#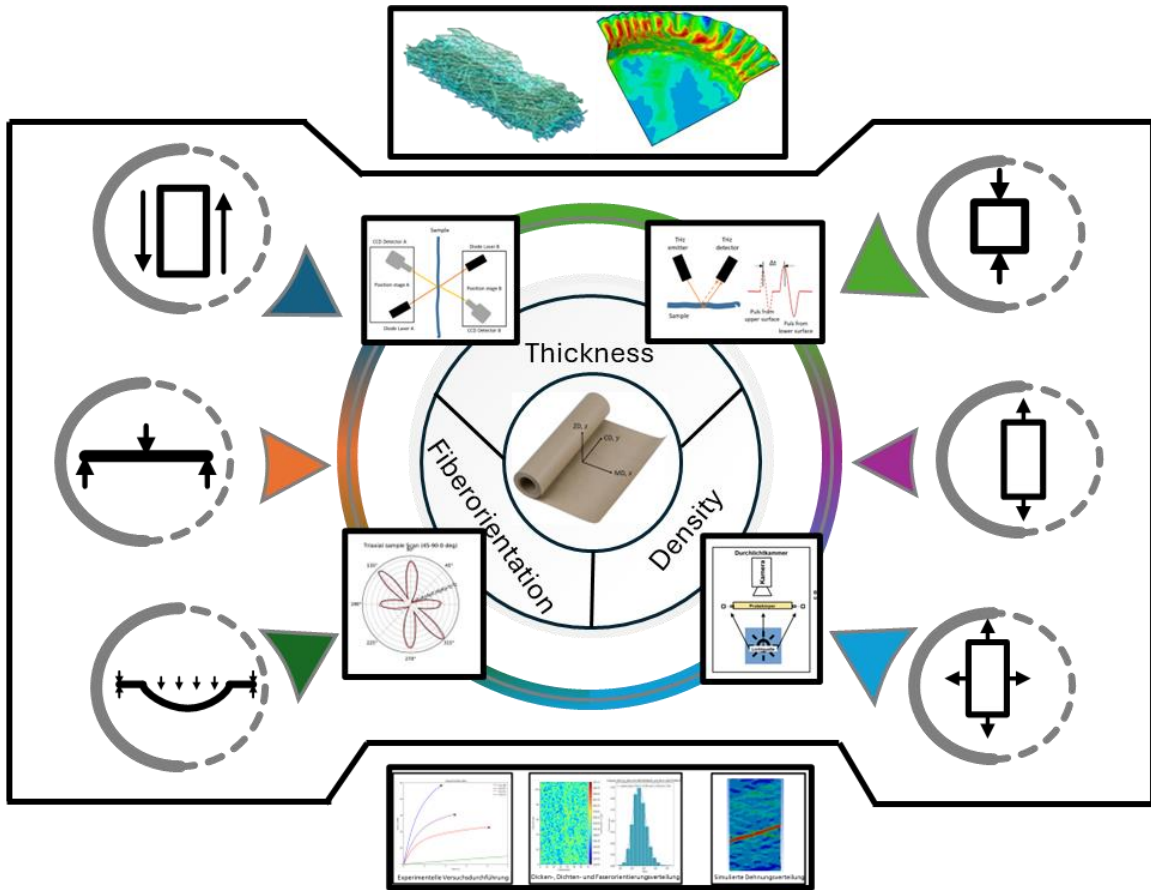 Methods for Characterization and Continuum Modeling of Inhomogeneous Properties of Paper and Paperboard Materials: A Review

Cedric W. Sanjon,[a,*] Yuchen Leng,[b,**] Marek Hauptmann,[a,c] Peter Groche,[b] and Jens-Peter Majschak [a,d]

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GRAPHICAL ABSTRACT

Methods for Characterization and Continuum Modeling of Inhomogeneous Properties of Paper and Paperboard Materials: A Review

Cedric W. Sanjon,[a,]* Yuchen Leng,[b,]** Marek Hauptmann,[a,c] Peter Groche,[b] and Jens-Peter Majschak [a,d]

The potential of paper and paperboard as fiber-based materials capable of replacing conventional polymer-based materials has been widely investigated and evaluated. Due to paper's limited extensibility and inherent heterogeneity, local structural variations lead to unpredictable local mechanical behavior and instability during processing, such as mechanical forming. To gain a deeper understanding of the impact of mechanical behavior and heterogeneity on the paper forming process, the Finite Element Method (FEM) coupled with continuum modeling is being explored as a potential approach to enhance comprehension. To achieve this goal, utilizing experimentally derived material parameters alongside stochastic finite element methods allows for more precise modeling of material behavior, considering the local material properties. This work first introduces the approach of modeling heterogeneity or local material structure within continuum models, such as the Stochastic Finite Element Method (SFEM). A fundamental challenge lies in accurately measuring these local material properties. Experimental investigations are being conducted to numerically simulate mechanical behavior. An overview is provided of experimental methods for material characterization, as found in literature, with a specific focus on measuring local mechanical material structure. By doing so, it enables the characterization of the global material structure and mechanical behavior of paper and paperboard.

INTRODUCTION

A wide range of fiber-based materials are used in packaging nowadays – from tissue paper for tea bags to heavy-duty cartons for distribution. Cellulose-based fiber materials can provide benefits such as low density, environmental friendliness, and economy. Thanks to the high recyclability and good sustainability of paper products, they are seen as an excellent solution for the packaging industry, which is reflected in both the raw materials and production processes. Paper designed for routine applications, such as office

documentation and newspapers, typically has a thickness of about 0.1 mm. The area density of paper products, expressed as mass per unit area, called grammage or basis weight (International Organization for Standardization 1995), typically ranges from 40 to 100 g/m^2 and it varies depending on the used type of paper. On the other hand, paper materials used for book covers or packaging can exceed 1 mm in thickness. Thick paper grades are known as paperboard, with a typically higher grammage range of 150 to 500 g/m^2 (Gustafsson and Niskanen 2021).

Despite the many advantages mentioned above, paper and paperboard as fiber-based materials have many limitations in processing, especially in the forming process, in comparison to plastic material, which can be easily formed into complicated shapes. Mechanical forming refers to a manufacturing process involving plastic deformation, wherein the physical shape of the material undergoes permanent alteration while maintaining its mass and material cohesion (Schuler GmbH 1998). Many phenomena are related to the forming process, such as material properties, *e.g.* elastic and plastic behavior; tribology, including friction, lubrication, and wear; and forming limits, *e.g.* fracture and defects such as wrinkles. Characteristics of paper and paperboard, such as anisotropy, inhomogeneity, and hygroscopicity within the material, as well as design parameters such as moisture, blank holder force, temperature, punch speed, and stress state during the forming process, all influence the quality of final products. It is therefore important to study the properties and response of the materials, the forming process and the relationship between them.

When it comes to the better control and prediction of forming processes, the finite element method (FEM) serves as a potent numerical technique that has found extensive application in modeling and analyzing diverse engineering processes. To study the process and system parameters and improve the process stability of the forming process, a paper and paperboard material model based on continuum mechanics is preferable, since the micromechanical models are extremely expensive with respect to computations. However, especially in paper and paperboard, many microscopic phenomena occur discontinuously due to the random arrangement of fibers. Therefore, a purely macroscopic description is unlikely to encompass all relevant effects. It follows that the range of details should be extended. The Stochastic Finite Element Method (SFEM) serves as an expansion of the traditional deterministic Finite Element Method (FEM), offering a means to address static and dynamic problems within a stochastic framework. This involves considering stochastic variations in mechanical, geometric, or loading characteristics (Stefanou 2009). While the physically based approach permits the parameter values to be transferred to other processes, it necessitates conducting microscopic-level experimental analyses and applying procedures to manage significant parameter value fluctuations (Volk *et al.* 2019). In addition to more detailed constitutive models, models for failure prediction with their own model parameters are needed, which also require parameter values. Thus, global mechanical tests and local structural measurements are necessary for the characterization of fiber-based materials as well as for the study of the forming process.

Some reviews are presently accessible, focusing on the modeling of paper materials or forming processes. Östlund (2017) provided an exhaustive examination of the literature regarding 3D forming processes, *i.e.* deep drawing, hydroforming, and press forming for paper and board. The work was carried out experimentally and numerically, encompassing analyses of deformation mechanisms, damage phenomena, and also friction behaviour. (Fadiji *et al.* 2018) reviewed the application of FEM in the food-related packaging industry, with an emphasis on corrugated packaging, along with an example of its application in the

forming process. More recently, Simon (2021) considered advancements in the material modeling methods of paper and paperboard across multiple scales, from the fiber and network level to the sheet and laminate scale. Multiscale modeling is a potential approach, but continuous models are more realistic for completely stochastic fiber-based materials, especially when it comes to application in forming processes. In order to incorporate inhomogeneity or varying local material structure into continuum modeling of paper and paperboard materials, the characterization of microscopic structure and macro-mechanical properties is of particular importance.

