IMPROVING CORRUGATED PACKAGE DESIGN WITH VIRTUAL COMPRESSION TEST

Lappeenranta–Lahti University of Technology LUT

Master’s Programme in Industrial Design Engineering, Master's thesis

2022

Susanna Heposalmi

Examiners: Associate Professor (Tenure Track) D.Sc. (Tech.) Ville Leminen

D.Sc. (Tech.) Amir Toghyani

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

LUT Mechanical Engineering

Susanna Heposalmi

Improving corrugated package design with Virtual Compression Test

Master’s thesis

2022

77 pages, 45 Figures, 6 Tables, and 4 Appendices

Examiners: Associate Professor (Tenure Track) D.Sc. (Tech.) Ville Leminen

D.Sc. (Tech.) Amir Toghyani

Keywords: finite element method, corrugated packaging, prototyping, compression strength

Physical and virtual prototyping are commonly used techniques to improve the product design process and product quality in the field of engineering. However, due to the complex mechanical nature of the corrugated board, which requires specific material models and finite element techniques, the corrugated board packaging industry has not been able to benefit from virtual prototyping on the same scale as the other industrial fields.

This case research investigates the advantages and disadvantages of physical and virtual prototyping with a focus on the effect of virtual prototyping on the design process, material optimization, and reliability. To examine these key parameters, the experiments toward design process, user experience, and prototyping outcome are implemented with comparative design processes in a corrugated board packaging company, where the finite element model-based tool has been developed to improve the product design process and product quality.

The results indicate that a virtually assisted product design process significantly reduces the product development time, enhances material optimization, and adds value to visual 3D content. The reliability of virtual prototyping was found to be acceptable in comparison with physical prototyping, however, to interpret any strength analysis results, a deeper knowledge of the subject and corrugated materials is needed in further research as well as model behavior validation with more complex corrugated designs.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Teknis-luonnontieteellinen

Konetekniikka

Susanna Heposalmi

Aaltopahvipakkausten tuotesuunnittelun parantaminen puristuslujuuden elementtimenetelmäanalyysin avulla

Diplomityö

2022

77 sivua, 45 kuvaa, 6 taulukkoa ja 4 liitettä

Tarkastajat: Apulaisprofessori (Tenure Track) TkT Ville Leminen

TkT Amir Toghyani

Avainsanat: elementtimenetelmä, aaltopahvi, laatikon puristuslujuus

Fyysisten ja virtuaalisten prototyyppien testaaminen ja tarkasteleminen ovat teollisessa suunnittelussa yleisesti käytettyjä menetelmiä tuotesuunnitteluprosessin ja tuotteen laadun parantamiseksi. Aaltopahvin monimutkainen mekaaninen rakenne vaatii kuitenkin yksityiskohtaisia materiaalimalleja ja elementtitekniikoita, minkä vuoksi pakkausteollisuus ei ole kyennyt hyödyntämään simulointitekniikoita kuten muut teollisuudenalat.

Tämä tapaustutkimus tarkastelee fyysisten ja virtuaalisten prototyyppien etuja ja haittoja keskittyen elementtimenetelmäsimuloinnin vaikutukseen suunnitteluprosessiin, materiaalioptimointiin ja puristuslujuuden mittaamisen luotettavuuteen. Tutkimus keskittyy suunnitteluprosessin, käyttäjäkokemuksen ja prototyyppien puristuslujuustestaamisen havainnointiin. Tutkimus on toteutettu vertailemalla fyysistä ja virtuaalista testausprosessia aaltopahvipakkauksia valmistavassa yhtiössä, joka on kehittänyt elementtimallipohjaisen sovelluksen tuotelaadun parantamiseksi.

Tulokset osoittavat, että simulointiavusteinen tuotesuunnitteluprosessi lyhentää merkittävästi tuotekehitysaikaa, tehostaa materiaalien optimointia ja luo lisäarvoa materiaalikäyttäytymistä osoittavan 3D-mallin avulla. Tutkittujen rakenteiden ja materiaalien elementtimenetelmäsimuloinnin luotettavuus todettiin hyväksytyksi, mutta lujuusanalyysin tulosten tulkitsemiseksi tarvitaan syvempää tuote- ja materiaaliosaamista.

ACKNOWLEDGEMENTS

Atticus (2017) once told: “Chase your stars fool, life is short.”

On the path chasing mine, I want to thank my family for enabling the journey.

I embrace my fellow students for the best travel companion, colleagues for the support, and my teachers and professors at the LUT for the best possible guidance on my way.

Thank you, what a journey it has been!

