture has a destructive effect on the mechanical properties of the cardboard. Water-soaked corrugated board can easily collapse, causing irreversible shape distortion. To make the cardboard water-repellent, a hydrolysis-resistant polyester-based thermoplastic polyurethane was proposed in Cataldi *et al*. (2019). The mechanical strength reduction of the carton occurs especially when transporting and storing fresh products in high relative humidity conditions, to reduce moisture loss in, *e.g.*, fruit, and preserve its quality (Fadiji *et al*. 2018; Berry *et al*. 2019). Changes in the mechanical properties of various fibrous materials widely used in packaging applications due to changes in moisture content were investigated by means of a tensile test in Nienke *et al*. (2022). To meet the demands of cold chain logistics, it is necessary to develop corrugated packaging that is suitable for high moisture environments. The papers (Su *et al*. 2023; Yang *et al*. 2023) investigate the mechanism of damage during cold chain transport. The effect of temperature and relative humidity on the moisture content of the undulating substrate was experimentally investigated and presented in Wang's (2018) work. Improving the water resistance of corrugated board products can also be achieved by spraying them with coatings such as polymeric, mineral-filled polymeric, and hybrid silica sol-gel products (Marinelli *et al*. 2022). Temperature, whether during production, molding, or usage, has a significant impact on the behavior of cardboard products. The ultrasound-induced temperature rise during the embossing process results in the structural changes of paperboard, and, in consequence, changes in the mechanical properties of the board (Kaeppeler *et al*. 2020). The change in fiber structure can be characterized by subjecting the samples to selected physical and visual analyses. The dimensional stability of press-formed cardboard trays during heating and cooling was investigated in Niini *et al*. (2021). The effect of heat input during folding on paperboard tray stiffness based on compression and torsion tests was evaluated in Niini *et al*. (2022). The use of higher folding temperatures proved an increase in the strength and stiffness of the trays. A study to evaluate the creep behavior of corrugated packaging under two environmental conditions of standard and refrigeration at a constant load for 12 h was reported in Fadiji *et al*. (2019).

In this study, attention is focused on the dependence of the physical properties of the cardboard, particularly Young's modulus, on changes in humidity and temperature, which undergo dynamic fluctuations both during the production of corrugated board and during its storage. The experiments are conducted numerically, exploiting numerical homogenization and sensitivity analyses. Both methods are implemented to determine the theoretical relationships between the change in humidity and/or temperature in each layer of corrugated board and its global bending, compression, and shear stiffness. The procedure is used to analyze several different types of 5-ply and 3-ply cardboard with various profiles of a corrugated web. The results obtained make it possible to map the relationship between the change in moisture content or temperature of selected layer/layers and the strength characteristics of the entire assembly of the corrugated board.

METHODS AND MATERIALS

Workflow of the Study

The paper investigates the influence of changes in temperature and relative humidity (RH) of individual layers of paper(s) on the mechanical properties of various types of 3- and 5-layer cardboard. A crucial part of the study was to determine the relationship between the temperature and the relative humidity and particular mechanical constants of papers. The relationship was assumed based on the literature research and is described in detail in the section “Influence of relative humidity and temperature on mechanical properties - literature study.”

The homogenization method of computational mechanics was used to assess the influence on the mechanical properties of cardboard expressed by the change in its stiffness of representative volume elements (RVE). The computational method used was the Garbowski and Gajewski homogenization technique (Garbowski and Gajewski 2021), see “Numerical homogenization” section.

In the main part of the work, corrugated board type B, C, and BC are presented. Other cases are also presented in the *Appendix*, *i.e.*, corrugated board type E, EB, BB, also taking into account different layer thicknesses, including unsymmetric cases.

In Fig. 1, the conceptual scope of the performed study was presented. The left part of the scheme represents the reference computational cases, namely, computed according to the laboratory conditions, *i.e.*, 23 °C temperature and 50% RH. In contrast, the right part of the scheme displays the cases with modified temperature and/or modified RH regarding the reference values. For each case the representative stiffness values of RVE were computed and compared with the reference case. The stiffness characteristics shown in Fig. 1 are: A_{11} − tension/compression stiffness in machine direction (MD), A_{22} − tension/compression stiffness in cross-machine direction (CD), A_{12} − coupled component of tension/compression stiffness in MD/CD, A_{33} − tension/compression stiffness in out of plane direction, D_{11} − bending stiffness in MD, D_{22} − bending stiffness in CD, D_{12} − coupled component of bending stiffness in MD/CD, and D_{33} − twisting stiffness, R_{44} − transverse shear stiffness in MD-out of plane direction and R_{55} − transverse shear stiffness in CD-out of plane direction.