The aim of this work was to facilitate the application of continuous modeling, particularly in the treatment of inhomogeneities. To achieve this, the stochastic modeling methodology, including SFEM, can be applied to enable the stochastic modeling, which will be summarized from the literature firstly. This involves identifying the necessary measurements to quantify inhomogeneity and conducting experiments for material modeling to implement global and stochastic modeling. The required microstructural measurements and the measurement methods used in the literature are presented first, followed by the summarization of experiments used to determine the in-plane and out-of-plane mechanical properties.

BASIC CHARACTERISTICS OF PAPER MATERIALS

Paper is a network of natural fibers bonded together. The mechanical properties of paper and paperboard remain similar despite variations in fiber types and manufacturing processes. Commercial paper is typically characterized as an anisotropic material, with principal directions identified as the machine direction (MD), cross-machine direction (CD), and thickness direction (ZD or out-of-plane direction), as illustrated in Fig. 1. In mass production, the tensile strength is typically higher in the MD than in the CD, with a factor of 1 to 5 due to different manufacturing principles and up to 100 times higher than in the ZD (Stenberg and Fellers 2002), but the elongation at break shows the opposite behavior. It is important to note that some papers may exhibit less anisotropic properties, resulting in minimal differences between MD and CD properties. In some cases, the laboratory paper may even be isotropic.
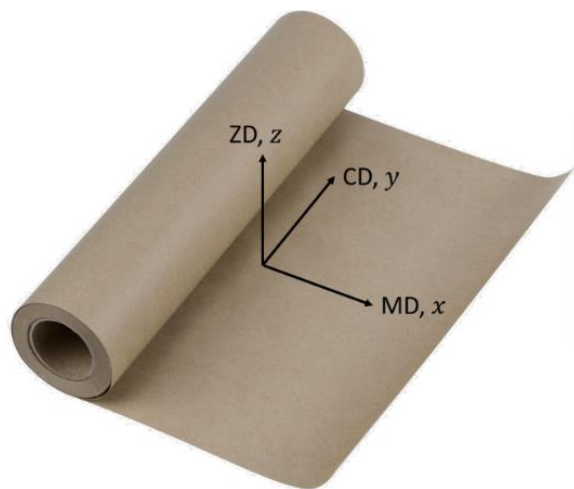

Fig. 1. Principal directions in paper

In addition to anisotropies, paper materials also manifest structural non-uniformity, referred to as inhomogeneity, leading to fluctuations in local mechanical properties and surface characteristics such as roughness. These fluctuations may arise longitudinally or transversely within the material and particularly in regions characterized by diminished thickness, density, and area-related attributes (Hauptmann 2010). Therefore, it is imperative to quantify this inhomogeneity to facilitate its numerical representation.

NUMERICAL METHODS OF MODELING STOCHASTIC MATERIALS

Progress in understanding material behaviors, achieved through experimental measurements covering both microscopic and macroscopic aspects, finds effective representation in numerical methods. Modeling mechanical, tribological, thermal material properties, or their combination contributes to achieving two main objectives. Firstly, material models are indispensable for predicting material properties, such as optimal parameters in a processing operation, to enhance product quality. Secondly, these material models play a crucial role in exploring the effects that transpire during processing operations and to enable the correlation of these effects with the underlying behavior and involved interdependencies of the components (Wallmeier 2018).

Motivated by these considerations, two distinct models have been devised for fiber-based materials. Continuum models, assuming homogeneity of material on the considered scale, are adept at simulating complex forming processes due to their more straightforward numerical modeling and faster calculations. However, discrepancies arise compared to experimental findings due to inherent inhomogeneity and random material behavior. Material models incorporating microstructural details facilitate the linkage of macroscopic loads to stresses and deformations within individual fibers, fiber-fiber bonds, or fiber networks (Mansour *et al.* 2019). This process involves the creation of a mathematical model that represents the interactions between fiber-fiber bonds, individual fibers, and either two-dimensional (Bronkhorst 2003) or three-dimensional network (Li *et al.* 2016b) structures. At scales below the network structure, it is necessary to consider the mechanical properties of individual fibers and the bonds between fibers. In addition, micromechanics has produced models integrating material property variability through randomly generated networks (Kulachenko and Uesaka 2012). Nonetheless, due to their significant computational demands, these models are typically unsuitable for simulating processing operations such as forming processes. Instead, they find utility in micromechanical investigations. To accurately characterize stochastic materials such as paper and paperboard, a numerical method is indispensable, allowing for the integration of their inhomogeneous structural properties with their homogeneously assumed mechanical properties.

Introduction of the Stochastic Finite Element Method

FEM stands as a widely embraced numerical technique for solving scientific and engineering problems, demonstrating its capability to handle intricate geometries with mixed material and boundary conditions. It is also proficient in addressing time-dependent issues and nonlinear material behaviors. However, the inherent determinism of the FEM imposes a limitation in directly dealing with systems containing uncertainties. The direct study of a system with a degree of uncertainty is not feasible using traditional FEM. A well-established approach for studying the relationship between microstructural geometry

and material macroscopic properties involves integrating microstructure models with finite element simulations.

SFEM, an extension of the basic FEM, incorporates random parameters to represent uncertainties. SFEM can introduce randomness into one or more of the main components of the classical FEM, including geometry, external forces, and material properties. It can be used to find correlations between microscopic and macroscopic behavior and represent inhomogeneous properties in continuum modeling. A comprehensive review of SFEM is presented in Stefanou (2009).

Random Fields (RFs)

A random field (RF) is a set of indexed random variables that characterize inherent randomness within a system. The indices denote the spatial, temporal, or spatiotemporal positions of these variables (Thomson 1983). RFs are defined by essential statistical information, including mean, variance, probability distribution, auto-correlation function, and other statistical parameters. An ideal random field should capture the main properties of a stochastic system by considering a minimal number of meaningful and quantifiable parameters. Various methods, such as the local average method (Vanmarcke and Grigoriu 1983), turning-bands method (Matheron 1973), Fourier transform method (Yaglom 2004), and local average subdivision method (Fenton and Vanmarcke 1990), have been developed to determine material properties.

For modeling the uncertainty of composites, researchers can integrate RF representation methods using techniques such as the representative volume element (RVE), homogenization, DIC-based characterization, and random media techniques. The RVE, the smallest volume providing a representative overall value when measured (Hill 1963), is particularly significant. The RVE should remain sufficiently small to be treated as a volume element within the framework of continuum mechanics. In random media, the situation is more complex than in periodic materials. Representative properties cannot be defined for volumes smaller than the RVE. Instead, the material must be described using statistical volume elements (SVE) and random fields (RF). To accurately describe random continuum fields below the scale of an RVE, determining the appropriate size of the RVE for deterministic continuum theories is crucial (Ostoja-Starzewski 1998).

Variants of the SFEM Techniques

The Stochastic Finite Element Method (SFEM) employs various techniques to investigate the uncertainty and inherent stochasticity of a system. Three widely accepted variants of SFEM are commonly used: Monte Carlo simulation (MCS) (Astill *et al.* 1972), perturbation method (Liu *et al.* 1986), and spectral stochastic finite element method (SSFEM) (Ghanem and Spanos 2003). MCS, the most general and direct approach, is suitable for a wide range of applications, including nonlinear issues. It provides exact approximations when the deterministic solution to the problem is available (La Bergman *et al.* 1997). Despite demanding high computational power, MCS is widely accepted and frequently used to validate perturbation methods and SSFEM. The perturbation method is a popular and straightforward technique for estimating the statistical moments of response variables. It is applicable to linear, non-linear, and eigenvalue problems, providing distribution-free results (Sudret and Der Kiureghian 2000). This method strikes a balance between complexity and computing load by estimating the effect of the mean, standard deviation, and covariance of the response variable on the structure's behavior. However, it is generally limited to random variable values not significantly different from the mean.

The Spectral Stochastic Finite Element Method (SSFEM), a recent extension of the SFEM, primarily focuses on representing the stochastic material properties of structures. It has garnered attention for its ability to reduce the computational effort required for analyzing random processes compared to Monte Carlo simulation (MCS). While SSFEM performs well in linear analysis, some researchers question its practicality for nonlinear analysis (Stefanou 2009). Arregui-Mena *et al.* (2016) provided a comprehensive review of SFEM's applications in science and engineering. In materials science, SFEM investigates the behavior of complex materials such as composites and fiber structures such as paper. Various technologies have been devised to characterize the stochastic properties of these materials. However, there are limitations to the application of SFEM (Arregui-Mena *et al.* 2016). One notable challenge is the absence of experimental procedures for measuring the spatial variability of material mechanical properties. The quality of SFEM studies heavily depends on both experimental data and model property assumptions. Furthermore, simulations are rarely validated against experimental data. An issue with data collection is the difficulty in measuring certain variables. In engineering, for example, while material properties are often well established, repositories of material data may not always provide sufficient information to determine the type of random field to be utilized.

