Corrugated Fiber Board as a Packaging Material: Experimental and Numerical Analysis of the Mechanical Behavior

Chandra Sekhar Kattamuri, Madhukar Chatiri
Affiliations
CADFEM Engineering Services India Pvt.Ltd.

Abstract

Corrugated Fiber Board (CFB) is a sandwich structure in which several paperboard materials, linerboard is glued to a sine wave shaped core, flute/corrugated medium. CFB packaging is a versatile, economic, light, robust, recyclable, practical and dynamic form of packaging. Boxes made from CFB are commonly used for the packaging of consumer goods, where better resistances to compressive forces, higher bending stiffness, better printability and greater moisture resistance are the most important requirements. The boxes are routinely custom designed to meet specific customer requirements.

CFB along with Expanded Polystyrene foam (EPS) and wooden bars form the major part of packaging for the home appliances at BSH Hausgeräte GmbH (B/S/H/). Good packaging is essential for storage and safe transportation of home appliances. To ensure better quality packaging design, transport tests at B/S/H/ are carried out which consist of clamp, compression, impact and shunt. These tests ensure fault-free or limited damage to packaging, as long as shipment is made without damage to the home appliance.

Virtual product development based on finite element method is applied to variety of home appliances at B/S/H/. Especially, numerical simulation applied to transport tests at product area cookers resulted in providing good quality and cost-effective packaging for the cookers. Cooker packaging mainly consists of EPS and wooden bars and good numerical modeling knowledge is available for these materials. In particular, for chimney hoods, CFB is the most important packaging material. To apply transport simulations for chimney hoods effectively, good numerical modeling knowledge is essential for CFB.

The aim of this study is to understand the mechanical behavior of CFB and later develop a nonlinear finite element model which is accurate, computationally efficient and easy to model. In order to achieve this goal, two research areas are combined: experimental testing and numerical analysis.

The experimental tests are divided into three different levels. Basic test comprises in-plane uniaxial tensile and compression tests. These tests are carried out to determine the characteristic material behavior of paperboard materials. Specimen test comprises four-point bending tests (FPBT), edgewise compression test (ECT) and flat crush test (FCT). These tests are carried out to determine the mechanical behavior of CFB. Component test consist of box compression test (BCT). This test is carried out to determine the mechanical behavior of CFB box. These experimental tests provide in depth understanding of the mechanical behavior of CFB and also provide necessary material inputs which are required for an accurate numerical simulation.

A systematic and stringent verification and validation procedures are followed for the numerical simulations. The identified characteristic material behavior of paperboard materials is implemented into a commercial general-purpose finite element program LS-DYNA®.

Motivation and Problem Identification

CFB is a versatile material used in the shipping, distribution and storage of almost every product. Boxes made from CFB provide protection from compression forces for products in transit or stacked in warehouses. Today they are the primary type of shipping containers due to their salient characteristics namely, lightweight, inexpensive, scope to recycle and high stiffness-to-weight and strength-to-weight ratios.

One of the important applications of CFB is the packaging of home appliances. Home appliances being the necessity for a better standard of living, Bosch und Siemens Hausgeräte GmbH (B/S/H/) is determined to provide the consumers with genuine value addition in terms of performance, convenience and user-friendliness in their new products and the products being developed.

Storage and safe transportation of home appliances are important issues for B/S/H/ (see, Figure 1). There are series of events that occur after a finished appliance is packaged. Firstly, the appliance is clamped to transfer it to a warehouse, where it could be stacked for many days/months and subsequently when being transported to the vehicle, there is always a possibility of drop and clamp. During transportation, the appliance undergoes vibrations and the possibility of its drop continues until the appliance is delivered to the consumer. Transport tests at B/S/H/ consist of various tests such as clamp, compression, vibration, impact and shunt. Packed Appliance Transport Test (PATT) provides the internal guideline for transport tests and all finished products and accessories sold by B/S/H/ or the brand distribution channels (Bosch, Siemens, Gaggenau, Constructa, Neff and local brands) should fulfill these tests. After running the tests, the appliances must be fault-free and must not have any visible defects. Limited damage to packaging is acceptable, as long as the shipment is made without damage to the appliance.