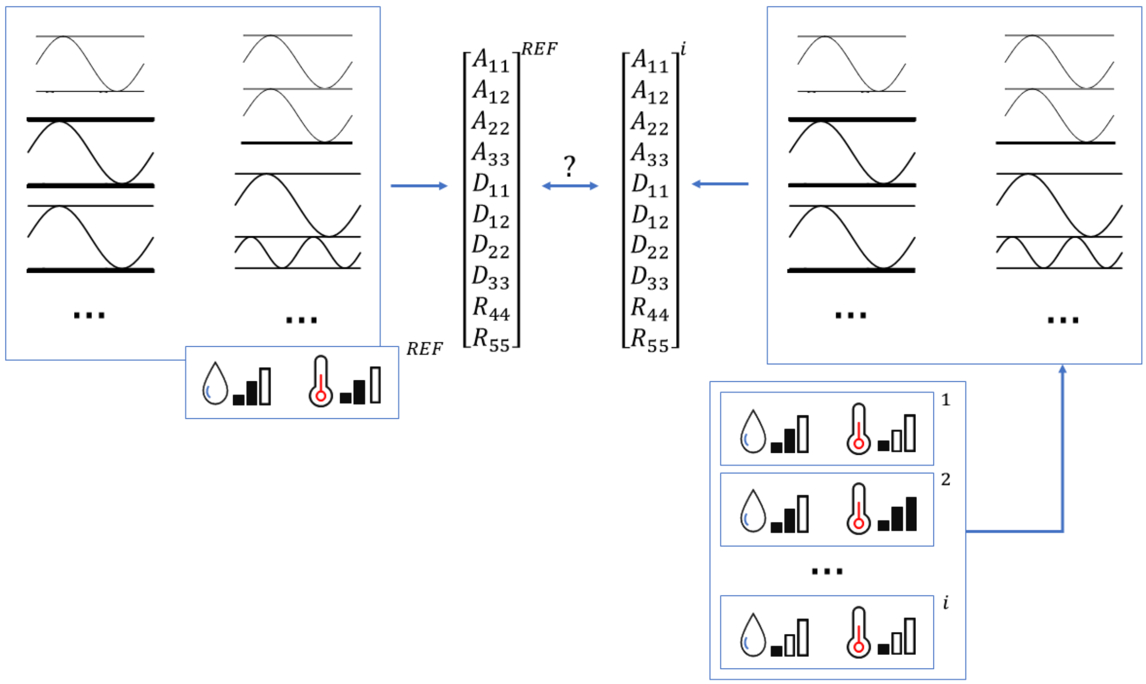


Fig. 1. The conceptual scope of the performed study: reference cases *vs.* cases with modified temperature and/or modified RH

Influence of Relative Humidity and Temperature on Mechanical Properties - Literature Study

Over the last several decades, the influence of temperature and relative humidity on paper, paperboard, and corrugated board has been considered and studied (Benson 1971). More recently, other works considered specific behaviors as: combined effects of moisture and temperature (Linvill and Östlund 2014), also observing reversed effects on longitudinal and tangential elastic moduli; the effect of moisture for various grammage paperboard (Marin *et al.* 2020a, 2020b); combined response during processing and heating phases (Askfelt and Ristinmaa 2017); effects of temperature and humidity on honeycomb structured paperboard (Wang *et al.* 2013); effects and possible defect formation in packaging paperboard due to temperature and humidity (Fadiji *et al.* 2018).

Despite several detailed studies, neither general validity models nor a complete database appears to be available in the literature, particularly with reference to anisotropic constitutive modelling. In view of a practical engineering methodological application, in the current paper, linearized interpolating relationships were assumed, as supported by experimental data and curves by the above-mentioned references. The assumed models, relating mechanical constitutive parameters to temperature and relative humidity variations, can be formulated by Eqs. 1 and 2, respectively,

$$E = E_{ref}\left(1 + \alpha_1\left(T - T_{ref}\right) + \alpha_2\left(RH - RH_{ref}\right)\right) \tag{1}$$

$$G = G_{ref}\left(1 + \alpha_3\left(T - T_{ref}\right) + \alpha_4\left(RH - RH_{ref}\right)\right) \tag{2}$$

where E and G represent, respectively, a longitudinal and tangential (shear) elastic modulus, T is the current temperature, RH holds for the relative humidity, ref subscript denotes reference laboratory-controlled conditions, and α_i are interpolation parameters from literature available data, where α_1 = -0.0045714·1/°C, α_2 = -0.0031429·1/%, α_3 = +0.0034615·1/°C, and α_4 = -0.0028846·1/% (elaborated from (Linvill and Östlund 2014)). In consideration of the above-described physical behavior, it is worth noting that the numerical values of such interpolation parameters are material-dependent and mutually temperature- and relative humidity-dependent. Specific mechanical parameters for the analysis study cases considered in the present paper are given in the subsequent section "Model setup." The Eqs. (1) and (2) are valid for both directions considered typically for corrugated boards, i.e., cross and machine directions, CD and MD, respectively.

Further research investigated the influence of temperature and relative humidity of paperboard strength (see, *e.g.*, (Linvill and Östlund 2014)), as a relevant behavior for loading capacity and buckling resistance, particularly in packaging configurations, to ensure sufficient supporting and standing capacity. Nevertheless, such features are not deepened in the present work, according to the main focus of the study, devoted to mechanical elastic stiffness values of the corrugated board.

An additional key point toward the understanding and assessment of the influence of temperature and relative humidity on corrugated board structure is the proper selection of representative scenarios for typical conditions of temperature and relative humidity, both during processing stages and in storage environments. While coupled hygro-thermo-mechanical analyses would turn out of scope for the present investigation, some literature cases were considered, namely, climatic conditions (Lamb and Rouillard 2017), processing drying phases (Östlund 2006), relative humidity and related moisture content variations (Wang 2018), and packaging configurations (Fadiji *et al.* 2016).

In this paper, the reference, ambient laboratory-controlled, conditions were assumed as temperature equal to 23 °C and relative humidity pairing to 50%, as reported in Table 1, tougher with the further investigated scenarios, also in agreement with standardized procedures (ISTA 2A 11-11 2011). No detailed data could be found regarding temperature gradients through corrugated board layers during processing phases from practical observations. The classic storage conditions (hot-humid, hot-dry, and cold-humid) were combined with processing conditions at higher temperature for various relative humidity levels (from humid to dry state), also with temperature gradients (for complete numerical description, see Table 1). It is worth noticing that the latter were considered only for 5-ply boards (labels s1 to s3 and p1 to p12 in Table 1), while 3-ply boards were restricted to testing conditions without temperature gradients due to reduced total thickness (labels s1 to s3 and p1 to p4, in Table 1).