Potentials of Stochastic Modeling in Forming Processes

Certainly, the matter of multiscale modeling is of paramount importance, seeking to integrate microscopic and macroscopic material properties, and there have been notable attempts with a few successes in this direction. Alzweighi *et al.* (2021) recently proposed a multiscale method that combines detailed micromechanical simulations, physical measurements of fiber-level variability, and mesoscale continuum models. This approach aims to quantify the influence of spatial variability in the structural properties of paper and paperboard resulting from the disorder of the fiber network.

The proposed method bridges the gap between intricate, computationally intensive micromechanical simulations and the continuum approach, which may overlook material inhomogeneity. However, there remains significant doubt about whether fiber network simulation can be applied to the forming process, considering computational time and modeling difficulty. While multiscale modeling is a relatively new methodology, there is still much to explore in this area, and there remains a gap in its application to the forming process.

Another attempt came from Lindberg and Kulachenko (2022), using implicit solver and Hill's plasticity with consideration of subsequent failure evaluation, to model the forming process of paperboard. MCS was applied to simulate the plane stress, where random numbers of the tensile and the compressive stresses were picked from their respective distributions. It was also proposed that this approach was conservative due to a deficit of the data for material size dependency.

LOCAL STRUCTURAL PROPERTY MEASUREMENTS

Image-based methods are frequently used to measure the local structural parameters of fiber-based materials, as well as other technologies. The following section describes common formation-related and fiber-level measurements.

Formation-related Measurements

Formation refers to the quantification of variations resulting from the non-uniform distribution of fibers both within the plane and in the thickness direction of a paper sheet (Bouydain *et al.* 2001b). The resulting local structural properties of paper and paperboard, including mass distribution, thickness distribution, and density distribution, are examined by various measurement methods.

Local grammage measurement

The main method of measuring the local grammage of paper is by the gravimetric method, in which the weight of a region is divided by its plane area. Several energy sources including light transmission, β-ray, soft X-ray and electrography have been used to determine the grammage of paper by recording the local transmission within a spatial region. The radiation will interact differently with the sample, depending on its mass distribution, which means absorption of radiation is related to the mass in the region. A comparison of these four paper imaging techniques based on their process parameters and image features was reviewed in Tomimasu *et al.* (1991).

The β-radiography technique provides detailed internal imaging and high sensitivity and specificity for detecting variations in material density and structure. The formation data from β-radiography could be recorded by application of either X-ray film (Tomimasu *et al.* 1989) or a storage phosphor screen (Keller and Patrice 2001) as the detector. Limitations of using X-ray film to detect transmitted energetic rays are the variability of the film, its development, and the digitization process, especially between laboratories. The use of stored phosphor screens reduces processing time and experimental variables while maintaining a high spatial resolution, which in the range of a few microns compared to X-ray film in the range of tens of microns. Exposure of the storage phosphor screen to irradiation produces a latent image that can be digitized by the scanning system to produce a mass formation map. Obviously, there are some limitations to the use of β-ray, such as necessity for specialized equipment and handling of radioisotopes, and also the limited to laboratory settings, so there have been some studies conducted with the objective of establishing a correlation between transmitted light and β-ray. For example, Raunio and Ritala (2009) devised a novel approach to deduce the basis weight using light transmittance, offering a promising avenue for approximating the basis weight of paper. The investigation delves into the correlation between basis weight and light transmittance, alongside exploring how this correlation evolves across diverse spatial scales. Notably, it was discerned that the strongest correlation manifests at relatively diminutive scales, signifying that fluctuations at larger scales do not disrupt the relationship; instead, the method adeptly filters out measurement noise.

Soft X-ray offers high-resolution imaging of paper and paperboard structure, including surface roughness and internal voids, sufficient to distinguish fiber features through the entire thickness of samples (Abedsoltan *et al.* 2016), but specialized equipment and expertise for sample preparation and analysis are required. Electrography can provide quantitative measurements of paper and paperboard formation based on toner deposition patterns, but has difficulty measuring grammage greater than 120 g/m^2 (Keller 1996).

The light transmission technique is the most popular due to its low cost, simplicity, relative safety, and the ability to obtain data with great rapidity (Bouydain *et al.* 2001a). It offers high-resolution images suitable for observing surface features and internal structures of the sample. However, limitations exist in its sensitivity to the nature of test material, especially the effect of sheet composition, the effect of local density variations, limitations

due to sheet opacity, and the inability to reliably determine the actual local basis weight (Abedsoltan *et al.* 2016).

A comparison of the methods for measuring paper grammage is presented in Table 1. Light transmission involves shining light through a paper sample and interpreting the patterns of transmitted light to determine grammage. This technique offers rapid exposure times, facilitating quick measurements. It is a safe option as it employs non-ionizing light sources. However, the method's accuracy may be impacted by the paper's transparency, composition, and moisture content, which can alter light transmission. It works well for lower to moderate grammage papers but is less effective with high grammage samples. Proper calibration and consistent lighting are essential for accurate results.

Table 1. Comparison of Light Transmission, Electrography, β-ray, and Soft X-ray

Factor	Light Transmission	Electrography	β-Ray	Soft X-Ray
Exposure Time	Fast (seconds)	Variable (minutes)	Quick (seconds to minutes)	Fast (seconds to minutes)
Contrast	Moderate, suitable for samples with significant variations in optical density	Moderate, depends on the charge distribution	High, depends on the material's electron density and thickness	High, based on variations in X-ray attenuation
Grammage Range	Low to moderate (<150 g/m²)	Wide range (<400 g/m²)	Wide range (<400 g/m²)	Wide range (<10,000 g/m²)
Spatial Resolution	Good (typically ~1 to 10 μm)	Moderate (typically ~10 to 100 μm)	Moderate (typically ~50 to 100 μm)	High (typically ~10 μm)
Effect of Sheet Structure	Influenced by opacity, thickness, and fiber orientation	Influenced by moisture, paper density, and electrical properties	Influenced by density and composition	Provides detailed information on internal structure
Safety	Very safe	Generally safe	Requires careful handling and shielding	Requires shielding and safety measures
Principle Employed	Analyzes transmitted light patterns	Measures charge distribution or electrical patterns	Measures β-ray absorption, correlates with fiber orientation	Analyzes X-ray scattering patterns
Inherent Limitations	Limited for high grammage samples; needs optimal lighting	Calibration needed; sensitive to environmental conditions	Radiation safety; specialized equipment required	Radiation safety; specialized equipment required

Electrography uses an electric field on the paper to measure the charge patterns on its surface. It provides moderate spatial resolution and can measure a wide range of grammages. While generally safe, it may require careful handling of electrical equipment. Electrography can be affected by environmental factors such as moisture, as well as paper

density, necessitating precise calibration for reliable outcomes. The β-ray method utilizes beta radiation to assess the absorption and scattering patterns in the paper, providing insights into grammage. This approach has fast exposure times and offers high contrast, distinguishing paper density and composition. It is effective across a range of grammages, though specialized equipment and safety measures are required due to the use of radioactive sources. Soft X-ray analysis uses low-energy X-rays to explore the paper's internal structure and determine grammage. This technique offers high contrast and spatial resolution, providing detailed internal structural information. It works across a broad range of grammages and can facilitate quick measurements. However, like β-ray, soft X-ray requires specialized equipment and adherence to safety protocols due to potential radiation exposure.

In summary, each method has its own pros and cons when measuring grammage. Light transmission is fast and safe but may face challenges with high grammage papers. Electrography provides versatility in grammage range but needs careful calibration. Both β-ray and soft X-ray methods deliver high contrast and spatial resolution, making them suitable for a range of grammages. Nonetheless, these methods require specialized equipment and strict safety precautions due to radiation exposure. The choice of method will depend on the specific requirements and available resources for each application.