Susanna Heposalmi

Susanna Heposalmi

SYMBOLS AND ABBREVIATIONS

Roman characters

a	constant	
b	constant	
C	constant	
CTf	Sum of compressive strength of liners	
CTl	Sum of compressive strength of board	
f	force	[N]
FR	geometrical mean	
h	material thickness	[mm]
k	constant	
l	length	[mm]
S^b	bending stiffness	[Nm]
Z	perimeter	
w	width	

Greek characters

δ	maximum displacement	[m]

Superscripts

^{b}	constant

Abbreviations

BCT	Box Compression Test
CAD	Computer-Aided Design
CCT	Corrugated Crush Test
CD	Cross Direction
ECT	Edge Compression Test
EUPS	End-Use Performance Standard
FEA	Finite Element Analysis
FEFCO	The European Federation of Corrugated Board Manufacturers
FEM	Finite Element Model
FoS	Factor of Safety
IQ	Installation Qualification
MD	Machine Direction
OQ	Operational Qualification
PQ	Performance Qualification
SCT	Short span Compression Test
S4R	Four-node general-purpose shell element
UX	User Experience
3D	A three-dimensional shape

Table of contents

Appendices

1. Introduction

Every product design process includes different kinds of development and evaluation techniques such as sketching, prototyping, and physical testing. The development of computer-aided design (CAD) tools and the growing demand for fast and cost-effective product development process has increased the relevance of virtual modeling and prototyping.

The automotive and construction industry have benefited from virtual prototyping successfully for decades, however, due to the complex mechanical nature of the corrugated board, which requires specific material models and finite element techniques, the corrugated board packaging industry has not been able to benefit from computer-aided virtual prototyping in the same scale as the other industrial fields.

This research aims to determine whether the use of virtual testing instead of or with physical testing is essential also in the corrugated packaging product development process. The research evaluates the effect of virtual and physical prototyping on the product development process and assesses the validity and user experience of finite element model-based virtual prototyping with experimental studies. The process, timeline, and results of the traditional corrugated product design process are compared to the finite element model (FEM) assisted process.

Results are evaluated with four perspectives: the box compression strength testing, product development process analysis, reliability assessment, and user experience observation. The evaluation is made through controlled experiments in a corrugated board packaging company, where the finite element model-based tool has been developed to improve the product design process and product quality. Results of the study are documented and analyzed to create a discussion and conclusion.

2. Corrugated Product Design

Corrugated fiberboard is the world's most popular packaging material, which is used especially in transport packaging, but also in consumer packaging, sheets, containers, brochures, and wrapping material. There are almost endless possibilities to variate corrugated board recipes with different ply types, wave heights, and basis weights. Equivalently with recipes, also packaging can be designed in a unique way depending on product dimensions and required technical features. (Finnish corrugated board association 2018, 4-5.)

Despite all the possibilities, corrugated packaging design has also its limitations and challenges considering Computer-Aided Design (CAD) tools, optimal material choice, and prototyping. To understand better the root cause of these fundamental limitations, in the following subchapters corrugated board is presented in more detail as a material, as packaging products, and with the corrugated product design process.

2.1 Corrugated fiberboard as a material

Corrugated fiberboard can be considered as a sandwich structure made of orthotropic materials. Orthotropic means that the material has different properties on three perpendicular orientations: in axial, radial, and circumferential direction. Sandwich structure means that corrugated fiberboard consists of multiple plies of surface and corrugated sheets: liners and flutings. (Finnish corrugated board association 2018, 6-7.)

The function of the liners is to bundle the corrugated board layers together; fluting keeps the surface sheets at the desired distance from each other and makes the corrugated board strong and rigid. The adhesive, usually starch glue, joins the liners and the fluting together for a strong and rigid structure. The protective properties of the corrugated boards can be improved by treating them with different substances to provide a barrier layer or other special properties. (FEFCO Corrugated Packaging 2021c.)

Liners can be divided into kraft liners and testliners. Kraftliner is mainly made of virgin fiber, sulphate pulp. Kraftliner has a smooth surface, and its tensile and puncture strength are high. Testliners are made entirely or mainly of recycled fiber. The surface layer of the board is either virgin or recycled fiber, but the base layer is usually recycled pulp. The strength and stiffness properties of the testliner are weaker compared to the kraft liner but can be adjusted by using bigger basis weights of the material. (Finnish corrugated board association 2018, 8-9.)

Primary fluting is made of semi-chemical hardwood pulp. It retains the rigidity well in humid and demanding transport and storage conditions. Recycled fiber-based flutings are weaker in strength in comparison with primary flutings, but they are widely used in many commercial packaging solutions. (Finnish corrugated board association 2018, 9.)

2.1.1 Manufacturing of corrugated sheets

Raw materials achieve their mechanical material properties when corrugated to the board structures. Boards are processed as sheets which are manufactured with a corrugated board machine presented in Figure 1.

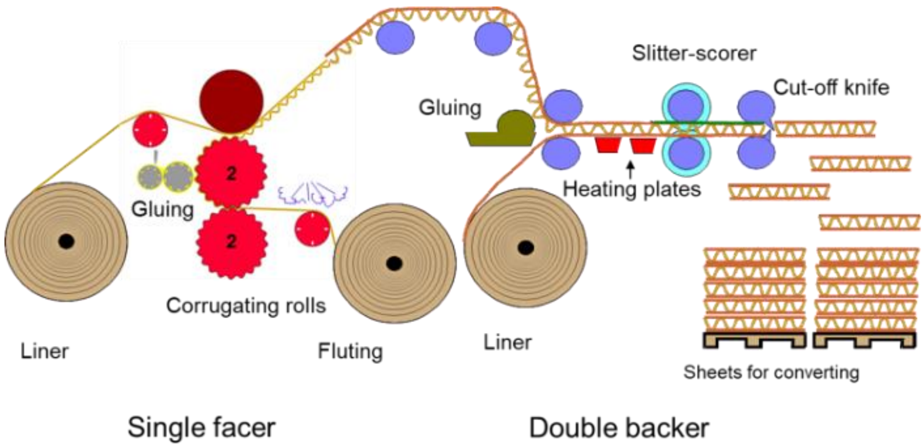


Figure 1. Corrugated board machine (Target Company 2019).