Table 1. Temperature and Relative Humidity Main Scenarios Considered for the Numerical Analyses

Scenario Label	Scenario Description	Temperature (°C)	Relative Humidity (%)
Ref	Laboratory-controlled conditions	23	50
s1	Storage, extreme heat, moderate humidity	60	30
s2	Storage, cold, humid	5	85
s3	Storage, extreme heat, dry	60	15
p1	Processing, humid	100	70

p2	Processing, ambient humidity	100	50
p3	Processing, moderate humidity	100	30
p4	Processing, dry	100	5
p5	Processing, temperature gradient, humid	100 70 (top liner)	70
p6	Processing, temperature gradient, ambient humidity	100 70 (top liner)	50
p7	Processing, temperature gradient, moderate humidity	100 70 (top liner)	30
p8	Processing, temperature gradient, dry	100 70 (top liner)	5
p9	Processing, temperature gradient, humid	100 70 (top liner and fluting)	70
p10	Processing, temperature gradient, ambient humidity	100 70 (top liner and fluting)	50
p11	Processing, temperature gradient, moderate humidity	100 70 (top liner and fluting)	30
p12	Processing, temperature gradient, dry	100 70 (top liner and fluting)	5

Note: Scenarios s1 to p4 apply to 3-ply cardboard models; Scenarios s1 to p12 apply to 5-ply cardboard models

Model Setup

With reference to the aforementioned modelling approach (section "Influence of relative humidity and temperature on mechanical properties - literature study"), the constitutive mechanical parameters were selected for an orthotropic material model as in previous works (Biancolini 2005; Garbowski and Gajewski 2021), here reported in Table 2, together with examples of temperature and relative humidity relationships sketched in Fig. 2.

The numerical model, built within the Finite Element Method (FEM) scheme for subsequent homogenization, was developed for the three main considered geometries, namely: board type B, C, and BC, defined on a one-period RVE, characterized by axis topology (see Fig. 3 and references (Biancolini 2005; Garbowski and Gajewski 2021)). In particular, fluting period (λ) and total height (H) were selected as 6.78 mm and 2.44 mm, respectively, for board type B, while equal to 8.00 mm and 3.51 mm, respectively, for board type C. For board type BC, fluting period was 8.00 mm and total height was 5.95 mm.

Within the FEM context, the paperboard layers were modelled by classic general purpose four-node shell elements, and the computational size of each model was totaled, respectively, to 969 nodes, 896 elements, and 5814 degrees of freedom, for type B and C 3-ply boards, while to 1936 nodes, 1536 elements, and 11616 degrees of freedom, for type BC 5-ply board.

Table 2. Thicknesses and Material Properties of Liners and Fluting Adopted in the Reference Laboratory-Controlled Conditions

Layer	t (mm)	E_1 (MPa)	E_2 (MPa)	ν_{12} (-)	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
Liners	0.29	3326	1694	0.34	859	429.5	429.5
Fluting	0.30	2614	1532	0.32	724	362	362

After (Garbowski and Gajewski 2021)

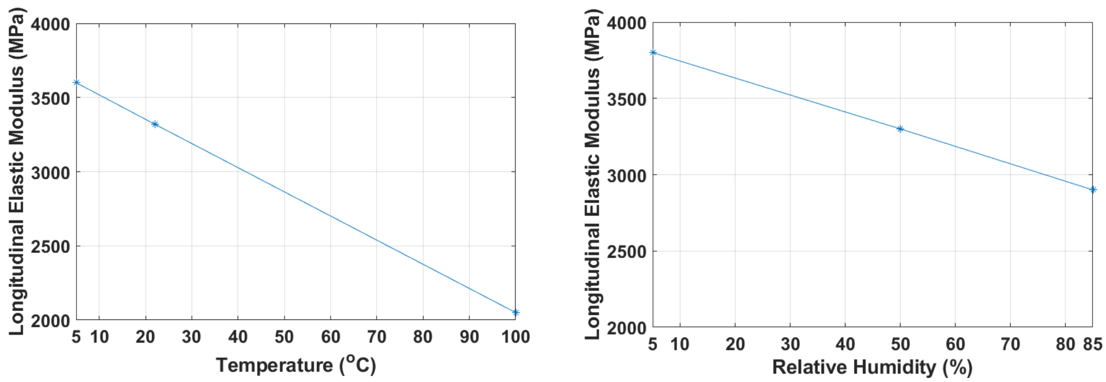


Fig. 2. Examples of constitutive parameter variation laws: (a) longitudinal elastic modulus *vs.* temperature; (b) longitudinal elastic modulus *vs.* relative humidity

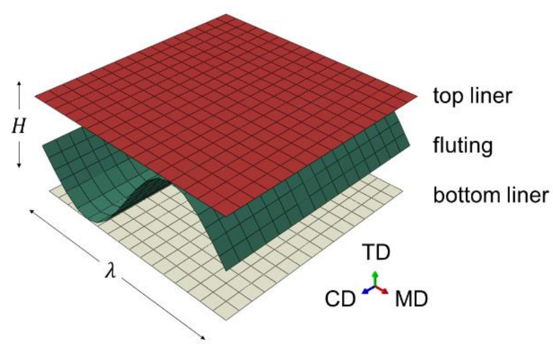


Fig. 3. Corrugated board geometric representative volume element model for homogenization, with highlighted geometric parameters (period (λ) and total height ($\boldsymbol{H}$)), sections (liners and fluting), and material orientation (MD- Machine Direction, TD- Transverse Direction, and CD-Cross Direction) reference system

Numerical Homogenization

One of the crucial elements of the paper is the numerical homogenization method used. The homogenization method enables computing the effective stiffness values of the laminate composite. Because the technique was employed on different layered corrugated boards, one may easily compare the representative mechanical properties between specific boards. Here, the method of Garbowski and Gajewski was used (Garbowski and Gajewski 2021). In this section, the brief overview of the method will be presented, for more details, see the original paper (Garbowski and Gajewski 2021).

The method is partially based on the FEM approach; however, it does not require solving the system of equations, which is characteristic of this technique. The method ensures the equivalence of the strain energy between the shell element and the three-dimensional reference representative volume element.