Local thickness measurement

The paper thickness is measured as the perpendicular dimension between the two main surfaces of the paper. It is difficult to measure thickness accurately due to the roughness, web discontinuity, compressibility, and the difficulty of defining the true outer boundaries of paper. Some contact measurement methods were applied to paper thickness measurement in the earlier period, such as hard platen caliper (Fellers *et al.* 1986), soft platen caliper (Wink and Baum 1983), and opposing spherical platens (Schultz-Eklund *et al.* 1992). These methods entail applying pressure to the surface of the sample and making contact with it, resulting in a deformation of the surface contours to varying degrees. However, the listed contact measurement methods, although simple in principle, have a slightly insufficient resolution for localized thickness measurements, and another is that they can have a slight effect on the surface of the material.
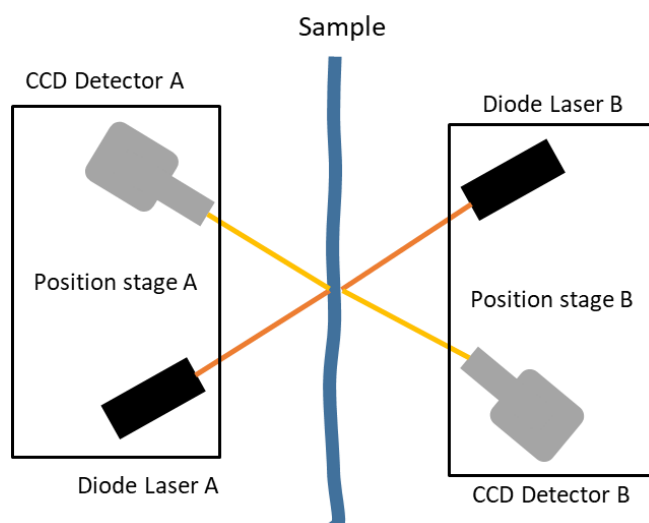

Fig. 2. Principle of non-contacted laser profilometry instrument

Non-contact local thickness measurements are available using different techniques, including laser, ultrasonic, and X-ray. The concept of non-contact profilometry was extended to encompass the measurement of local thickness by means of a simultaneous scanning of both sides of the paper with laser sensors (see Fig. 2). Izumi and Yoshida (2001) developed a dynamic confocal sensor-based instrument for mapping the local thickness irregularities from surface data of the front and back surfaces of a sample with a 50×50 mm^2 area. The instrument has an in-plane spatial resolution of 500 μm and micrometer-scale in the thickness direction. The similar method introduced by (Sung *et al.* 2005), known as the twin laser profilometer, utilizing triangulation-based sensors, involves the interference of two laser beams to accurately measure the distance to a surface, offering an expanded scope of surface topography. The resolution has been enhanced to 25 μm with the incorporation of high-precision stages.

The above-mentioned thickness assessment techniques are still in the face of some challenges: radiation hazards, contact media required, limitations with respect to measurement speed and depth resolution, or deficiencies in the use of multi-layer board systems. The advent of terahertz (THz) technology offers an innovative method to overcome the limitations, and structures in the order of mm can be detected without great technical effort. Terahertz (THz) radiation falls within the electromagnetic spectrum between millimeter-waves and infrared wavelengths. Employing the short-pulse technique along the beam direction allows for significantly enhanced resolution, enabling the current capability to resolve layer thicknesses of approximately 10 *μ*m (Wietzke 2021). The principle of thickness measurement with THz is shown in Fig. 3, in which each layer interface reflects part of the terahertz pulse, so the thickness can be analyzed by calculating the time difference between the signal returns.
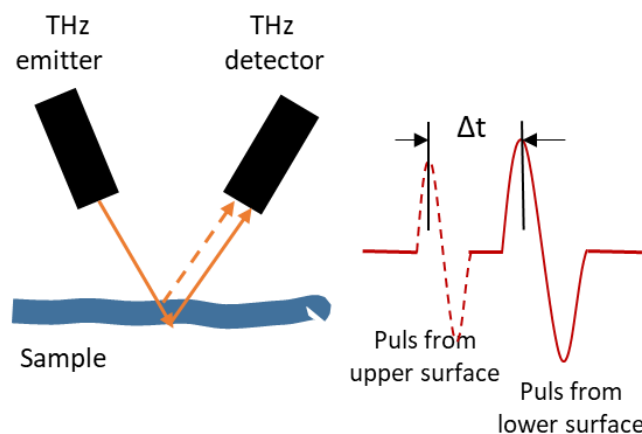

Fig. 3. Principle of thickness measurement with THz

Remarkable strides have been taken in the recent industrialization of this innovative technology. THz time-domain spectroscopy (THz-TDS), employing short pulses of THz radiation to probe material properties, has emerged as a promising spectroscopic technique having high spectral resolution ranging from sub-micrometers to micrometer levels. In comparison to continuous-wave THz spectroscopy, THz-TDS provides ample sample information through pulsed THz excitation, making it a powerful technique for a wide range of applications in materials science, chemistry, biology, and physics. In THz-TDS, a short-duration pulse of terahertz radiation is emitted and directed towards the sample. The interaction of this pulsed terahertz radiation with the sample results in the generation of a

time-domain waveform (Withayachumnankul *et al.* 2014). In a study by Mousavi *et al.* (2009), a non-contact method was proposed for simultaneous measurements of the thickness and moisture content of paper using THz-TDS.

Local density determination

Paper density can be calculated by dividing its mass by the thickness in the same area. Dodson *et al.* (2001) employed an opposing laser non-contact thickness tester developed by Izumi and Yoshida (2001) to measure local thickness and density variation maps. Sung *et al.* (2005) utilized TLP instrumentation to acquire a local thickness map and combined it with a local mass map through storage phosphor β-radiography. This approach generated localized apparent density image pixels ($200\ \mu m$) for analyzing the in-plane inhomogeneity of printing paper's thickness, grammage, and apparent density. Similarly, Keller *et al*. (2012) applied this method to study the distribution of local mass, thickness, and density in different nonwoven materials, utilizing a binary mask for segmentation and distinguishing relief features from random background structure.

Given the porous nature of paper, mercury intrusion porosimetry (MIP) serves as a viable method for measuring aspects related to paper and paperboard density. MIP is a commonly used technique for analyzing porous material structures, involving subjecting a sample to controlled pressure while immersed in mercury (Johnson *et al.* 1999). As the pressure increases, mercury is forced into the pores of the sample. The pores fill with mercury in a sequential manner, starting from the largest pores to the smallest. During the intrusion process, the volume of mercury that enters the sample is measured at regular intervals, while at the same time, the change in volume is recorded as a function of applied pressure. MIP measurements are rapid and straightforward, providing valuable structural parameters such as porosity, pore size, pore volume, pore distribution, and density (Giesche 2006). When coupled with microscopic measurements such as scanning electron microscopy (SEM) and X-ray 3D micro tomography (X-μCT), as will be discussed in the next section, MIP measurements can offer more in-depth information regarding the shapes or spatial distribution of pores within multilayer structures, such as thick-structured paper (Charfeddine *et al.* 2019).

Fiber Network Structure Measurements

In addition to grammage and thickness measurements, the fiber structure of paper also significantly influences its mechanical behavior. Therefore, the measurement of fiber structure is equally crucial in understanding the mechanical properties of paper materials, which are characterized by a non-unique network of interconnected fibers. Measurements related to fiber structure, including fiber length, width, and orientation, are pivotal for the examination of material properties.

Image acquisition technology

Image acquisition technology has been a significant focus in recent research, particularly concerning the analysis of 3D paper structures. In a study by Chinga-Carrasco (2009), various imaging techniques were assessed for evaluating printing paper structures. These methods included transmission electron microscopy (TEM), focused-ion-beam (FIB), scanning electron microscopy (SEM), light microscopy (LM), confocal laser scanning microscopy (CLSM), and X-ray microtomography (X-μCT). A comparison of diverse image acquisition devices used in paper structure measurement is presented in Table 2.

Table 2. Imaging Systems Employed for the Structural Examination of Paper Materials

Techniques	Resolution (μm)	Advantages	Disadvantages
TEM	0.0002	• Unrivaled nanoscale resolution • Reveal details such as individual fibers and pores	• Extensive time requirement • Sample preparation may necessitate microtomy or polishing • High vacuum environment
FIB	0.01	• Optimal for nano-scale examination of coatings and printing inks • Enabling cross-sectional imaging and analysis	• Labor-intensive and time-consuming • May cause damage to the sample due to ion beam bombardment • Restricted resolution in depth direction
SEM	0.001 to 0.02	• High resolution and contrast • Adaptable in image acquisition	• Time-consuming process • Requires coating to prevent charging effects • Limited information about internal structures
LM	0.2	• Widely accessible • Relatively simple sample preparation	• Limited resolution • Lack contrast for certain components of paper
CLSM	0.2 to 0.7	• Improved depth resolution compared to LM • Facilitates automated 3D reconstruction • Allows observations in moist conditions	• Relatively modest resolution • Limited penetration depth into thicker paper samples • Subdued contrast between paper components • Diminishing intensity and resolution in depth direction
X-μCT	0.7 to 1.0	• Non-destructive 3D imaging • Uniform resolution in x, y, and z directions • Suitable for analysis in moist states	• Limited contrast differentiation between various components • Scarce availability of requisite equipment • Relatively low resolution compared to other techniques