Figure 1: Packaged home appliances at B/S/H//

CFB along with Expanded Polystyrene foam (EPS) and wooden bars form the major part of packaging for the home appliances. Good packaging is essential to protect the appliance from undesirable damages during transportation and provide the end user an undamaged appliance. Substantial costs are incurred by B/S/H/ every year for replacement and transportation damages. Thus, B/S/H/ is determined to provide a good packaging design which secures the appliance and minimizes the packaging costs.
Both the experts from packaging industry and B/S/H/ arrive at a solution that a particular packaging design is good for a particular home appliance. In particular for chimney hoods, CFB is the most important packaging

material. The packaging design for chimney hoods is in such a way that CFB strength is vital for the purpose of stacking (See Figure 2, top view – chimney hoods) and to withstand clamp and drop impulses. Better resistances to compressive forces, higher bending stiffness, greater moisture resistance, material damage and creep are the most significant requirements. Considering all the factors, 2.50 BC double-wall CFB (see, section 2.5) is selected for the packaging of chimney hoods. However, there is always a scope to improve the design and packaging of the appliances.

CFB Structure

The basic structure of CFB is shown in Figure 2, where the linerboard material is glued to a sine wave shaped core, corrugated medium or flute. The machine direction (MD) coincides with the fiber alignment of the paper and is perpendicular to the principal axes of the corrugated medium. The direction parallel to the corrugation medium is called the cross-machine direction (CD) and the through thickness direction is referred to as out-of-plane direction (ZD).

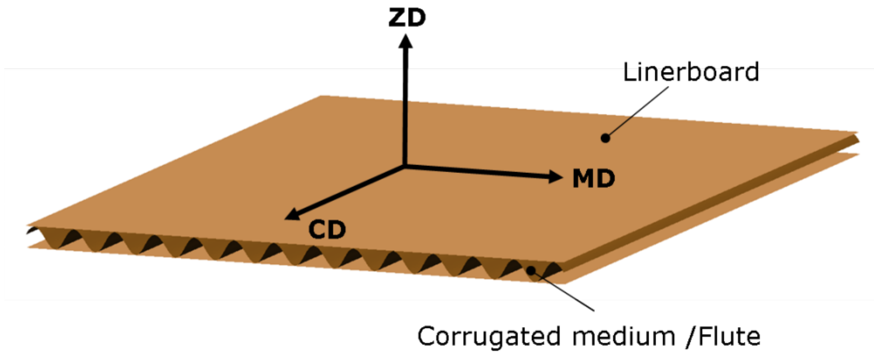


Figure 2: Basic Structure of CFB

The structure is an adaption of the engineering beam principle of two flat, load-bearing panels separated by a structure, in this case, flute. The structure resists bending and pressure from all directions. When the flutes help to support a stack of boxes and begin to bend in one direction, the tensile strength of the linerboard on the other side resists the bend.

CFB box flutes normally run from the top to bottom of a box, acting like columns to support the stack above. The flutes also act like arches, resisting flat crush, to provide cushioning trap air, and give some insulation properties. Thus, the compression strength in the CD, parallel to flutes, is very important which is directly related to box strength. To facilitate the tilling and dispensing of interior packages, boxes are sometimes stacked side-to-side or end-to-end or handled as unit loads by clamp trucks where MD strength becomes equally important.

Different types of adhesive such as water-soluble, cornstarch based are used to bond the linerboard and flute. Water being the biggest enemy of CFB, the moisture weakens the paper, the board structure and the board to debond, when it gets wet. In uses for products such as fish, vegetables where there is a high potential for water damage, the paper can be coated and/or impregnated with wax or plastic, and the board can be combined with water resistant adhesive. There has been much advancement in water resistant adhesives and treatments that do not cause problems in the recycling process.

CFB packaging offers almost unlimited possible combination of board types, flute sizes, adhesive types, treatments and coatings. It is routinely, custom designed to meet specific customer requirements. CFB is usually selected depending on the application.

2.50 BC Double-wall CFB

2.50 BC double-wall CFB which is used for the packaging of chimney hoods is the focus of this study. The structure and materials of 2.50 BC double-wall CFB are shown in Figure 3 and Table 1. In this CFB, 2.50

signifies the grade of the CFB, which is generally used for transportation purposes, BC double wall signifies the mixed flute double-wall/triple faced CFB with B-flute on the outside for its good flat crush resistance and better printing surface, and C-flute on the inside for its good cushioning and stacking strength.