The finite element degrees of freedom for RVE are considered in a decoupled form, by separating the external (index e) and internal (index i) nodes:

$$\mathrm{K\,u = F} \;\rightarrow\; \begin{bmatrix} \mathrm{K}_{ee} & \mathrm{K}_{ei} \\ \mathrm{K}_{ie} & \mathrm{K}_{ii} \end{bmatrix} \begin{bmatrix} \mathrm{u}_e \\ \mathrm{u}_i \end{bmatrix} = \begin{bmatrix} \mathrm{F}_e \\ 0 \end{bmatrix}. \tag{3}$$

where **K** is the global stiffness matrix, **u** is a nodal displacement vector, and **F** is the external nodal load vector.

In the present paper, the RVE is considered as the periodic element of the corrugated board, *i.e.*, a single unit with one flute period in MD and with the same length in CD (see Fig. 3). In the method, the static condensation is performed and internal nodes are omitted from further consideration.

Therefore, from static condensation the total energy of elastic deformation, E, is computed from the following Eq. 4:

$$E = \frac{1}{2}\mathbf{u}_e^T\,\mathbf{F}_e \tag{4}$$

The positions of external nodes may be computed by the generalized constant strains according to the relation, which for a single node takes the form of Eq. 5:

$$\begin{bmatrix} u_x \\ u_y \\ u_z \\ \theta_x \\ \theta_y \end{bmatrix}_i = \begin{bmatrix} x & 0 & y/2 & z/2 & 0 & xz & 0 & yz/2 \\ 0 & y & x/2 & 0 & z/2 & 0 & yz & xz/2 \\ 0 & 0 & 0 & x/2 & y/2 & -x^2/2 & -y^2/2 & -xy/2 \\ 0 & 0 & 0 & 0 & 0 & 0 & -y & -x/2 \\ 0 & 0 & 0 & 0 & 0 & x & 0 & y/2 \end{bmatrix}_i \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}_i . \tag{5}$$

Now, the total energy of elastic deformation for external nodes may be written by the following,

$$E = \frac{1}{2}\mathbf{u}_e^T\,\mathbf{K}\,\mathbf{u}_e = \frac{1}{2}\boldsymbol{\epsilon}_e^T\,\mathbf{A}_e^T\,\mathbf{K}\,\mathbf{A}_e\,\boldsymbol{\epsilon}_e \tag{6}$$

which for shell in bending, traction, and transverse shearing may be rewritten as,

$$E = \frac{1}{2}\boldsymbol{\epsilon}_e^T\,H_{\mathrm{k}}\,\boldsymbol{\epsilon}_e\{area\} \tag{7}$$

in which the laminate stiffness matrix, $\mathbf{H}_k$, is stated in discrete form:

$$\mathbf{H}_k = \frac{\mathbf{A}_e^T\,\mathbf{K}\,\mathbf{A}_e}{area} \tag{8}$$

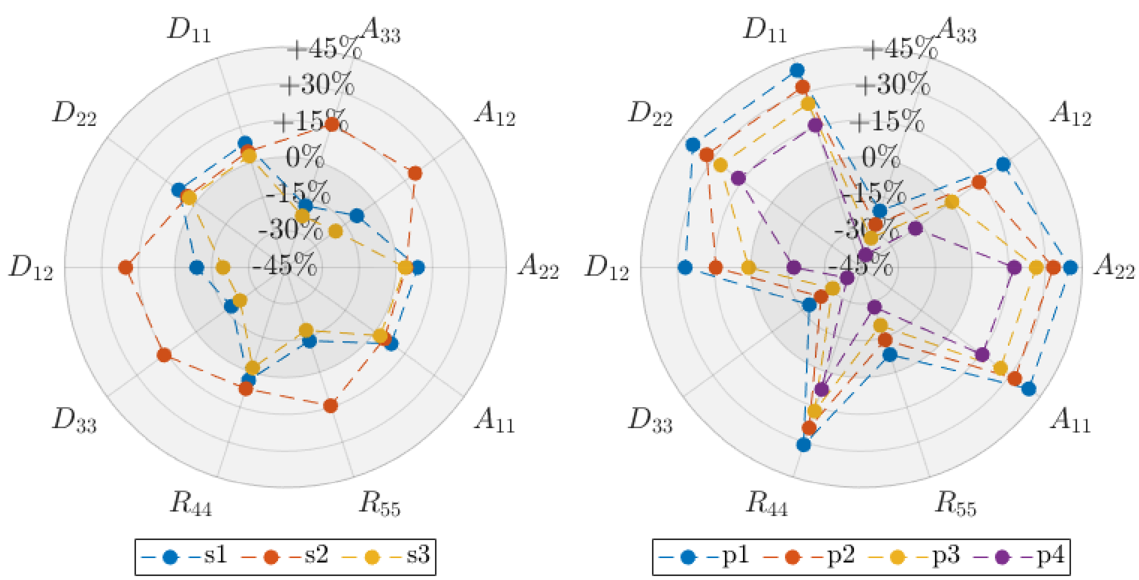
The matrix $\mathbf{H}_k$ can be also expressed by the submatrices **A**, **B**, **D**, and **R** as follows,

$$\mathbf{H}_k = \begin{bmatrix} \mathbf{A}_{3\times 3} & \mathbf{B}_{3\times 3} & 0 \\ \mathbf{B}_{3\times 3} & \mathbf{D}_{3\times 3} & 0 \\ 0 & 0 & \mathbf{R}_{2\times 2} \end{bmatrix} \tag{9}$$

in which **A** is traction and shear effective stiffness values, **B** is coupled traction-bending effective stiffness values, **D** is bending and torsional effective stiffness values, and **R** is transverse shear effective stiffness.

RESULTS AND DISCUSSION

Following the above devised methodology, described in the section "Methods and Materials," therefore employing global sensitivity on the selected representative scenarios and numerical homogenization, the current section gathers the most meaningful results. These results refer to variation of homogenized stiffness values, as influenced by temperature and relative humidity, as affecting the corrugated board layers. Such results are here reported, with normalization to percentage variations for ease of comparison, in graphical form (see Figs. 4 through 7) and numerical values (see Tables 3 through 6), together with some relevant observations. Changes in effective stiffness values can be clearly represented in multi-axis polar diagrams. Therefore, the figures were presented as polar plots for easier comparison between case-by-case outcomes. Additional numerical results are collected in the *Appendix*, for further deeper case studies. In particular, Figs. 4 through 6 and related Tables 3 to 5 compare the storing (s1 to s3) and processing (p1 to p4) scenarios, respectively for B, C, and BC board types. Figure 7 and associated Table 6 display results for processing (p5 to p12) scenarios, with temperature gradients through layers, for BC board type.