Corrugated board production begins with wetting of fluting and preheating of a liner. The pretreated fluting is pressed into the wave shape using hot corrugated rolls. Starch glue is applied to the corrugations of the fluting and the board is formed by attaching fluting with the preheated surface liners for both sides of the fluting. On the hot heating plates, the corrugated board dries, and the starch glue gelatinizes. After the grate, the corrugated board is cut into desired lines and, if necessary, driven machine direction bends. The cross-cutter cuts the tracks into sheets, which are stacked with automatic machines. (FEFCO Corrugated Packaging 2021a.)

2.1.2 Corrugated board types

In this research corrugated board is introduced as a single corrugated and double-corrugated board, though there are also triple corrugated and single-phase boards on the market. As presented in Figure 2, the single corrugated board consists of three layers: two liner layers as a surface layer, and fluting in between. A single corrugated board, known also as single wallboard, is considered the most popular packaging material. A double corrugated board, known also as double wallboard, is used in high-strength applications. It consists of five layers: two liner layers as a surface board, and of the two layers of fluting inside them and a straight layer of paperboard therebetween as seen in Figure 3. The strength properties of the board can be adjusted by changing the basis weights of used layers. (Finnish corrugated board association 2018, 6.)

Figure 2. Single flute board (Finnish corrugated board association 2018, 6).

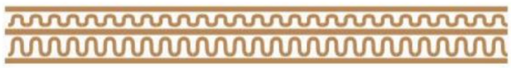


Figure 3. Double flute board (Finnish corrugated board association 2018, 6).

The thickness of the corrugated board can be determined with the corrugation height, or with the sum of the thickness of the used liners and flutings. Different board types based on the thickness are also presented through their wave profile presented in Figure 4 below. This research has a focus on materials of B, C, EB, and BC flutes.

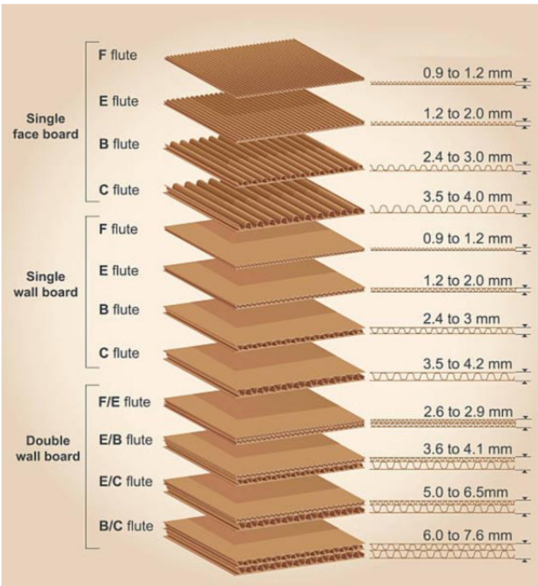


Figure 4. Wave profiles and thicknesses of corrugated board (iStock 2021).

Strength, stiffness, and the protective properties of double corrugated boards are usually better when compared to single corrugated boards. Especially stacking strength and durability of corrugated products can be improved with a thicker board. Increasing board thickness increases the basis weight of the corrugated board and through this end product weight. Different ways to determine the strength properties of the material and end product are presented shortly in chapter 2.4. (Finnish corrugated board association 2018, 6-8.)

2.2 Corrugated product design process

Corrugated products can be identified with the FEFCO code, which is an internationally used category numbering for corrugated packaging design. FEFCO system includes the design of almost 200 different kinds of commonly used, packaging types with a code numbering assigned to each design. Different FEFCO box types based on box style are presented in Table 1. (FEFCO Corrugated Packaging 2021b.)

Table 1: FEFCO box types and category numbers (FEFCO Corrugated Packaging 2021b)

Category number	Box type
0100	Commercial rolls and sheets
0200	Slotted type boxes
0300	Telescope type boxes
0400	Folder type boxes
0500	Slide type boxes
0600	Rigid type boxes
0700	Ready glued cases
0900	Interior fitments

Without going too technical detailed manufacturing descriptions, the 0200 and 0500 category boxes are slotted and side-glued with almost no waste, while the other category boxes have a more complex design manufactured with die cutter machines. In manufacturing processes, boxes can be printed for the requirements of transport, storage, sales, or international directives and regulations (Finnish corrugated board association 2018, 15).