Paperboard materials (see, Table 1) are used in the manufacturing process of 2.50 BC double-wall CFB. The most common way to specify the paper/paperboard is by grammage. It is the mass of the paper/paperboard per unit area. It is expressed in grams per square meter (g/m^2). The grammage for different paperboard materials used in 2.50 BC double-wall CFB is mentioned in Table 1.

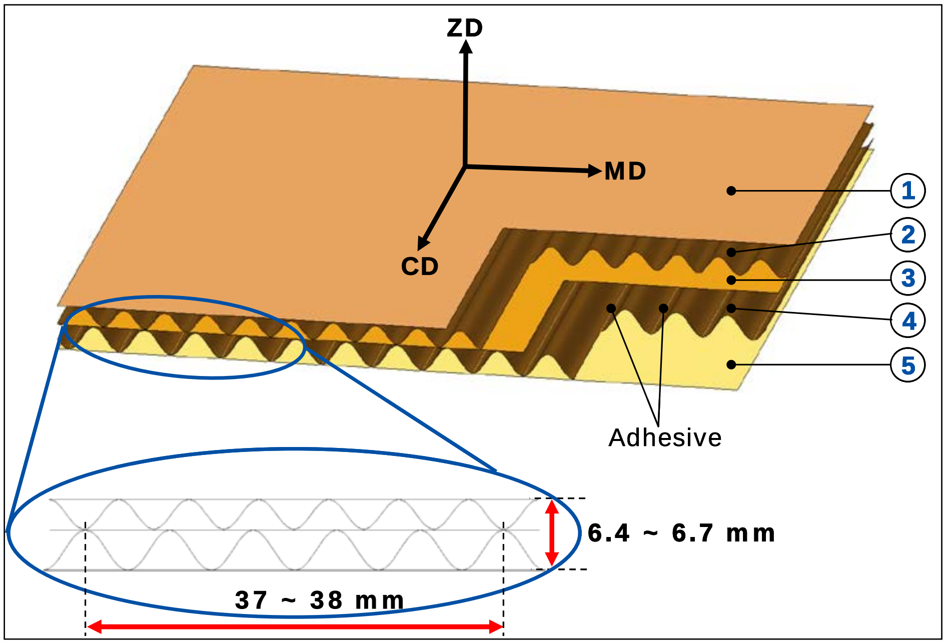


Figure 3: 2.50 BC double-wall CFB structure.

	Paperboard Materials	Industrial Name *(Suedwestkarton GmbH)*	Grammage (g/m^2)
1	Outer Linerboard	K – Liner 447	177
2	B-Flute	Wellenstoff 990	90
3	Intermediate Linerboard	Schrenz 10	100
4	C-Flute	Wellenstoff 990	90
5	Inner Linerboard	Testliner 519	190

Table 1 2.50 BC double-wall CFB materials

Methodology

In this study two research areas are combined: experimental testing and numerical analysis (see Figure 4). A very systematic and stringent verification and validation procedure is followed.