Among these methods, X-μCT as a non-destructive method has received increasing attention in recent years. 3D reconstruction using X-μCT results can create cross-sections of a physical object at μm resolution without destroying the original object. The measurement principle of the X-μCT system is shown in Fig. 4. The X-μCT technique, commonly employed in medical imaging and industrial computed tomography, has gained recognition for its potential in elucidating the internal properties of fiber network structures. Gregersen and coworkers (Samuelsen *et al.* 2001) pioneered the application of X-μCT for the 3D characterization of paper structure. However, current 3D images obtained through X-μCT exhibit somewhat lower resolution in comparison to SEM, limiting the description of fiber and pore networks to diameters larger than 0.8 μm (Chinga-Carrasco *et al.* 2008). While suitable for quantifying various properties such as thickness, porosity, surface microroughness, and microporous morphology, X-μCT may obscure structural details due to its relatively low resolution. In contrast, 3D synchrotron radiation X-μCT has been applied to characterize paper structure with the introduction of micro- and

nanofibrillated cellulose (Mohamed *et al.* 2016). This approach offers significantly higher resolution (sub-micron levels) and image quality compared to desktop X-μCT (several microns to tens of microns) (Holmstad *et al.* 2005). Nevertheless, access to synchrotron facilities may be limited and require beamtime allocation. Additionally, the cost and complexity of experiments conducted at synchrotron facilities are generally higher compared to desktop X-μCT.
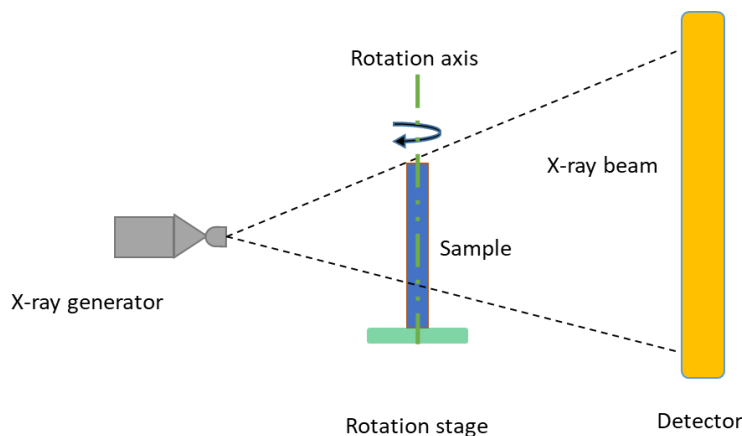
Fig. 4. Principle of X-μCT system

Methods for fiber segmentation

In fiber analysis, the crucial and challenging task is the separation of individual fibers within a three-dimensional network, known as fiber segmentation. Fiber segmentation provides details on fiber-level properties such as length, cross-sectional area, orientation, and network-level properties, including the coordination number of fiber-fiber bonds. As 3D μCT images only offer absorption coefficients relative to air, segmenting individual fibers becomes indispensable for direct measurements on fibers themselves during image acquisition. One set of methods involves marking and tracing inner lumens, which are distinguished from the background by thick fibrous walls (Donoser and Bischof 2006). However, these methods necessitate users to select multiple seed points for each fiber, initiating the segmentation process. Sharma *et al*. (2015) introduced a novel algorithm for automated fiber segmentation in μCT images, calculating the thickness and length of the segmented fiber. Another includes graph-based methods (Wernersson *et al.* 2009), in which each edge represents an individual free-fiber segment, and clusters indicate fiber-fiber connections. However, the computational complexity of these methods is high for large-scale fiber segmentation in 3D space. Recently, Wernersson *et al.* (2014) developed a semi-automatic methodology combining manual scribing and automatic measurements to extract essential paper properties, such as free fiber length and fiber-to-fiber relative contact areas. Despite advancements, the computational effort remains high for a large number of fiber segmentation in 3D.

Determination of fiber orientation

In addition to measuring the specimen with μCT to obtain comprehensive information about the network of paper and paperboard, there are two other types of methods that can be used for fiber orientation measurement. In the paper industry, the fiber orientation is commonly measured indirectly *via* the ratio of the elastic modulus in MD and CD directions with the aid of ultrasonic technology (Lindblad and Fürst 2001). The

TSO-Tester serves as an optimal tool for measuring the tensile stiffness index (TSI) and tensile stiffness orientation (TSO). This method is often used to globally determine the fiber orientation, depending on the size of the measured sensor diameter, usually around 100 mm. Nevertheless, it is important to note that ultrasonic testing, such as TSO-Tester, is sensitive to factors such as fiber-to-fiber bonding and drying stresses within the sheet, as highlighted by Vahey *et al.* (2008). This sensitivity implies that variations in the bonding between fibers and drying-related stresses within the paper sheet can influence the accuracy and reliability of the measurements obtained using ultrasonic testing methods.

Sheet splitting is a typical method when measuring layered fiber orientation over large areas, which can be performed by adhesive tape (Erkkilä *et al.* 1998) or laminating device (Söderberg and Lucisano 2005). In Kellomäki *et al.* (2003) two algorithms for estimating fiber orientation distribution were compared, *i.e.* angular estimation in the form of a magnification-weighted distribution perpendicular to the direction of the gradient in the image, or calculation based on scaled variograms of the grey values scanned along the sampling line and their relation to fiber orientation. In Hirn *et al.* (2007) an improved method employing the laminate method for sheet splitting, a high-resolution scanner for imaging was introduced. It allows arithmetic correction of uneven sheet splitting, which reduces noise in the fiber orientation measurement. However, a major drawback of this method is its destructive nature.

Dias *et al.* (2023) introduced a fast, portable, and cost-effective method to estimate the in-plane fiber orientation on the surface of laboratory paper sheets. This approach, known as the camera-GSM methodology, combines a digital camera with low-angle illumination and a gradient-segmentation method (GSM) algorithm to determine polar fiber orientation distribution. The adaptive GSM algorithm uses an adaptive thresholding scheme to optimize image processing and enhance edge detection of fiber segments. This method demonstrated high internal consistency, accurately identifying offset angles relative to the machine direction (MD) during imaging. While effective for distinguishing sheets with varying anisotropy levels on rougher top surfaces, the method was less successful for smoother bottom surfaces, possibly due to the camera's lower resolution. Future research will focus on optimizing the camera-GSM method and transferring it to industrial processes for real-time application in paper manufacturing.

MECHANICAL PROPERTY DETERMINATION

Paper can be viewed as a heterogeneous material at different levels of its structure (Bristow and Kolseth 1986), so that the deformation within the specimen could be localized. To determine the global mechanical properties of paperboard, a number of destructive tests are performed routinely to obtain the out-of-plane and in-plane mechanical properties, as well as the friction behavior of fiber-based materials. This section introduces mechanical measurement techniques based on different principles, such as those used for measuring local strain during deformation and at the point of fracture. The experimental methods listed here are limited to the sheet level of paper or paperboard. This means that experiments on the mechanical properties of fibers, corrugated board especially in thickness direction, and finished packaging products such as cartons, *etc.*, are not considered. The purpose of these experiments is to obtain the parameters required for modeling in-plane and out-of-plane behaviors of paper and paperboard.

Tests for In-plane Mechanical Properties

In the forming process of fiber-based materials, the in-plane mechanical properties play a crucial role in process control and for determining product quality. Tests of primary interest can be broadly categorized into two types: tensile and compression tests. These tests are typically conducted in various directions such as the machine direction (MD), cross-machine direction (CD), 45°, or other complementary directions, depending on the specific objectives of the testing.

Tests for tensile behavior

Tensile testing is the most widely used method for examining the mechanical behavior of paper and paperboard under tensile load. This test can determine various tensile behavior parameters, including elastic modulus, yield strength, breaking strength, tensile stiffness, and elongation at break. Tensile tests can be classified into two categories based on stress state: the most commonly used are uniaxial tensile tests and biaxial tensile tests. In addition to the typical tensile test to fracture, the former includes the cyclic tensile test, which facilitates the determination of the elastic modulus. The latter has two variants: cruciform tests and bulge tests (Fig. 5). For uniaxial tension experiments, only two points longitudinally along the direction of the specimen are required to determine strain values. (Suhling *et al.* 1989) conducted uniaxial tension experiments on a testing machine with a servo-operated x-y recorder, testing specimens in the machine direction (MD) and cross-machine direction (CD) for the measurement of flow curves. Biaxial tensile tests with cruciform-shaped specimens were employed by researchers, including Garbowski et al. (2012), Linvill and Östlund (2016a), and Castro and Ostoja-Starzewski (2003) to study biaxial in-plane yield strength and material failure. The cruciform-shaped tensile test is particularly well suited for materials such as paperboard, as it allows for uniform stress distribution and minimizes the risk of premature failure at the clamping points. Additionally, the cruciform shape ensures that the test captures both MD and CD mechanical properties of the paperboard, providing a comprehensive characterization of its mechanical behavior. Groche *et al.* (2012) designed a new test device for investigating the quasi-plastic behavior of paperboard through the bulge test. The bulge test exhibited a significant correlation with flow curves obtained by standard tensile tests, providing better predictability of forming results. Additionally, cyclic tensile tests (Thakkar *et al.* 2008) can be employed to measure yield strength and differentiate between elastic and plastic material behavior by repeatedly loading and unloading the sample.
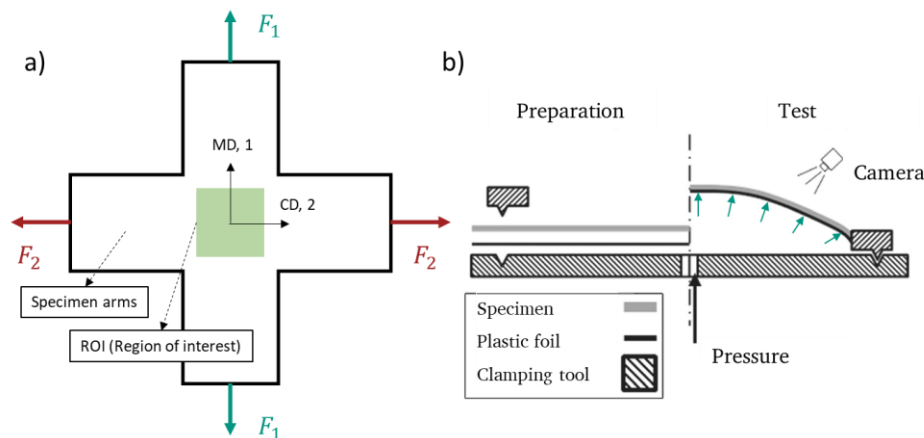