The corrugated product design process starts with customer needs. The material selection of the packaging supports the geometrical strength properties of the package in all types of packaging. In general, the strength properties of the box can be specified in two ways. One way is to determine the compressive strength demanded from the box. The desired cardboard quality is chosen through mathematical calculations or experimental test results. Another way is to determine the edge crush test value (ECT) for the selected board.

In Target Company, the optimal material for the product is selected either according to customer information such as named flute, ECT, or End-Use Performance Standard (EUPS) value, or the decision is done by the designer with the best knowledge of the product. The material database provides the ECT and EUPS values for all the materials, which makes material choice relatively easy. However, the guiding factor for choosing material for a new product is often the knowhow: knowing if a similar product for similar demand has been done before, or if the material has functioned in similar products successfully. Generally, the design process follows the flow presented in Figure 5.

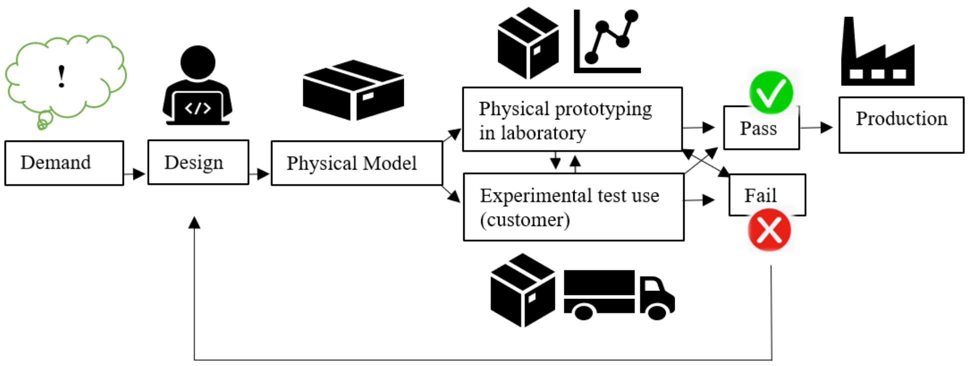


Figure 5. The corrugated design process includes a variety of development and evaluation methods.

The physical testing is time-consuming and thus rarely used if the design is not remarkably complex or new, or the application does not set special demands for the package. Though, it`s very common that the design´s functionality and suitability for the designed application are evaluated with physical models at the customer. If problems occur and re-design is required, it is more likely to run laboratory tests, especially if the comparative materials or designs are evaluated.

2.4 Physical testing of materials and end products

There are almost endless possibilities to variate corrugated board recipes, and equivalently with recipes, also packaging can be designed in a unique way depending on product dimensions and required technical features. In corrugated board production, raw materials, plies, corrugated boards, and end products can be tested to ensure the material and product quality according to the test presented in Table 2. As presented in Tables 2 and 3 below, many standards are regulating and guiding the testing processes.

Table 2: Containerboard tests and standards (Target Company)

Test	Unit	DIN	ISO	TAPPI
Short span Compression Test (SCT)	kN/m	54518	9895	T826
Corrugated Crush Test (CCT)	kN/m	x	16945	T843/T824
Tensile Stiffness	kN/m	53112	1924-3	x
CMT30 / First Peak	Nm	53134	7263	T809
Moisture	%	53103	287	T412
Cobb	G/m2	53132	7263	T441
Bursting strength	kPa	x	2758	

Table 3: Corrugated board tests and standards (Target Company)

Test	Unit	FEFCO	DIN	ISO	TAPPI
Compression resistance of the box (BCT)	N/kg	TM50	55440	12048	T804
Bursting Strength (BST)	kPa	TM4	53141	2759	T810
Flat Crush Resistance (FCT)	kPa	TM6	x	3035	T825
Edge Crush Resistance (ECT)	kN/m	TM8	53149	3037/13821	T811/T841/ T838/T839
Bending Stiffness	Nm	x	53121	5682	T820/T836
DST (Torsional Stiffness)	BPI	x	x	x	x

The most common corrugated board tests qualify the strength of the package. The connection between material and testing properties is presented in Figure 6.

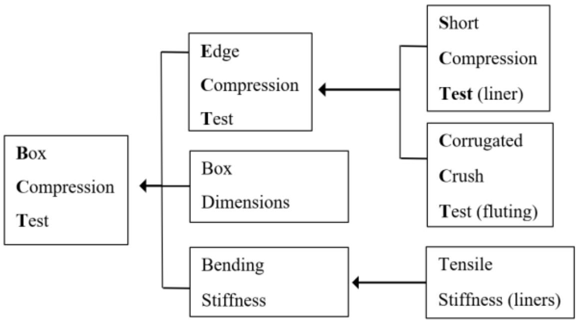


Figure 6. The connection between material and testing properties.

In the following subchapters, some of the principal tests of the corrugated material and product tests are shortly presented through aim, process, and mathematical equations.

2.4.1 Short span Compression Test

The Short span Compression Test (SCT) evaluates the maximum edgewise compression strength of boards and is especially used for testing liner properties. 15x60 mm piece of material is fastened with clamps when a middle segment of 0.7 mm is free, as seen in Figure 7. (Brandberg and Kulachenko 2020.)