(a) **(b)**

Fig. 4. Stiffness percentage variations, with respect to the reference conditions, for type B corrugated board in (a) storing scenarios, s1 to s3, and (b) processing scenarios, p1 to p4

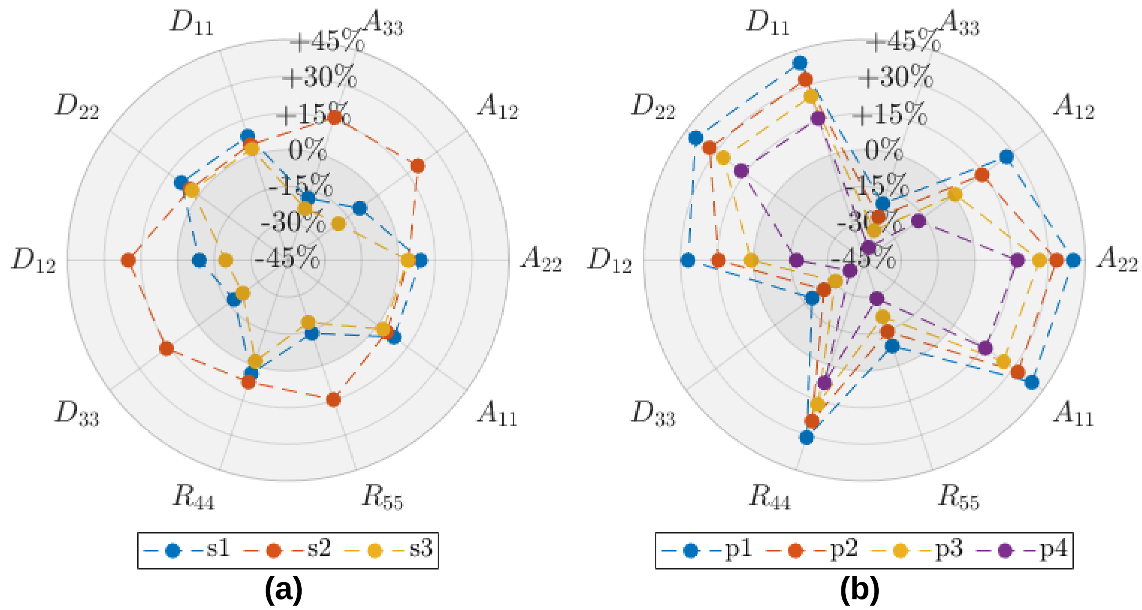


Fig. 5. Stiffness percentage variations, with respect to the reference conditions, for type C corrugated board in (a) storing scenarios, s1 to s3, and (b) processing scenarios, p1 to p4

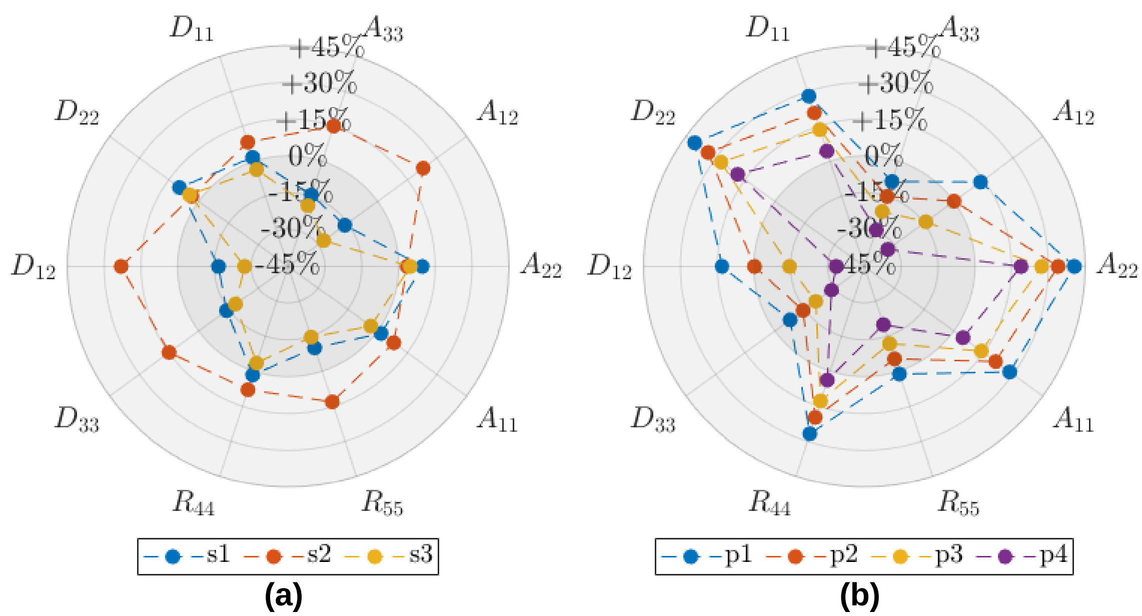


Fig. 6. Stiffness percentage variations, with respect to the reference conditions, for type BC corrugated board in (a) storing scenarios, s1 to s3, and (b) processing scenarios, p1 to p4