Fig. 5. The schematic a) cruciform test and b) bulge test (Franke *et al.* 2021)

Tests for compressive behavior

In-plane compression testing can be conducted using various methods, including the Long-Span-Compression Test (LCT, Fig. 6a), Short-Span-Compression Test (SCT, Fig. 6b), and Ring-Crush Test (RCT, Fig. 6c) (Shallhorn *et al.* 2005). LCT involves a larger sample size with clamping lengths ranging in tens of millimeters, where the length of the specimen is much greater than its width and thickness. This is in contrast to SCT, which has a clamping length shorter than 1 millimeter. Within LCT methodology, vacuum cups, sample vanes, or support plates are employed to prevent bending (Fellers and Donner 2002). Values measured in LCT are typically smaller than in SCT due to the higher likelihood of local weak points in LCT samples. Despite these differences, significant correlation has been demonstrated between values measured with SCT and LCT methods (Hagman *et al*. 2013). Both compression tests are only appropriate for small deformations, as large deformations can cause instabilities such as buckling. Compared to SCT, the RCT may have an element of flexion in addition to compression, which must be taken into account when processing the experimental results (Frank 2003).
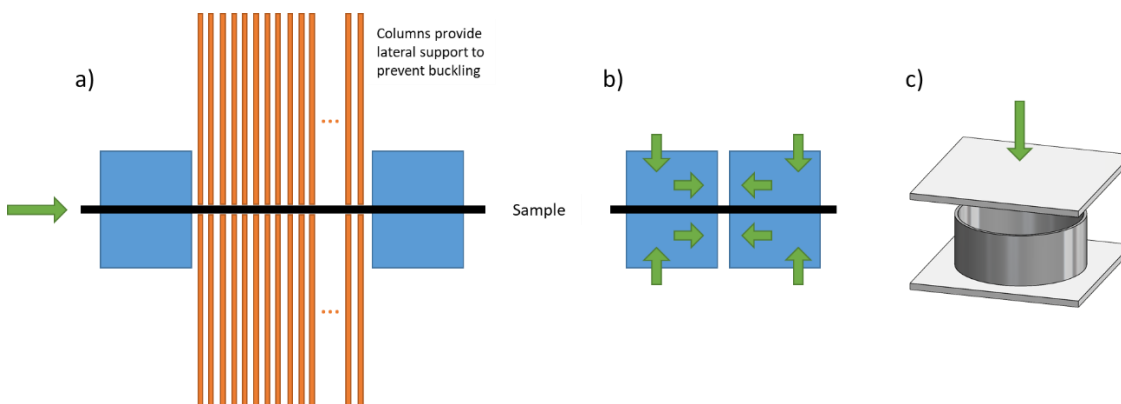

Fig. 6. The schematic a) Long-Span-Compression Test (LCT), b) Short-Span-Compression Test (SCT), and c) Ring-Crush Test (RCT)

Tests for shear behavior

When considering in-plane mechanical properties, shear strength becomes crucial, although measuring it can be quite challenging. Previous studies (Fellers 1977; Heckers and Göttsching 1980) have explored in-plane shear strength of paper through a simple shear test, in which both sides of the specimen are clamped, and tensile force is applied in the opposite direction of the fixture. However, this approach has limitations, as failures often initiate and propagate from the clamped part, potentially leading to inaccurate results. In the asymmetric four-point bending test (Yoshihara and Yoshinobu 2014), as shown in Fig.7a), rectangular pieces of medium-density fiberboard are bonded to paper specimens to determine the shear behavior of the specimen in the middle. However, both simple shear and asymmetric four-point bending test tests require two rails or tabs for shear application, which can be time-consuming due to the need for gluing. To address these concerns, Yoshihara and Yoshinobu (2014) also proposed the off-axis tension test (Fig.7b)), determining that a 35° off-axis angle is promising for predicting shear strength, in which the contribution of the shear stress component is maximum. A recent method, the tensile-loaded shear test (Fig.7c)), was proposed as an alternative to off-axis tension test (Yoshihara and Yoshinobu 2017). In this test, two circumferential holes and two asymmetrical slots are cut along the axial centerline of the sample. Tensile load is applied

to induce shear stress in the region between the edges of the holes. This test offers advantages over the off-axis tension test by utilizing pure shear stress conditions.
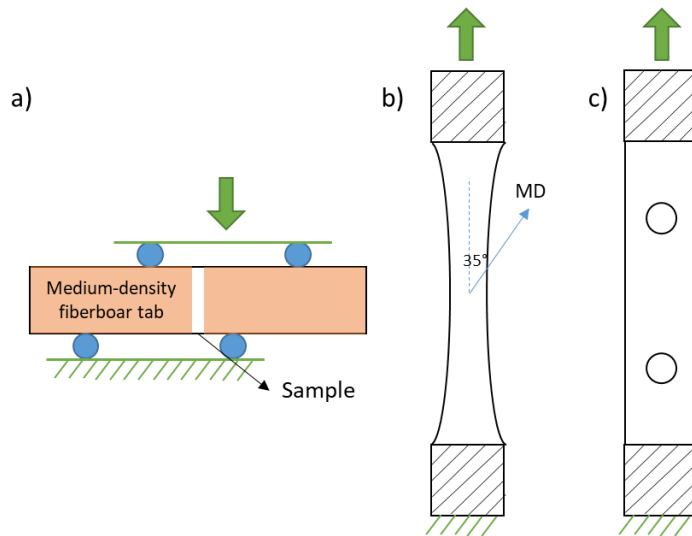

Fig. 7. The schematic a) asymmetric four-point bending test, b) off-axis tension test, and c) tensile-loaded shear test

Tests for Out-of-plane Mechanical Properties

Mechanical properties of paper and board in the thickness direction (ZD) are equally crucial for specific processing operations, particularly in 2D forming processes such as creasing and bending (Huang and Nygårds 2012b), when compared to the in-plane mechanical properties. The alignment of fibers in the sheet results in mechanical properties of paper in the machine direction (MD) and cross direction (CD) that significantly differ from those in the thickness direction. Consequently, a series of tests can be employed to identify various mechanical behavior and interface damages, such as delamination in the thickness direction.

Tests for tensile behavior

The Z-directional tensile test (ZDT) is typically performed by affixing the paper to metals using double-adhesive tape. Liew (1974) pioneered the examination of material behavior under out-of-plane tension, using a standard tensile tester with circularly shaped test pieces. Girlanda and Fellers (2007) developed a testing procedure to measure the stress-strain properties in the thickness direction of paper. This procedure allows for the extraction of ZD elastic modulus, tensile strength, and strain at break of paper materials. Fellers and Andersson (2012) improved the technique for evaluating the entire stress-strain curve in the thickness direction by employing a lamination technique to secure the paper onto the metal plates. This approach enabled the extraction of z-strength, z-modulus, z-strain at break, z-energy at break, and z-fracture energy from the curve.

Tests for compressive behavior

Determining the out-of-plane modulus of elasticity through out-of-plane tensile tests presents challenges due to the simultaneous delamination of the core fibers and delamination between fiber layers. Therefore, out-of-plane compression tests may be more useful for obtaining the parameters. Stenberg (2003) conducted out-of-plane compression

tests to characterize the out-of-plane mechanical behavior of multilayer paperboard. The cyclic compression test, involving successive loading and unloading at an increasing total load, is employed to evaluate the elastic-plastic behavior. Yang (2022) designed a ZD tester consists of a lifting device, a probe augmented with a massive body, and a position detector for the rapid compression of materials in the thickness direction. This facilitates the measurement of viscoelastic properties in the depth direction.