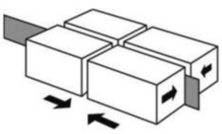


Figure 7. The SCT test (Clifford Packaging 2015).

A force-controlled program moves the clamps with a pressure of 5 MPa and documents the force applied both in the machine direction (MD) and for cross direction (CD). When the magnitude of the force at the time t is smaller than the magnitude of the previous load step, the test stops. The SCT value is expressed as kN/m. (Brandberg and Kulachenko 2020.)

2.4.2 Corrugated Crush Test

The Corrugated Crush Test (CCT) evaluates the edgewise compression strength of laboratory corrugated fluting in the direction parallel to the flute. According to standards, a rectangular test piece is corrugated between heated corrugating rolls. After the corrugator, the test piece is mounted vertically to the flute direction in a holder, and the crush test is subjected to a compression tester (Figure 8). The CCT value is a maximum compression force per unit length and expressed as kilonewton per meter [kN/m]. (SCAN P 42:81 2013.)

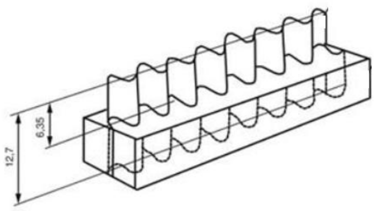


Figure 8. The CCT test (SCAN P 42:81 2013).

CCT value X [kN/m] can be calculated by dividing the maximum compression force by the length of the sample with

$$X = f/l \tag{1}$$

where f is maximum compression force [N] and l is the length of the sample [mm] (SCAN P 42:81 2013).

2.4.3 Flat Crush Test

The Flat Crush Test (FCT) estimates flute rigidity with the resistance of the flutes to a load applied perpendicularly to the top of the sample piece as seen in Figure 9.

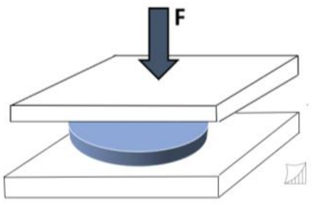


Figure 9. The FCT test.

FCT demonstrates the ability to resist damage to the packaging and through this helps to improve the material properties and packaging in general. The FCT value is expressed as kilopascals [kPa]. (TAPPI T 82 2014.)

2.4.4 Edge Crush Test

The Edge Crush Test (ECT), also known as Edgewise Compression Test, measures edgewise compression strength align to the flute direction of the corrugated board as seen in Figure 10. ECT test provides a deeper knowledge of the maximum overall load and stacking strength of the box.

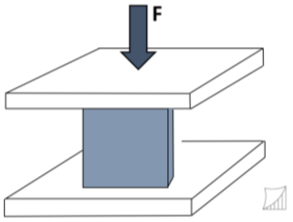


Figure 10. The ECT test.

ECT is measured by compressing a sample board on its edge, perpendicularly to the direction of the flutes, between two rigid plates. The compression is performed until the board collapses. ECT is measured with kilonewton per meter [kN/m] and can be counted with

$$ECT = k * (CTl + a * CTf) + b \quad (2)$$

where CTl is the sum of the compressive strength of liners, CTf is the compressive strength of the corrugated board, a is the corrugation factor of the wave profile, k and b are experiential constants. The peak load is expressed with kilonewton per meter [kN/m]. (Mecmesin 2020.)

2.4.5 Bursting strength

The bursting strength, also called the Mullen test, measures the force needed to burst or tear the corrugated board from one side. The value is measured by subjecting hydraulic pressure to the sample, in Figure 11, until it bursts. (ISO 2759:2014 2021.)

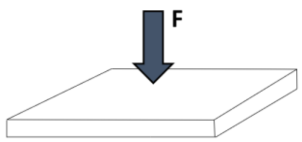


Figure 11. The bursting strength test.

The test predicts both the forces subjected to package in handling, but also the maximum weight the box can carry. The results are expressed as kilopascals [kPa]. (ISO 2759:2014 2021.)

2.4.6 Four-point bending stiffness

The flexural and cross direction rigidity of corrugated cardboard is measured with the four-point bending stiffness method. The bending stiffness value has a major role in determining the overall stacking strength and buckling resistance of boxes. The bending stiffness of the board is measured by bending the board against the counterparts at both ends of the sample strip with force F. The deviation of the center of the sample strip is measured from the horizontal orientation. The testing principle is presented in Figure 12 below. (ABB AB 2017.)

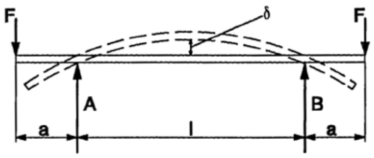


Figure 12. Measuring the bending stiffness (ABB 2017).

Four-point bending stiffness rate S^b [Nm] can be calculated with

$$S^b = \frac{F \times a \times l^2}{w \times \delta \times 8} \tag{3}$$

where F is the loading force [N], a is the distance of the loading point from the support point [m], l is bending length [m], δ is maximum displacement [m] and w is the width of the test sample [m]. (ABB 2017.)