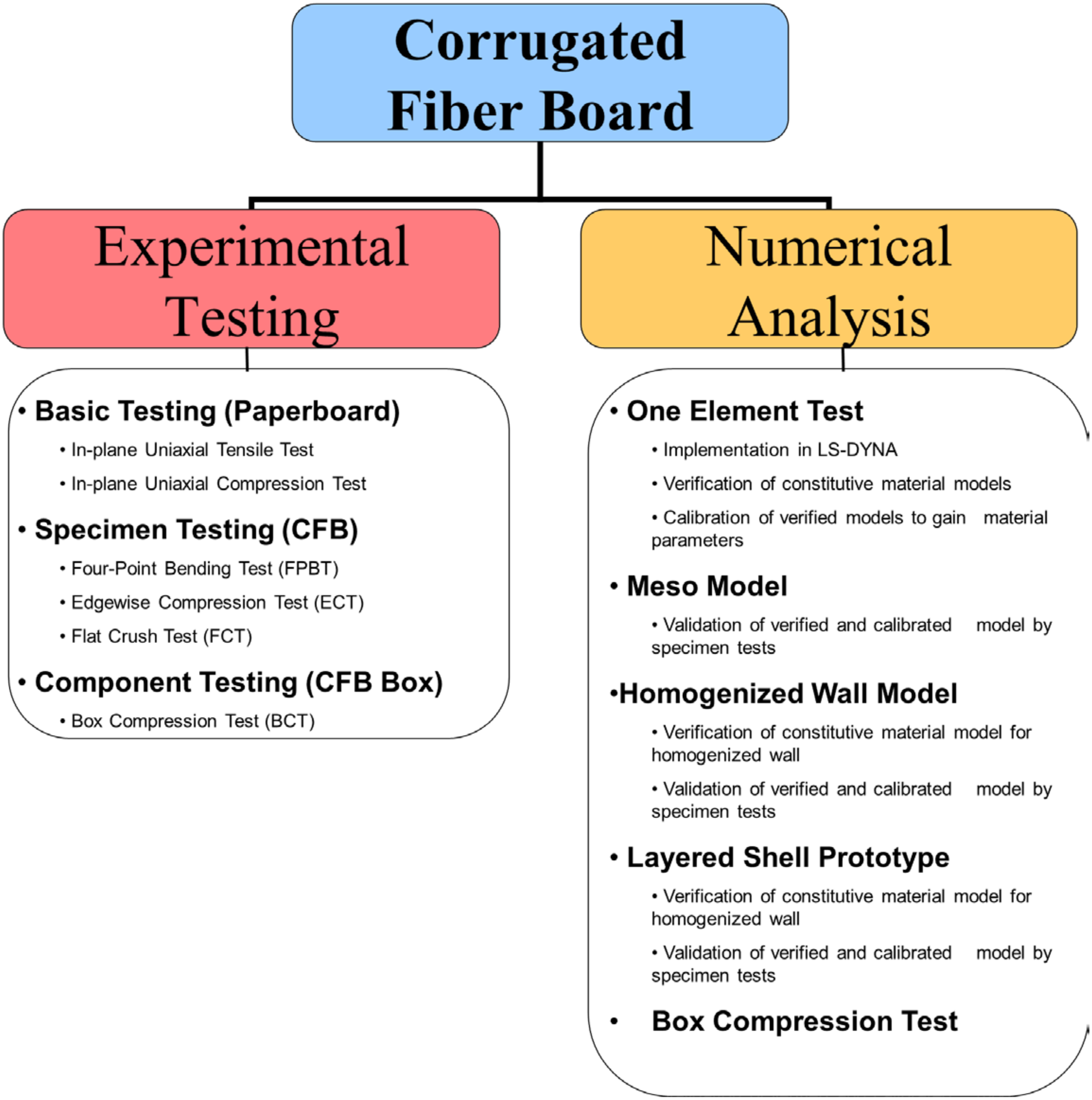


Figure 4: Methodology.

Experimental Testing

- **Basic Testing (Paperboard)**
  - **In-Plane Uniaxial Tensile Test**

The in-plane uniaxial tensile test is carried out on the conditioned samples according to the standard ISO 1924 – 2 with different choice of test piece widths. The specifications are shown in Figure 13.

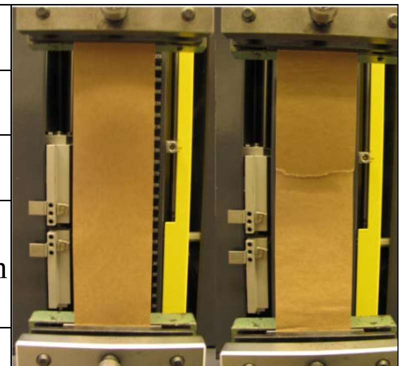
Type of Test	In-plane Uniaxial Tensile Test	
Standard	ISO 1924 – 2	
Loading	MD, 45^0 MD/CD, CD	
Geometry	180mm x *w*(*w*=15, 25, 50) in mm x t in mm	
Test Speed	12.5mm/min	Before After

Figure 5: In-Plane Uniaxial Tensile Test

Figure 6 shows the test samples before and after the test. The test is carried out until the material failure. The failure is observed almost at the center of the sample which according the standard ISO 1924 – 2 is correct and the test results from the samples with failure near the clamping position are rejected. The force-displacement data is measured during the experiment.

  - **In-Plane Uniaxial Compression Test**

The in-plane uniaxial compressive strength is considerably more difficult to measure than the tensile strength. It is through the development of the short-span compressive test (SCT) method by the Swedish Pulp and Paper Research Institute (STFI), in collaboration with the instrument development resources at Lorentzen & Wettre that this has become possible. The method is internationally accepted through the standard ISO 9895:2008. The specifications and the samples before and after the test are shown in Figure 17. Interestingly, debonding between the several pulp layers is observed in the paperboard materials.