Tests for shear behavior

In traditional out-of-plane shear tests of fiber-based materials, such as the rigid support test (RST), specimens are attached to rigid supports and deformed in the depth direction. Various methods have been explored in the literature, including the Arcan device (Stenberg *et al.* 2001), the rigid block method (Byrd *et al.* 1975), and the Iosipescu method (Qiu *et al.* 1999). However, these methods have limitations, as accurate testing requires the use of paper materials with a grammage equal to or greater than 60 g/m^2, and glue penetration can impact the results (Girlanda and Fellers 2007). To overcome these limitations, Nygårds *et al.* 2007) introduced the double-notch shear test (DNST), where notches are made in the specimen, and shear damage occurs between them during tensile loading, eliminating the need for bonding. However, DNST has limitations when the shear zone is too large, leading to potential tensile damage rather than pure shear stress. In response, the notched shear test (NST) was proposed as an enhancement of the DNST. In NST, the paper material is lightly laminated and reinforced on both sides of the cut sample with plastic film for improved shear test results. The strip shear test (SST) represents an extreme version of NST, where notches extend through the entire sample. SST offers a quick measurement of shear strength and demonstrates good agreement with RST results (Nygårds *et al.* 2009).

Tests for fracture/delamination

When paperboard undergoes loading, the internal structure undergoes changes, leading to fiber separation and the formation of voids in the paperboard without fibers, a phenomenon known as delamination. In addition to the mentioned tests for tensile and shear strength, various experimental tests are employed to measure the delaminating resistance of paper and paperboard.
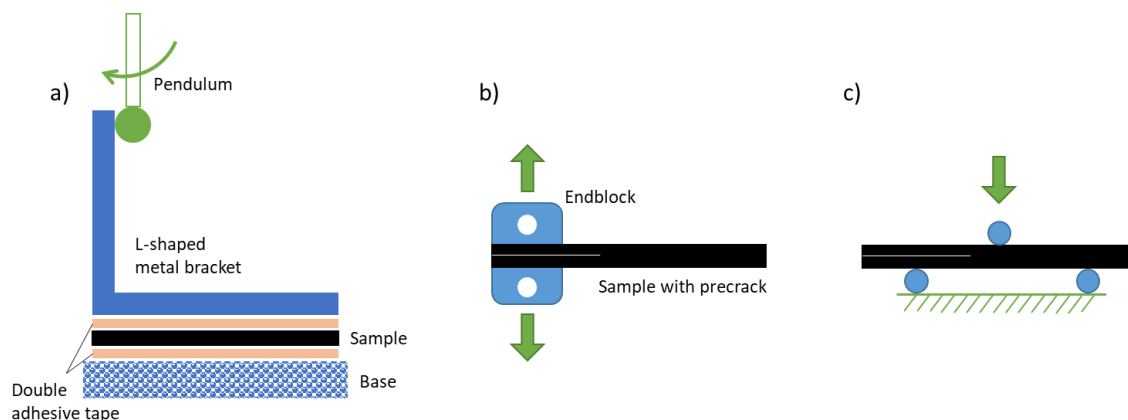

Fig. 8. The schematic a) Scott bond test, b) double-cantilever beam test (DCB), and c) end-notched flexure test (ENF)

These tests include the Scott bond test (Reynolds 1974), end-notched flexure test (ENF), double-cantilever beam test (DCB), and mixed-mode bending test (MMB) (Reeder and Crews Jr 1990). Fellers *et al.* (2012) validated the hypothesis that the Scott bond value is influenced by the sum of energy under the stress-strain curve in the ZD tensile test. Li *et al.* (2016c) investigated the interface fracture behavior in sliding mode, determining the maximum shear stress using DCB and the fracture toughness using ENF, both experimentally and numerically. Sarrado *et al.* (2015) proposed a methodology based on the J-integral approach for experimental data reduction in the MMB test to measure the inter-laminar fracture toughness of composites under mixed-mode loading.

Supporting Measurement Technology

Additionally, supplementary measurement techniques are employed to more accurately document local alterations in displacement or temperature, or to monitor the progression of failure.

Digital Image Correlation (DIC)

Various techniques have been employed to assess local strain in paper, including holography (Lyne and Bjelkhagen 1981), laser spectrometry (Lyne and Bjelkhagen 1981), photo spectrometry (Choi *et al.* 1991), and digital image correlation (DIC). DIC, a widely accepted method, has been extensively utilized to measure micrometer and nanometer scale deformations in fibrous networks subjected to mechanical loading. This photo-mechanical technique employs image alignment algorithms, such as the correlation product, to quantify surface displacements by comparing the reference image with the image captured during the test (Roux *et al.* 2012). DIC offers "full-field" measurements, enabling accurate assessments of surface displacements at numerous pre-selected grid "nodes" on the specimen surface *(Sutton et al.* 2009). In comparison to interferometric optics for planar deformation measurement, the DIC method necessitates a straightforward experimental setup and provides a wide range of measurement sensitivity and resolution (Pan *et al.* 2009). The concept of utilizing DIC to determine surface deformation was introduced by researchers at the University of South Carolina in the early 1980s, initially applied to solid mechanics (Peters and Ranson 1982). Considine *et al.* (2005) utilized DIC to investigate the local strain behavior of fibrous networks in tensile tests. The results indicated that the variation of strain from DIC was considerably higher than previously reported, due to the fact that DIC utilizes smaller regions to calculate and record the entire sample. Mirzaei *et al.* (2023) devised a DIC technique for measuring localized deformation at folds, enabling monitoring of deformation in both cross-sectional and apparent views. This method holds potential applications in common material characterization tests, such as tensile and bulging tests, especially for inhomogeneous materials with a uniform strain distribution. The resolution of a camera and the optics of a digital image correlation (DIC) system can range from one to one hundred pixels per millimeter. Typically, the frame rate of a DIC system is between ten and one thousand frames per second (fps), with higher frame rates required to capture deformations at faster rates.

Digital Volume Correlation (DVC)

DIC monitors numerous small areas on the material surface, whereas digital volume correlation (DVC) tracks many smaller 3D volumes during the deformation process. Therefore, when employing DVC to analyze a sample's response to external loads, knowledge of the entire specimen volume structure, not just the surface, is required

(Andersson and Hedberg 2018). With advancements in synchrotron and laboratory tomography, 3D reconstructed volumes can be obtained during mechanical testing through X-ray tomography. These volumes can be correlated by DVC algorithms to determine three-dimensional displacements of different materials (Hild and Roux 2015). Tran *et al.* (2013) and Viguié *et al.* (2011) employed DVC to analyze the deformation of paper. DVC necessitates small intervals between successive images, and the image regions compared by the correlation algorithm must exhibit sufficient similarity in the subsequent images. 3D strain field maps of paper or paperboard materials are not uncommon. Golkhosh *et al.* (2017) presented an application of synchrotron tomography and DVC to analyze notched paper specimens in a tensile test. It was demonstrated that an increase in out-of-plane deformation is accompanied by a decrease in inter-fiber bonding. More recently, Wallmeier *et al.* (2021) conducted a conceptual analysis of the restrained in-plane compression of cardboard using μCT imaging and the DVC method. This was done with the aim of improving understanding of in-plane compression, buckling, wrinkling, and compaction. It was demonstrated that delamination is the predominant failure mechanism for multilayered paperboard. The formation of uniform wrinkles and compaction is facilitated by a porous network structure, which is formed through the incorporation of long softwood fibers. Johansson *et al.* (2023) also investigated the in-situ compression of paperboard, quantifying and analyzing the microstructure evolution of the fiber network concerning the loaded real boundary conditions. Theoretical treatments of paperboard compression often overlook the compression of the fiber wall. Nevertheless, this study proposes that the stored elastic energy within the fiber wall could play a significant role in driving the elastic recovery of the fiber network upon unloading.

Infrared (IR) thermography

Remote thermal sensing *via* infrared (IR) imaging, known as thermography, is a non-contact technology that allows the surface temperature distribution of objects to be measured quickly and remotely with high accuracy. This accuracy is on the order of tens to hundreds of pixels per inch or millimeter, and the temperature sensitivities are on the order of millikelvins per pixel. Dumbleton *et al.* (1973) employed a line-scan IR thermography camera to track the temperature changes that occur in the paper during tensile testing. It was found that the temperature increase was greater at the fracture point, despite the uniform dissipation of energy throughout the specimen. IR thermography has been found to be an alternative to calorimetry to detect the localized temperature changes and heat transfer in paper during tensile loading (Yamauchi and Murakami 1992; Yamauchi *et al.* 1993). Recently, Hyll *et al.* (2012) successfully analyzed the elastic and plastic energies involved in the deformation and breakage of paperboard and paper specimen. They also paid special attention to ensuring correct emittance values based on the thermographic measurements. All the aforementioned applications are passive thermography with no external heat source, while in active thermography, the temperature of the material varies with time and position. Sato and Hutchings (2010) applied active IR thermography to both qualitatively and quantitatively non-destructive test of laminated paper products. Hagman and Nygårds (2017) analyzed the thermal response of paper during tensile testing using IR camera with a frame rate of 32 Hz and a resolution of 640*512. They observed a warming streak pattern in the plastic regime. The temperature difference between the area of the rupture and the rest of the surface at the moment of breakage was up to 8°. A comparison of the results with those obtained using DIC revealed

a proportional relationship between the heat pattern generated during plastic straining and the local straining.

