Stiffness

After grammage and thickness, stiffness is the next most important property that a paperboard specifier usually considers when choosing paperboard. Stiffness is particularly important when determining the correct grade of paperboard for packaging applications.

It is stiffness that enables paperboard to be used for a wide range of packaging and graphical applications. Without stiffness paperboard would not be able to perform its primary function of providing the packaged contents with physical protection.

Stiffness itself also relates to other strength properties such as compression strength, toughness, creasability, foldability, etc. It is, however, in itself a very individual property which is easily measured, although less easily understood in terms of its interaction with other parameters.

To the converter or end user, stiffness is a critical parameter which impacts heavily on conversion and packaging line efficiency. Maximum stiffness has to be achieved at the lowest possible grammage and thereby cost, whilst maintaining a consistent and uniform level. Beyond the packaging line, stiffness continues to play an important role in the distribution chain right through to the retailer and then the consumer.

To the paperboard maker, stiffness is one of the major considerations during manufacture and production conditions are carefully controlled to ensure maintenance of the specified values. Much effort has been expended in designing the product to ensure that the chosen fibre composition and structure offer the most cost-effective route to achieve the desired, and most consistent, performance.

Stiffness characteristics

Stiffness is defined as the paperboard’s resistance to bending caused by a given applied force.

Stiffness can also be defined as a measure of the force which must be applied to deflect a defined piece of material through a defined distance or angle. This definition is applied to the most generally accepted methods of stiffness measurement.

High values of stiffness can be achieved with high thickness and a high modulus of elasticity concentrated in the outer layers of a multi-ply sheet. High tensile stiffness in the surface plies is of great importance for enduring the stress applied during bending. The elastic properties are greatly influenced by the type of fibre used. Long fibres from chemical pulp make it possible to have good bonding and hence a high elastic modulus, and are most efficiently utilised in the outer plies of the paperboard. The type of fibre also influences thickness, for example mechanical fibre creates higher bulk when used in the centre plies. This approach to increasing stiffness can be compared to the I-beam principle, which offers a higher rigidity per unit weight when compared with a solid cross section. The various layers of fibres have to be well bonded together for optimum utilisation of the fibre characteristics.

Different paperboard ply constructions

When choosing between different paperboard products, an important consideration is to analyse what happens when a sheet of multi-layered paperboard is bent. The layers on the convex side are extended and those on the concave side compressed. There is also an intermediate surface called the neutral plane where no change in length occurs. It is the resistance of the surface layers to this extension and...
compression, as measured by their modulus of elasticity, which significantly influences the stiffness of the sheet.

A high modulus of elasticity is achieved by the use of pure, bleached, chemically separated cellulose pulp produced from wood species such as spruce and pine. The pulp contains relatively long fibres and achieves excellent fibre to fibre bonding during consolidation on the paperboard machine.

**Elasticity**

Elasticity is the physical property that enables a material, in this instance paperboard, to regain its original shape when the applied stress is removed. The elastic limit is the maximum stress which can be applied before the material is permanently deformed. These concepts apply to the strength of all solid materials, including paperboard.

They are summed up in Hooke’s law which states that for small deformations up to the elastic limit, involving both compression and extension, the stress is proportional to the resulting strain:

\[
\text{Stress} = E \times \text{Strain} \\
/ \quad \downarrow \quad \downarrow \\
\text{Applied force} \quad \text{Dimensional change}
\]

where \( E \), the constant of proportionality, is called the elastic modulus or Young’s modulus, expressed in N/m\(^2\) or Pa.

Every material, such as steel, glass, plastic and paperboard has a defined modulus of elasticity depending on composition.

Stiffness itself, as defined above, is the resistance to bending caused by an externally applied force. This is related to the modulus of elasticity and thickness by the expression

\[
\text{Stiffness} = S = \text{Constant} \times E \times t^3
\]

The cubic relationship is valid for homogeneous materials provided the elastic limit is not exceeded. For Solid Bleached Board and Folding Box Board the index is in fact slightly lower than 3, at about 2.5–2.6. Hence stiffness depends very much on thickness. For example, if the thickness of a given grade of paperboard is doubled the stiffness increases by about 5.5 times.

The moisture content of the paperboard has a strong influence on the elastic modulus and hence on stiffness. A rule of thumb is that stiffness decreases about 10 % per 1 % increase in moisture content.

**Assessment of stiffness**

The property of stiffness relates to the way a material reacts to an externally applied force or strain. When stress is applied it produces a strain or dimensional change. This may be an extension or compression depending on the type of stress.

A large number of different procedures have been developed for the assessment of stiffness in paper products. Of these, some are more suitable for lower stiffness products (<150 g/m\(^2\)), e.g. the resonance method, and others for higher stiffness (corrugated or fluted material), e.g. the four point beam method.

For paperboard, however, there are four methods which are probably the most widely recognised:

- bending stiffness ISO 5628 (mNm) (L&W 5 °) (DIN 53 121)
- bending resistance ISO 2493 (mN) (L&W 15 °)
- bending moment ISO 2493 (mNm) (Taber 15 °)
- bending stiffness ISO 5629 (mNm) (L&W Resonance) (DIN 53 123).

Folding Box Board products are tested using the Taber method and measurements of bending moment are converted by a simple calculation into bending resistance.

Solid Bleached Board products are converted to Taber from bending resistance in the opposite way.