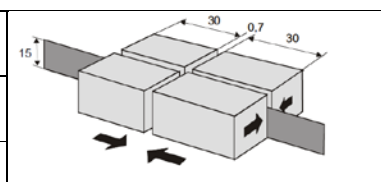
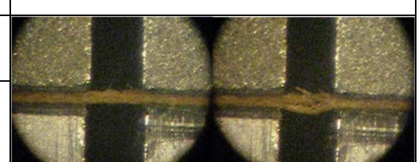
Type of Test	In-plane Uniaxial Compression Test	
Standard	ISO 9895:2008	
Loading	MD, CD	All dimensions in mm
Geometry	0.7mm x 15mm x t in mm	
Test Speed	3mm/min	Before After

Figure 6: In-Plane Uniaxial Compression Test

- **Specimen Testing**
    - **Four-Point Bending Test**

Bending stiffness is defined as the relationship between the applied bending moment and the deflection within the elastic region. According to McKee, the bending stiffness in both in-plane directions (MD & CD) of the CFB is very important for the compression strength of CFB box. Bending stiffness is closely related to the thickness of the CFB material and the ability of the outer and inner linerboard layers to resist tensile and compressive forces. The bending stiffness will dramatically change if the board thickness, the flute structure, raw material type or the grammages of the liner/flute materials are varied.

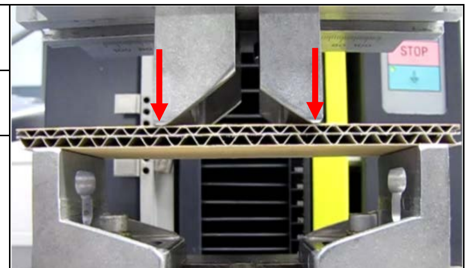
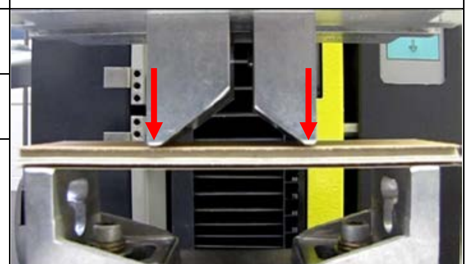
Type of Test	Four-Point Bending Test	 MD
Standard	ISO 5628	
Loading	B-Flute facing the loading anvils	
Principal Direction	MD, CD	 CD
Geometry	140mm x 40mm x 6.6mm	
Test Speed	12.5mm/min	

Figure 7: Specifications for FPBT – B-flute facing the loading anvils

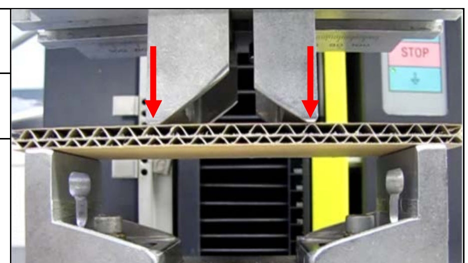
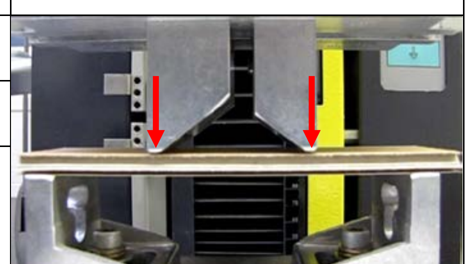
Type of Test	Four-Point Bending Test	 MD
Standard	ISO 5628	
Loading	C-Flute facing the loading anvils	
Principal Direction	MD, CD	 CD
Geometry	140mm x 40mm x 6.6mm	
Test Speed	12.5mm/min	

Figure 8: Specifications for FPBT – C-flute facing the loading anvils.

o Edgewise Compression Test

ECT is a direct measure to predict the top-to-bottom compression strength of a CFB box [2], because CFB box flutes normally run top-to-bottom when the box is loaded in the top-to-bottom fashion. Thus, the compression strength in CD is very important. ECT-CD is a standard test and widely accepted in the CFB industry. Though ECT-MD is not a standard test and not interesting in terms of CFB industry, this test is carried out because the measured data is useful in the numerical simulations. ECTMD and ECTCD refer to the edgewise compression strength in MD and CD of the CFB respectively.