Acoustic emission and ultrasonic wave's methods

Acoustic emission (AE) and ultrasonic waves are non-destructive techniques used to evaluate the damage status of materials or structures (Hellier 2013). AE is a useful non-destructive methodology in detecting the fracture behavior of dynamically deformed materials, which was started in Germany with metal research by Kaiser (1950). The results show that the AE signal is correlated with the deformation and breakage behavior of cardboard (Suzuki *et al.* 2005). Gradin *et al.* (1997), Salminen *et al.* (2002), and Isaksson *et al.* (2004) conducted studies on paper fracture during tension using AE analysis. They assumed that the emission of acoustic energy is associated with irreversible deformation, micro-cracks, and plasticity, since the stress waves begin to be emitted in the early stages of loading. Kishi *et al.* (2012) estimated the deformation and fracture behavior of coated cardboard with AE method. The AE signal can be detected and divided into three regions on the same timescale in order of amplitude, corresponding to compression deformation (< 25 dB), crack generation (25 to 40 dB), and delamination (> 40 dB) of paperboard.

Ultrasonic wave propagation is employed to assess mechanical properties, including the elastic modulus of materials like paper (Lindblad and Fürst 2007). However, paper is an imperfect material, exhibiting local inhomogeneities such as fiber flocs or damaged regions. Ultrasonic wave methods may not be sensitive to such defects unless they happen to be situated on the line between the two transducers (Sato *et al.* 2008).

OVERVIEW ON MODELING OF FIBER-BASED MATERIALS AND FORMING PROCESS

Hauptmann (2010) outlines the diverse properties of paper and paperboard, including anisotropy, inhomogeneity, hygroscopicity, and viscoelasticity. Anisotropy, viscoelasticity, and the effects of humidity and temperature have been modeled successfully on many occasions. However, there is still a scarcity of experimental and numerical studies on inhomogeneity. For instance, Hagman and Nygårds (2012) delved into the impact of inhomogeneity on the compressive and tensile mechanical characteristics of paperboard. Inhomogeneity, characterized by structural non-uniformity, introduces variations in mechanical properties, leading to "weak points" within or on the material's surface. Given the continuum model's application in the forming process, incorporating inhomogeneity into the constitutive model becomes imperative for process stability and enhancing the quality of papers, especially in the production of high-quality end products.

Material Modeling of Paper and Paperboard

A comprehensive overview of in-plane and out-of-plane elasto-plasticity models with particular emphasis on the yield function and hardening for paper at the sheet scale is given in (Simon 2021). Based on his work, as well as some new developments in material modelling, an overview is given in Table 3 taking into account damage. It should be noted that only these two material models (Alzweighi *et al.* 2021; Lindberg and Kulachenko 2022) consider inhomogeneity.

Table 3. Overview of Continuum Material Models of Paper and Paperboard

Reference	Model basis	In-plane, out-of-plane or both	Yield function and hardening	Damage
(Xia *et al.* 2002)		In-plane *	6 sub-surfaces, plastic yield follows an associated flow rule; Anisotropic hardening	no
(Mäkelä and Östlund 2003)		In-plane	Non-quadratic yield surface; isotropic hardening	no
(Stenberg 2003)		Out-of-plane	Bonding yield surface; Hardening dependent on compressive and shear strain	no
(Harrysson and Ristinmaa 2008)		In-plane	non-associated plasticity model, linear combination of a quadratic and a linear function; Distortion hardening	Tsai–Wu stress failure criterion
(Nygårds 2009)	Xia	Out-of-plane	Two different yield functions; Hardening dependent on compressive and shear strain	Delamination failure
(Huang and Nygårds 2010)	Hill	both	In-plane: Hill's yield criterion with isotropic hardening Out-of-plane: orthotropic cohesive law	Delamination failure
(Borgqvist *et al.* 2015)	Xia	both	12 yield sub-surfaces; Distortion hardening	no
(Wallmeier et al. 2015)		In-plane *	four yield surfaces; Quadrant hardening	no
(Tjahjanto *et al.* 2015)	Xia	both	Anisotropic hardening with kinematic effect; Densification with through-thickness compression	no
(Li *et al.* 2016a; Borgqvist *et al.* 2015; Li *et al.* 2018)	Xia	both	multi-surface based yield criterion with nonlinear kinematic and isotropic hardening	no
(Pfeiffer and Kolling 2019)	Hill	In-plane	Quadratic yield function follows an non-associated flow rule; Anisotropic hardening	no
(Alzweighi *et al.* 2021)	Hill	In-plane	Orthotropic yield function; Isotropic hardening	no
(Lindberg and Kulachenko 2022)	Hill	In-plane	Orthotropic yield function; Isotropic hardening	Tsai–Wu stress failure criterion

* out-of-plane behavior as purely elastic

Process Modeling of Forming Processes

Several continuum mechanics-based models have been developed to incorporate paper and paperboard into finite element simulations of forming processes. In contrast to traditional 2D forming processes such as creasing and folding, 3D forming processes offer the capability to directly manufacture products with more intricate geometries (Hauptmann *et al.* 2015). There are three fundamental process variants for the 3D forming of paperboard and paper, hydroforming, press-forming, and deep drawing. An overview of the process modeling in forming processes is provided in Table 4. It can be noticed that only the

continuous model has been used in the forming process. Meanwhile, explicit solvers are always preferred in simulating paperboard forming processes that exhibit large non-linearities to avoid convergence problems.

Table 4. Overview of Process Modeling in Forming Processes

Forming process	Reference	Material model	Features	Solver method	Software
Hydroforming	(Huang and Nygårds 2012a)	(Huang and Nygårds 2010)	Combination of an anisotropic continuum model and a softening interface mode	Explicit	Abaqus
	(Groche *et al.* 2012)		Elastic–plastic material with von Mises yield criterion	Explicit	Abaqus
	(Linvill and Östlund 2016b)	(Wallmeier *et al.* 2015)	moisture-dependent and temperature-dependent constitutive model	Explicit	LS-DYNA
Press-forming	(Awais *et al.* 2017)	(Huang and Nygårds 2010)	Effect of creases on the formability; Frictionless	Explicit	Abaqus
	(Lindberg and Kulachenko 2022)	(Lindberg and Kulachenko 2022)	Failure evaluation with Maximum Strain theory and Tsai–Wu theory	Implicit	Ansys
Deep drawing	(Wallmeier *et al.* 2015)	(Wallmeier *et al.* 2015)	Temperature effects	Explicit	LS-DYNA
	(Linvill et al. 2017)	(Wallmeier *et al.* 2015)	Wrinkle prediction and post-wrinkle behavior	Explicit	LS-DYNA

CONCLUSIONS AND OUTLOOK

Fiber-based materials undergo mechanical characterization through a range of tests including tension, compression, bending, and shearing. These evaluations gauge properties such as tensile strength, modulus of elasticity, and flexural strength, which are pivotal for comprehending material response under varying loading conditions. Accurate prediction and optimization of the forming process necessitate experimentally determined material parameters. This not only enhances material fabrication but also facilitates numerical modeling of material behavior. Advanced methodologies like microstructural analysis and non-destructive testing supplement conventional techniques, providing insights into internal structure and defect identification. A comprehensive mechanical assessment enables informed material selection and optimization, catering to diverse engineering applications.

In order to describe more accurately the inhomogeneous behavior of fiber substrate materials, stochastic finite element methods and multiscale modeling methods can be applied. Descriptions of the stochastic nature can be based on measurements of the inhomogeneity of the fiber network structure, such as local mass, density or thickness distribution, and fiber orientation distribution. This stochastic nature has been correlated with localized strain and material damage, as evidenced by the observed rise in local temperature due to energy dissipation during tensile testing (Lahti *et al.* 2020).

A series of experiments is required to ascertain both in-plane and out-of-plane tensile, compressive, and shear behaviors, as well as mechanical failure properties. This facilitates the formulation of diverse continuum material models, which, when integrated with stochastic structural properties, enhance the accuracy of numerical modeling in describing and predicting forming processes, thereby boosting efficiency and refining forming behaviors. The selection of local measurements is also dependent on the size of the specimen being simulated. For mm-scale specimens, µCT is the optimal choice to obtain local mass, thickness, and fiber measurements simultaneously. However, for larger specimens up to the centimeter scale, obtaining local measurements can be challenging, particularly for fiber orientation analysis.

Modeling the behavior of paper and paperboard is a complex endeavor, given the myriad factors influencing their performance, including moisture, temperature, time, loading history, strain rate, friction behavior, and inhomogeneity. Achieving a comprehensive understanding of which structural and mechanical properties are crucial for strength and ductility becomes imperative for enhancing the manufacturing and forming processes of paper. The challenge lies in developing a model that encompasses all of these influential factors, allowing its application across various processes. However, creating a perfect model with such universal applicability remains impractical at present. Researchers face the arduous task of navigating a multitude of considerations when selecting or creating a model for specific purposes. Criteria such as accuracy, precision, model execution and response time, robustness, flexibility, and knowledge gain play vital roles in this decision-making process (Volk *et al.* 2019).

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