2.4.7 Box Compression Test

The Box Compression Test (BCT), in Figure 13, estimates the strength and stackability of corrugated cardboard boxes. The packaging is loaded up to nominal load or to failure between two metal plates which, depending on used standard, are either both fixed or the upper plate is floating. (Frank 2013.)

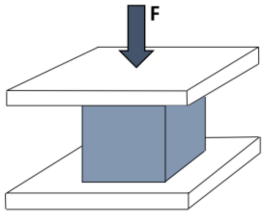


Figure 13. The BCT test.

BCT is measured in Newtons [N], and it can be counted with McKee´s equation

$$BCT = a * ECT^{b} * FR^{1-b} * Z^{2b-1} \quad (4)$$

where a is constant, ECT is edge crush test value of material [kN/m], b is constant, FR is the geometrical mean of MD and CD bending stiffness, and Z is perimeter of the box [mm].

Frank (2013) states that quick estimation of BCT value [N] can be calculated with the simplified McKee formula

$$BCT = k_1 \times ECT \times \sqrt{h \times Z} \quad (5)$$

where k_1 is the constant value, ECT is edge crush test value [kN/m], h is material thickness of the corrugated board [mm], and Z is box perimeter 2*(length+width) [mm]. The simplified formula does not take into account the effect of height on stacking strength, nor the relationship between length and width, but is commonly used if the bending stiffness of corrugated board is not known.

3. Finite Element Method

Zienkiewicz et al (2013, 2) define the Finite Element Method (FEM) as *"a general discretization procedure of continuum mechanics problems posed by mathematically defined statements*", meaning the FEM is a numerical method for solving differential equations. In turn, Finite Element Analysis (FEA) is the term for the analysis made with FEM.

FEM is based on a CAD model converting the original continuous problem into a linear group of equations by discretization. The complex problem is divided into small elements which enable describing and solving the problem with a mathematical model. FEM represents material properties, design geometry, and applied stresses, and is described by a set of small elements called an element mesh. (Lähteenmäki 2018.)

3.1 Creating finite element model

Shebab et al. (2013) state that in creating finite element models there are three preliminary stages: problem classification, discretization i.e. creating a mesh, and modeling. According to Syrjä (2019, pp. 103–106) the main points of this three-stage process are:

- simplification of geometry,
- dividing the structure into elements,
- simplification of material properties,
- simplification of boundary conditions,
- simplification of loads,
- verification of the accuracy of the model and its results.

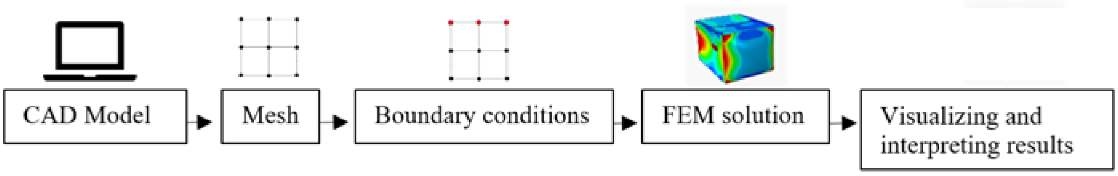


Figure 14. The developing process of a finite element model.

The simplified steps of building FEM are described also in Figure 14 above.

3.2 Physical prototyping vs. virtual prototyping

Due to the complex nature of corrugated board materials and design geometry, the physical BCT testing of the packaging is often the only way to ensure the packaging quality. However, as Biancolini and Brutti (2013) state, there is a wide distribution in box performance of the standard box compression tests, which often leads to overdesigning the products. The cause of the distribution of results is difficult to identify as the results are dependent on multiple different features such as geometry, raw material quality, manufacturing imperfections, humidity, temperature, and design geometry (Biancolini&Brutti 2013).

The corrugated industry is based on company-specific material management in which recipes vary even between different units of the company - though the plies used for materials are the same. It is also common that there are many suppliers for the same ply. Every supplier´s materials have unique properties which cause variation in material properties. In material management, the variation compensated with granted minimum values in strength and stiffness properties. Specific material management and variation in material properties make creating the shared CAD tool for virtual BCT testing challenging, and therefore the solutions currently on the market have been created based on the customized materials and needs of certain research institutes and private companies. (Jimenez et. al. 2009.)

The motivation behind finite element model tools in the corrugated board packaging design is to predict the behavior of corrugated boxes with varying designs, geometries, and comparative materials with reasonable accuracy. Robertson (2009) has stated that using virtual prototyping improves visualization and imparting of design. Due to the time consumption, unavailability of the laboratories performing BCT tests, and the complexity of the physical prototyping resulting in high safety margins or the opposite – insufficient strength and customer claims – virtual prototyping could improve the product quality, product design process, and customer experience.

In November 2021, paperboard producer Metsä Board Fibre released an article where they introduced the Dassault Systèmes' 3DEXPERIENCE based virtual prototyping technology. The article states that the technology will provide an even 85% faster product development process when compared to traditional processes. Metsä Board also stated that virtual prototyping decreases the carbon footprint of packaging and helps to manage the life cycle of the packaging by optimizing both the material and design of the products. (Sustainable Packaging News 2021.)