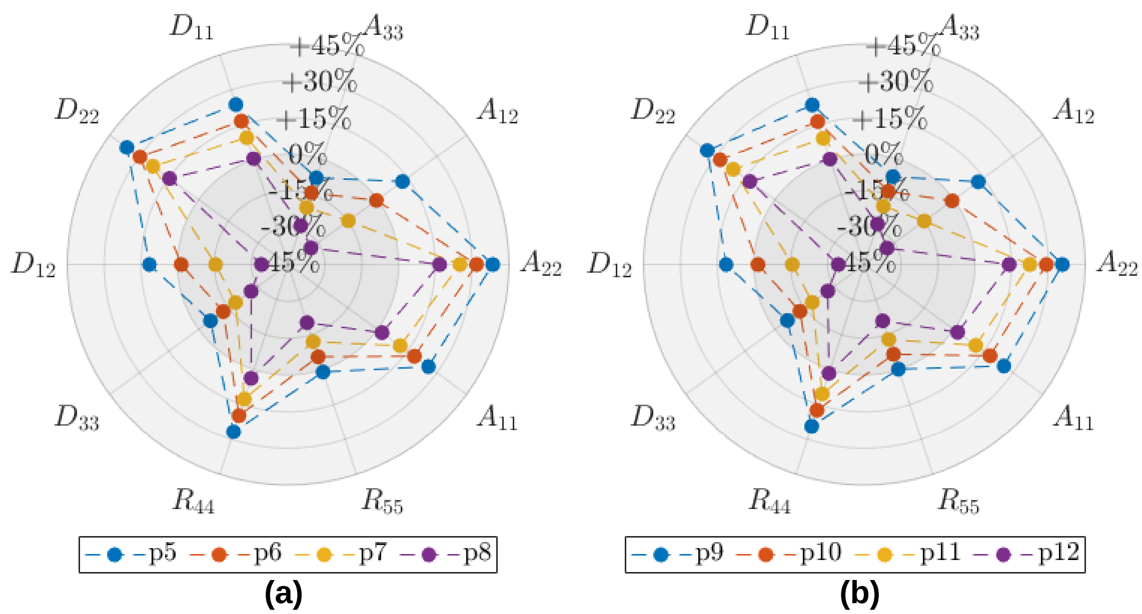


Fig. 7. Stiffness percentage variations with respect to the reference conditions, for type BC corrugated board in (a) processing scenarios with one-layer-temperature gradient, p5 to p8, and (b) processing scenarios with two-layer-temperature gradient, p9 to p10

From graphical and, in detail, from numerical results, it is possible to observe that diverse board types, *i.e.*, B and C for 3-ply geometries and BC for 5-ply geometry, are subjected to similar influence effect by modifications of both temperature and relative humidity, namely displaying similar trends on stiffness variations. Therefore, such results allow for possible extension of the observed effects to various geometries, specifically focusing on mechanical, rather than geometrical behavior.

Although it was not possible to specifically distinguish between influences caused by temperature or relative humidity variations, due to their intrinsic combined relationship on constitutive parameters, clear differences are highlighted between storing and processing scenarios. At this stage, it is worth mentioning that diverse trends are obtained for each type of homogenized stiffness, namely for traction and shear, traction-bending, bending and torsional, and transverse shear stiffness values, however with regular and smooth variation for each specific quantity. A comparison between storing and processing conditions displays more evidenced variations in the processing situations on the specific stiffness parameters, while the storing cases present more averaged modifications. This is especially visible while using the polar plots with multi-axes representing the effective stiffness. For example, scenario s2 (5 °C and 85% RH) in Fig. 6a is almost perfectly convex and above 0, which means that all stiffness values are approximately equally increased. While in Fig. 6b, dashed lines cross the 0% level, which means that some of the stiffness values were increased (*e.g.*, A_{12}, R_{44}), while the others were decreased (*e.g.*, A_{11}, D_{11}).

In particular, for storage conditions, while limited variations are observed between hot moderate humid and hot dry conditions, significant changes are produced by the reversal of temperature and humidity environment, such as in cold humid configuration. Contrastingly, for drying processes at constant temperature, regular trends are observed, as a consequence of humidity variation, without any abrupt change in the homogenized stiffness values.

Additional comments may be derived by the discussion of results computed on the scenarios, for 5-ply boards, with temperature gradients through the layers. Particularly, the presence of a temperature gradient reduces the effects of stiffnesses changes, with increasing and smoother influence provided by less sharp temperature gradients.

The above-mentioned observed behaviors and the consequent reasoning appear to be of significant scientific and industrial interest for proper understanding of the mechanical influence of temperature and relative humidity of corrugated board, particularly toward its use in box manufacturing and various practical applications, therefore involving structural performance capacity. The possible rise of defects, during processing stages, and damages or deformations, in storage configurations, may consistently be interpreted as effects of changes of mechanical stiffnesses, particularly in uneven conditions, which may alter, in transient conditions, the paperboard inner structural behavior and response.

Table 3. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type B Corrugated Board, in Scenarios s1 through p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	8.1	4.7	2.6	39.4	32.3	25.1	15.7
A_{22}	8.9	4.1	3.7	40.2	33.3	26.3	17.4
A_{12}	-9.1	20.3	-19.8	26.5	14.1	0.5	-17.9
A_{33}	-18.6	16.3	-22.9	-20.8	-26.6	-32.4	-39.6
D_{11}	8.2	4.6	2.7	39.6	32.5	25.2	15.9
D_{22}	8.7	4.3	3.3	40.0	33.1	26.0	16.9
D_{12}	-8.9	20.2	-19.6	26.9	14.4	0.9	-17.5
D_{33}	-17.8	16.0	-22.1	-18.8	-24.7	-30.5	-37.8
R_{44}	3.5	7.1	-1.8	31.1	23.9	16.7	7.4
R_{55}	-13.4	14.4	-17.9	-7.5	-13.8	-20.0	-27.8