Since paperboard is an anisotropic material, measurements are made on strips cut in the machine direction (MD) and cross direction (CD) of the paperboard web. The stiffness ratio (MD/CD) gives an assessment of paperboard anisotropy.
**Stiffness**

**Definition of bending resistance and bending stiffness**
Bending resistance is the force required to bend a rectangular paperboard sample through an angle of 15°. Bending stiffness is calculated from the force registered at an angular deflection of 5°.

For the majority of paperboards a bending angle of 15° greatly exceeds the elastic limit. An angle of 5°, however, usually remains within the elastic limit, and is accepted as a standard value. Set-up accuracy is very important since a degree of error of only 0.5° will result in a measurement error of some 10%.

Bending stiffness, bending resistance, and bending moment are measured using the two-point method. In this method, one end of the sample is fastened in a clamp as shown below and the sample is loaded with force, \( F \), at a distance, \( l \), from the clamp. The sample then bends through a distance, \( \delta \).

**Explanation of terms**
Because paperboard is an anisotropic material, which means that the properties have a direction caused by the alignment of fibres in the machine direction (MD), it is necessary to make measurements of stiffness both in this direction and in the cross direction (CD). This directional effect will always result in higher stiffness values in MD than in CD.

Stiffness ratio is an expression of the relation between MD and CD levels of stiffness. The higher the ratio, the higher the MD stiffness relative to the CD.

\[
\text{Stiffness ratio} = \frac{S_{\text{MD}}}{S_{\text{CD}}}
\]

In order to express stiffness as a single value, it is possible to take both MD and CD values and calculate the geometric mean stiffness (GM) value, which is:

\[
S_{\text{GM}} = \sqrt{S_{\text{MD}} \times S_{\text{CD}}}
\]

GM stiffness is rarely used when specifying stiffness requirements but is useful when comparing products for absolute levels of stiffness and is particularly important when the carton design does not favour either direction. As a general rule, larger carton designs place greater demands on MD stiffness and small carton designs require greater attention to CD stiffness.

**Measurable properties**
Bending stiffness (ISO 5628)
Test method and equipment, PTE
Bending stiffness is commonly measured using a Messmer-Büchler stiffness tester. A 38 mm wide strip is clamped in the instrument and bent through an angle of 5°. The free end of the paperboard makes contact with a load cell and the force registered is proportional to the paperboard stiffness. The clamp is then turned through a further 10° and the force at 15° is registered as the bending resistance 15° in mN.

\[
\text{Bending stiffness} = \frac{60 \times \pi}{\pi \times \text{deg} \times b} \times \text{Bending force (5°)}
\]

(Units = mNm)
\( l \) = sample length (m) = 0.050
\( \pi \) = 3.14
\( \text{deg} \) = bending angle (°) = 5
\( b \) = sample width (m) = 0.038
therefore:

Bending stiffness = 0.2514 \times \text{Bending force (5°)}
(L&W 5°)

**Measurable properties**
Bending resistance and Bending moment (ISO 2493)
Note that it is not possible to convert from bending stiffness to bending moment or bending resistance with any degree of accuracy.
Bending resistance (L&W 15°) mN = bending moment (Taber 15°) mNm \times 20.70

**Definition of bending moment**
Bending moment is the product of bending resistance and the sample length to which a force has been applied to bend the sample through an angle of 15°.

Test method and equipment, Taber
Measurement of bending moment is done using a Taber stiffness tester. A 38 mm wide strip is clamped at one end and a force applied to the other to induce a 15° bend. The bending moment is read directly from the scale and corrected for the range weight used.

The mean value of readings taken in opposing directions is recorded and expressed in mNm.

Bending moment (Taber 15°) mNm = bending resistance (L&W 15°) mN \times 0.0483

Note: If Taber is expressed in gcm (gramme · centimetre) then: Taber in mNm = Taber in gcm \times 0.0981
The paperboard choice
Stiffness is probably one of the most commonly specified paperboard parameters and in this respect the converter or end user is given a significant amount of information.

Initially, however, the choice of stiffness is not so easy to relate to end use requirements. In the majority of cases this is done by experience. There are many complex theories available to assist the specifier with his choice but unfortunately most are beyond a simple explanation and can be affected by even minor changes in packaging or process design.

When specifying for a new end use or product, several factors must be taken into account. First are the weight and size of the product to be packaged, or, if it is not a packaging application, the strain that is to be applied to the material. Once this is understood the design can be finalised to take account of these factors. With cartons it is only possible to consider the stiffness after the shape and dimensions have been decided. At this stage it is important to emphasise that not all paperboards of the same grammage or thickness have the same stiffness, and a careful judgement must also take the desired print result and appearance into account.

Solid Bleached Board (SBB) offers excellent stiffness and strength characteristics per unit grammage of material. In contrast, because of their high bulk characteristics, Folding Box Board (FBB) products are able to offer very high levels of stiffness in relation to grammage.

As primary fibre products, both SBB and FBB, offer excellent consistency and reproducibility. They have distinct advantages when compared to high density recycled materials which cannot offer the advantage of 100% primary fibre contents, or high bulk characteristics, and thus give a low return on stiffness per unit grammage.

Key properties
Stiffness is itself a prime paperboard strength property that is relatively simply measured. Basic paperboard features that impact on stiffness are:

- grammage
- thickness
- bulk or density
- multi-ply and single-ply.

Other related properties that are closely linked to stiffness:

- tear strength
- tensile strength
- moisture content.

Moisture content can impact considerably on stiffness with high moisture levels significantly reducing stiffness. Conversely, a drier product will have improved stiffness. Other dependent properties include:

- gluability (spring back force)
- creasability.

Stiffness also has a major effect on the carton’s resistance to bulging.