However, as Coutts and Pugsley (2018) have stated, using virtual prototyping does not completely exclude the need for physical prototyping which provides cognitive advantages and extra information such as practical functionality. Studies state that by implementing virtual prototyping in the product design process, the overall process time and costs of physical testing and material use reduction. However, virtual prototyping lacks interaction and does not completely exclude the need for physical prototyping (Coutts and Pugsley 2018).

3.3 Virtual Compression Test

The increasing demand for fast, modern, and low-cost product development processes has increased the development of virtual modeling and prototyping also among the corrugated packaging industry. As the importance of virtual prototyping has been identified in the target company of this research, the international project called Virtual Compression Test was launched.

Corrugated packaging is currently designed by using CAD software but testing the box strength is mainly performed with experimental tests which only a few business units of the company have available daily. In practice, every time the information of the strength properties is the package desired, the box undergoes physical testing demanding lots of effort and time. As the industry relies heavily on experimental know-how and real-life end-user tests, the lack of virtual testing leads to non-optimized box designs which can generate reclamations and a need for redesigning.

The objective of this project is to implement a FEM-based virtual prototyping tool using detailed virtual material models in the product design and product quality processes. With a digital tool, testing can predominantly be performed in a virtual environment. The tool enables designers and sales representatives to assess how different parameters in design and material selection impact the strength properties of the box without a physical testing procedure. The tool would also provide a possibility for comparative material simulation to observe the differences in the material and strength behavior under load. The objective of the Virtual Compression tool is to bring the benefits of FEM available to all stakeholders – designers, sales, and customers – without previous experience in finite element techniques. Traditionally utilizing FEM has required in-depth expertise in the subject, and therefore has set limitations for the use.

As Target Company operates both on a national and international level, the fundamental idea of the project is to provide the virtual prototyping tool equally available for all the business units. Despite the differences in material management between units, all the board recipes are based on the same plies everywhere which makes a shared database for materials possible. In addition to recipes, variations in used CAD programs should be harmonized.

Due to the challenges presented and for providing the equal possibility for virtual prototyping through business units, the parallel tool on the web application interface with server-side calculations was created. The web application provides virtual prototyping tools for everyone despite the used CAD without a need to obtain a license for users.

3.3.1 Virtual Compression Test - assisted product design process

In the simplest form, FEM assisted product design process follows the process presented in Figure 15. In the virtual prototyping interface, the design created is developed and tested with a finite element method model to ensure the strength properties. If the packaging passes the virtual test and the structure is simple enough that a physical prototype and additional testing are not needed, the packaging could continue directly to the production process.

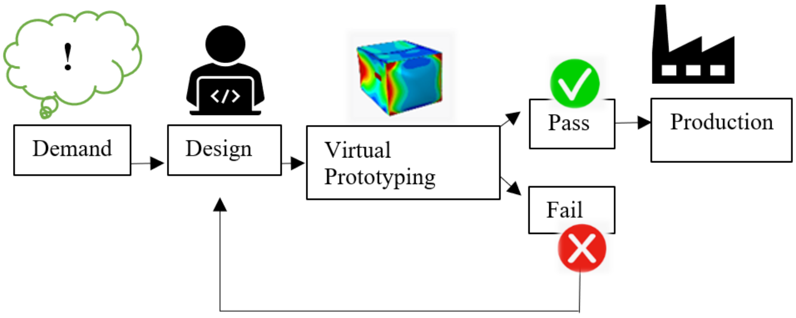


Figure 15. In the virtual prototyping process, the design is tested with the finite element method model to ensure the strength properties of the package.

The project group of the Virtual Compression Tools has estimated that on the monthly level the saved working time in person-hours would be around 10% per designer when the process is compared to the traditional product design process. However, it is important to evaluate how many other persons are involved in the experimental process besides the designer - laboratory staff, material management, logistics - to consider the saved total working hours.

3.3.2 User needs

The target group of the thesis is a pilot group of the Virtual Compression project. The pilot group consists of ten professionals with more than 5 years of experience in corrugated board product design, or in material and product management. To evaluate the functionality and suitability of the workflow of the Virtual Compression Test, fundamental user needs were specified through observing and interviewing the current workflow and design process steps of the pilot group.

To be able to operate and also benefit the most from virtual prototyping, the users should have the ability to:

- design and test standard boxes without excessive knowledge of or FEM
- design a customized packaging in Virtual Compression with a unique size, material, and special geometries
- import existing designs to Virtual Compression Test environment
- run tests with two or three different recipes
- compare test results between two different designs
- trust that the material information is up to date
- create new corrugated board recipes
- run tests with new recipes
- import and run virtual prototyping with reasonable time and workload
- read and understand test results without deeper FEM knowledge
- export test results
- be able to trust the results of virtual prototyping.

The defined user needs are taken into account as a part of the evaluation of the user experience and functionality of virtual prototyping applications, as well as in the application development process.