Table 4. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for type C Corrugated Board, in Scenarios s1 to p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	8.2	4.6	2.7	39.5	32.4	25.1	15.8
A_{22}	9.0	4.0	3.7	40.2	33.4	26.4	17.5
A_{12}	-9.0	20.3	-19.7	26.6	14.1	0.6	-17.8
A_{33}	-18.5	16.3	-22.9	-20.8	-26.5	-32.3	-39.5
D_{11}	8.2	4.6	2.7	39.6	32.5	25.3	15.9
D_{22}	8.7	4.2	3.3	40.0	33.1	26.0	16.9
D_{12}	-8.9	20.2	-19.6	26.9	14.5	1.0	-17.4
D_{33}	-17.8	16.1	-22.2	-18.8	-24.7	-30.5	-37.8
R_{44}	3.5	7.1	-1.8	31.0	23.8	16.6	7.4
R_{55}	-13.8	14.6	-18.4	-8.3	-14.5	-20.8	-28.6

Table 5. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type BC Corrugated Board, in Scenarios s1 to p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	1.7	8.1	-3.4	28.3	21.1	13.8	4.6
A_{22}	9.7	3.4	4.7	40.6	34.0	27.3	18.9
A_{12}	-16.5	23.0	-27.1	13.4	0.1	-14.1	-33.2

A_{33}	-14.5	15.0	-19.0	-8.7	-15.1	-21.5	-29.4
D_{11}	1.6	8.1	-3.6	28.0	20.7	13.5	4.3
D_{22}	9.6	3.5	4.5	40.5	33.8	27.1	18.7
D_{12}	-16.7	23.1	-27.3	13.0	-0.3	-14.6	-33.6
D_{33}	-14.1	14.8	-18.6	-7.7	-14.2	-20.6	-28.5
R_{44}	1.6	7.9	-3.5	26.7	19.7	12.7	3.8
R_{55}	-10.0	13.1	-14.6	1.2	-5.3	-11.8	-19.9

Table 6. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type BC Corrugated Board, in Scenarios p5 to p12

Stiffness	p5	p6	p7	p8	p9	p10	p11	p12
A_{11}	25.7	18.5	11.3	2.2	25.3	18.2	11.0	1.9
A_{22}	38.4	31.8	25.1	16.8	35.7	29.2	22.5	14.1
A_{12}	12.5	-0.6	-14.7	-33.5	12.3	-0.9	-14.9	-33.6
A_{33}	-7.9	-14.3	-20.6	-28.4	-7.4	-13.7	-20.0	-27.7
D_{11}	23.7	16.6	9.5	0.4	23.5	16.4	9.2	0.2
D_{22}	36.3	29.7	23.0	14.6	34.2	27.6	20.9	12.5
D_{12}	11.5	-1.5	-15.5	-34.2	11.3	-1.7	-15.7	-34.4
D_{33}	-6.0	-12.4	-18.6	-26.4	-6.3	-12.6	-18.8	-26.6
R_{44}	26.7	19.7	12.6	3.7	24.3	17.4	10.4	1.6
R_{55}	1.0	-5.5	-12.0	-20.1	-0.2	-6.6	-12.9	-20.9

CONCLUSIONS

1. To date, state-of-the-art investigation of the influence of different humidity and temperature on the mechanical properties of cardboard is lacking. For example, on the basis of scientific literature, although a general understanding is clearly provided, it is difficult to predict precisely, and for specific material, how a change in temperature or humidity of a single layer of paper will affect the mechanical properties of a particular corrugated cardboard.
2. In this work, based on computational analyses, developed by numerical homogenization and global sensitivity, it was systematically calculated how the change in temperature and/or relative humidity of individual layers of paper affects the change in the effective mechanical stiffnesses of 3- and 5-ply corrugated cardboards.
3. The most noteworthy and realistic examples, in storing and processing conditions, of analyzed calculation cases of changes in temperature and/or relative humidity of paper layers of corrugated boards were discussed. Those cases are: (1) very high storing temperature – moderate relative humidity, (2) low storing temperature – high relative humidity (3) very high storing temperature – low relative humidity, (4) very high processing temperature – varying relative humidity levels, and (5) very high processing temperature with gradients – varying relative humidity levels. All results were compared to reference cases, namely to the cardboards in laboratory conditions, 23 °C temperature and 50% relative humidity.
4. Temperature and relative humidity influence displayed coupled effects, however supported by regular trends, smoothened by gradient configurations, to be considered as advantageous features in processing stages against occurrence of defect formations.

5. Storing and processing conditions showed different trends in stiffness variations, with more evident and uneven effects produced by the latter. Therefore, the processing conditions are proposed as a more delicate/weak stage, requiring more research.
6. Diverse types of board presented similar results and trends, allowing for general validity observations, possibly to be extended as guidelines in the investigation and understanding of the considered physical conditions and phenomena.
7. The overall changes in mechanical stiffnesses for various, though realistic, scenarios highlighted global significant effects (approximately up to 40% variations), which confirm the need of specific insights of the presented problem, and devoted consideration of the observed results in practical applications.
8. The changes in mechanical stiffnesses may be interpreted as sources of defects and damages in corrugated board, therefore requiring proper understanding and modelling of the temperature-relative humidity scenario (also with reference to possible transient stages and gradient fields). This has the consequent influence on constitutive mechanical parameters, and effects on structural behavior, as proposed in the methodology devised by this paper.

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APPENDIX
Supplementary

To present a wider set of cases of practical interest, this section collects numerical results for corrugated board types E (Table S7), C with different liner thicknesses (Table S8), EB (Tables S9 and S10), and BB (Tables S11 and S12). The results were obtained by the computational methodology devised in the paper. For stiffness definitions and temperature and relative humidity scenarios, as labelled in the tables, please, see the descriptions in the article text.