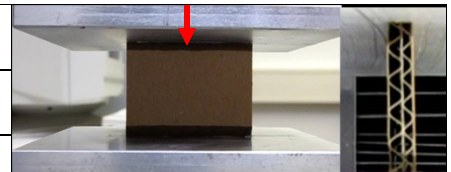
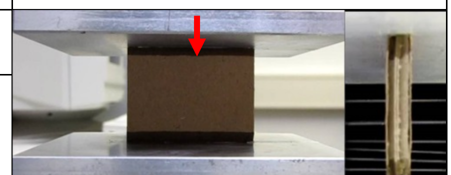
Type of Test	Edgewise Compression Test	
Standard	TAPPI T–811 om-07	
Principal Direction	MD, CD	ECT_{MD}
Geometry	51mm x 38mm x 6.6mm	
Test Speed	12.5mm/min	ECT_{CD}

Figure 9: Edgewise Compression Test

o Flat Crush Test

FCT is also an important material test, which measures the ability of CFB to resist compressive forces, normal to the plane (ZD) of the CFB. Low FCT resistance can reduce a box's compression strength because crushed board is less stiff and easier to bend.

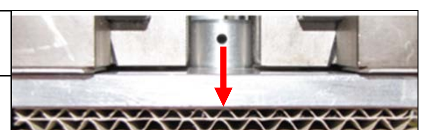
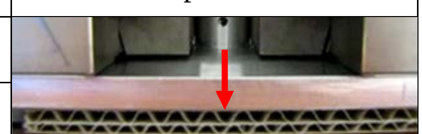
Type of Test	Flat Crush Test	
Standard	ISO 3035:1982	
Loading	B- and C-flutes facing the compression plate	B-Flute facing the compression plate
Geometry	100mm x 100mm x 6.6mm	
Test Speed	12.5mm/min	C-Flute facing the compression plate

Figure 10: Flat Crush Test

Numerical Analysis

A systematic and stringent verification and validation procedures are followed for the numerical simulations. The identified characteristic material behavior of paperboard materials is implemented into a commercial general-purpose finite element program LS-DYNA. The Numerical Analysis consisting of One Element Tests, Meso Modelling, Homogenized Wall Modelling, Layered Shell Prototype will be discussed during the presentation.

References

1. Packed Appliance Transport Test (PATT): B/S/H/ packaging guideline, 2005
2. **Schwer LE**: An Overview of the ASME Guide for Verification and Validation in Computational Solid Mechanics, LS-DYNA Anwenderforum, Ulm, 2006
3. **Haufe A, Duerkoop S, Frank T, Feucht M**: Verification and Validation Procedure for Constitutive laws in Crashworthiness Simulation exemplified on the Gurson Model, crashMAT, Freiburg, 2006
4. **LS-DYNA, Keyword Users' Manual**: Version 971, Release 4, Beta, LSTC, 2009
5. **DIN 55468-1**: Corrugated fiberboard-Part 1: Requirements and testing, 2004
6. **ISO 534**: Paper and board-Determination of the thickness of single sheets
7. **ISO 536**: Paper and board-Determination of grammage
8. **ISO 1924-2**: Paper and board-Determination of tensile properties, 2008
9. **ISO 9895**: Paper and board Compressive strength-Short-span test, 2008
10. **ISO 5628**: Paper and board Determination of bending stiffness by static methods – General principles, 1990
11. **ISO 3037**: Corrugated fiberboard-Determination of edgewise crush resistance (unwaxed edge method), 2007
12. **TAPPI T-811-om 07**: Edgewise compressive strength of corrugated fiberboard (short column test), 2007
13. **TAPPI T-838 om 07**: Edge crush test using neckdown, 2007
14. **JIS Z-0401**: Edgewise crush test method for corrugated fiberboard
15. **ISO 3035**: Corrugated Fiberboard-Determination of flat crush resistance, 1982
16. **ISO 12048**: Packaging-Compression and stacking tests using a compression tester, 1994
17. **Hörmann M**: LS-DYNA Introductory course, CADFEM GmbH
18. **Bois PD:** Crashworthiness Lecture script for master course "Applied Computational Mechanics", Landshut/Ingolstadt, 2009