Table S7. Stiffness Percentage Variations (%), with Respect to The Reference Conditions, for Type E Corrugated Board, in Scenarios s1 to p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	8.0	4.7	2.5	39.3	32.2	24.9	15.6
A_{22}	8.9	4.0	3.7	40.2	33.3	26.3	17.4
A_{12}	-9.2	20.3	-19.9	26.3	13.8	0.2	-18.2
A_{33}	-18.6	16.3	-22.9	-20.8	-26.6	-32.4	-39.6
D_{11}	8.2	4.6	2.7	39.6	32.5	25.2	15.9
D_{22}	8.7	4.3	3.3	40.0	33.0	26.0	16.9
D_{12}	-8.9	20.2	-19.6	26.9	14.4	0.9	-17.5
D_{33}	-18.0	16.1	-22.3	-19.5	-25.3	-31.1	-38.3
R_{44}	3.4	7.3	-1.9	31.3	24.1	16.7	7.4
R_{55}	-14.5	14.7	-19.0	-11.0	-17.0	-23.1	-30.7

Table S8. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type C Corrugated Board with Different Liner Thicknesses, in Scenarios s1 to p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	8.2	4.6	2.7	39.5	32.4	25.2	15.8
A_{22}	8.8	4.2	3.5	40.1	33.1	26.1	17.1
A_{12}	-9.0	20.2	-19.7	26.6	14.1	0.6	-17.8
A_{33}	-18.5	16.3	-22.9	-20.8	-26.6	-32.3	-39.6
D_{11}	8.2	4.6	2.8	39.6	32.5	25.3	16.0
D_{22}	8.6	4.3	3.2	39.9	32.9	25.8	16.6
D_{12}	-8.8	20.2	-19.6	27.0	14.5	1.0	-17.4
D_{33}	-18.1	16.1	-22.4	-19.5	-25.3	-31.2	-38.4
R_{44}	2.9	7.4	-2.4	29.6	22.5	15.3	6.0
R_{55}	-14.5	14.8	-19.0	-10.1	-16.3	-22.5	-30.2

Table S9. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type EB Corrugated Board, in Scenarios s1 to p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	1.1	8.3	-4.0	26.8	19.6	12.3	3.2
A_{22}	9.8	3.3	4.9	40.7	34.1	27.5	19.2
A_{12}	-17.2	23.2	-27.7	11.6	-1.8	-15.9	-34.9
A_{33}	-12.9	14.4	-17.4	-4.2	-10.8	-17.4	-25.5
D_{11}	1.1	8.2	-4.0	26.6	19.4	12.2	3.2
D_{22}	9.8	3.4	4.8	40.6	34.1	27.5	19.1
D_{12}	-17.2	23.2	-27.8	11.3	-2.0	-16.2	-35.1

D_{33}	-12.6	14.3	-17.1	-3.7	-10.3	-16.8	-24.9
R_{44}	1.5	8.0	-3.6	26.7	19.7	12.6	3.6
R_{55}	-9.9	12.9	-14.5	0.8	-5.6	-12.0	-20.0

Table S10. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type EB Corrugated Board, in Scenarios p5 to p12

Stiffness	p5	p6	p7	p8	p9	p10	p11	p12
A_{11}	25.7	18.5	11.3	2.3	25.4	18.3	11.1	2.1
A_{22}	39.1	32.5	25.9	17.6	36.9	30.3	23.8	15.5
A_{12}	11.4	-1.9	-16.0	-34.8	11.2	-2.0	-16.1	-34.9
A_{33}	-4.3	-10.9	-17.4	-25.4	-4.6	-11.1	-17.6	-25.6
D_{11}	24.6	17.5	10.4	1.4	24.4	17.3	10.2	1.3
D_{22}	37.5	30.9	24.3	16.0	35.7	29.1	22.5	14.2
D_{12}	11.0	-2.2	-16.2	-35.0	10.7	-2.4	-16.4	-35.2
D_{33}	-3.4	-9.9	-16.4	-24.4	-4.1	-10.6	-17.0	-24.9
R_{44}	26.7	19.7	12.6	3.6	25.2	18.2	11.2	2.3
R_{55}	0.8	-5.7	-12.1	-20.0	-0.2	-6.6	-12.9	-20.8

Table S11. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type BB Corrugated Board, in Scenarios s1 to p4

Stiffness	s1	s2	s3	p1	p2	p3	p4
A_{11}	1.4	8.2	-3.8	27.4	20.2	13.0	3.8
A_{22}	9.7	3.4	4.8	40.6	34.0	27.4	19.1
A_{12}	-16.9	23.2	-27.4	12.4	-0.9	-15.1	-34.1
A_{33}	-13.9	14.8	-18.4	-6.8	-13.4	-19.8	-27.8
D_{11}	1.4	8.2	-3.7	27.5	20.3	13.0	3.9
D_{22}	9.6	3.5	4.6	40.5	33.9	27.2	18.8
D_{12}	-16.9	23.1	-27.4	12.4	-0.9	-15.1	-34.2
D_{33}	-13.6	14.6	-18.2	-6.5	-13.0	-19.5	-27.4
R_{44}	1.1	8.2	-4.0	25.7	18.7	11.7	2.9
R_{55}	-8.9	12.6	-13.5	3.8	-2.8	-9.4	-17.5

Table S12. Stiffness Percentage Variations (%), with Respect to the Reference Conditions, for Type BB Corrugated Board, in Scenarios p5 to p12

Stiffness	p5	p6	p7	p8	p9	p10	p11	p12
A_{11}	24.3	17.1	10.0	1.0	23.8	16.7	9.6	0.6
A_{22}	38.1	31.6	25.0	16.6	35.2	28.6	22.0	13.7
A_{12}	11.4	-1.8	-15.8	-34.5	11.0	-2.1	-16.0	-34.7
A_{33}	-6.0	-12.5	-18.8	-26.7	-5.5	-11.8	-18.2	-26.0
D_{11}	22.4	15.4	8.3	-0.7	22.1	15.1	8.0	-0.9
D_{22}	35.8	29.3	22.6	14.2	33.8	27.2	20.6	12.2
D_{12}	10.7	-2.4	-16.3	-34.9	10.4	-2.6	-16.5	-35.1
D_{33}	-4.5	-10.9	-17.2	-25.1	-5.0	-11.3	-17.6	-25.4
R_{44}	25.7	18.7	11.7	2.8	22.8	15.9	9.0	0.2
R_{55}	3.5	-3.1	-9.6	-17.8	1.8	-4.6	-11.0	-18.9