4. Methodology

In this project, FEM is used to solve the structural differential equation. Technically, the equation is solved by dividing geometry into smaller finite elements for which there are solutions, giving a large set of simpler equations. The structural FE problem solves from 3 to 6 unknowns and equations in each node – 3 forces and 3 displacements for all types of elements and additionally 2 or 3 moments and 2 or 3 rotations for shells. The inline moments and rotations are dependent on shell type. Inside the elements, the stresses and strain rates are solved in the integration points, also called Gauss Points. (Andersson 2022.)

The challenge in modeling corrugated boards is not only in the complex mechanical structure of plies but also in the corrugated board structure and their relation to failure modes. A corrugated board can be modeled in various ways depending on the scope. The more detailed is the model, the slower it is to build and operate.

Using composite shells enables fast calculation and utilization of Abaqus modeling scripts, therefore in this project finite element model is based on modeling composite shells. If other finite element models would be used, the demand for manual rework of the scripts and an increase in the calculation time from minutes to hours would occur. The objective of this chapter is to provide a general overview of simulation technology applied for virtual testing without going into a detailed description of the built finite element model.

4.1 Modelling the Virtual Compression Tool

Composite shell elements can be described as one element in thickness, which has different properties in the different directions with connecting Gauss Points. The composite shells can be also described as panels or planes. Figure 16 presents the setup of composite shell structure for a double board material.

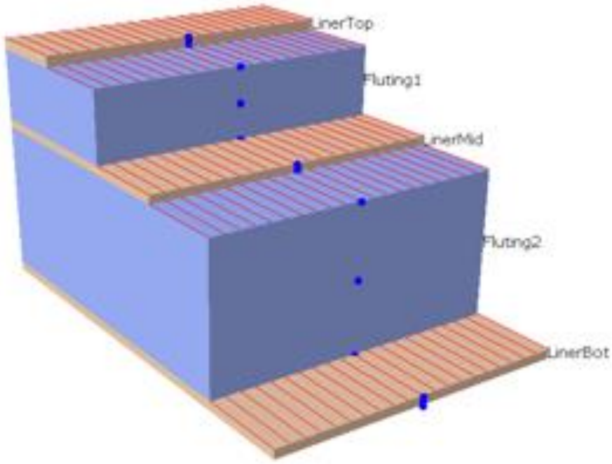


Figure 16. The finite element model is based on modeling composite shells. The figure presents a double board corrugated composite shell (Andersson 2022).

The model is based on Abaqus standard simulation where the specific material behavior for all possible loads and their combinations is defined based on standard board thickness and individual ply material master data. In designing, the board is the main element, but in modeling the material behavior is based on plies. The equivalent mechanical material properties of the plies are considered for a corrugated core geometry and the shell type is selected. In this project both single and double flute boards utilize general-purpose four-node (S4R) thick-shells with a global mesh size of 10 mm, which decreases in corners and crease lines.

In modeling, two different approaches are used: The Elastic and Plastic approaches. In the Elastic, linear elastic simulations are conducted, and the failure is estimated in the post-processing with the Tsai-Wu criterion. The Tsai-Wu criterion defines with which combination of stresses - shear stresses and normal stresses such compression and tension - the ply is estimated to fail. The criterion is built up with the strength data, where the most important value is the SCT, the CD compression strength. The behavior of the corrugated material is specified, though experimental data of the manufacturer lacks information. Due to the lack of ply data of compression strength in MD, tension, and shear strengths, the relationship between the model and the lacking data is estimated according to previous research of the subject. (Andersson 2022.)

In the Plastic approach, the failure criterion is estimated with the built-in Hill criterion available in Abaqus. The criterion is symmetric: it has similar strength properties in compression and tension, leading up to a bit conservative value in tension. Besides the failure criterion, the local buckling causing failure at loads significantly lower than for strength failure is evaluated in both approaches with the corrugation period, ply thickness, and stiffness. In the web application, the script extracts Tsai-Wu stress and plastic strain and presents it as a 3D model like in Figure 17 below. (Andersson 2022.)

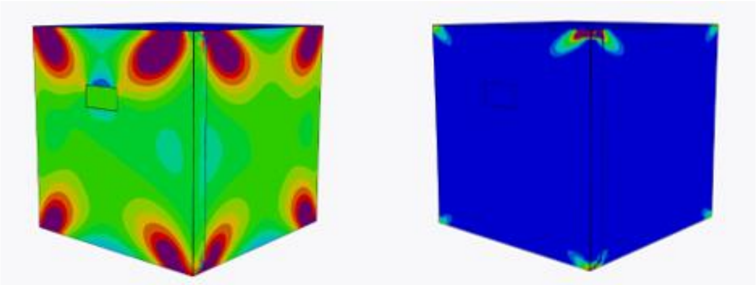


Figure 17. The virtual simulation presents both Tsai-Wu stress and plastic strain with a 3D model. The Tsai-Wu stress is presented in the figure on the left side, and the plastic strain is on the right.

In both approaches, the stiffness of the liners and flutings is modeled using the tensile stiffness data of plies. However, the shear behavior is more complex, and mathematical considerations of compression behavior are done for defining MD and CD shear. Despite the modeled FEFCO design, the compression behavior is based on the material models and their properties in design details such as creases and corners.

4.2 Technical functionalities

Virtual Compression Test operates in web application interface served by Azure Web App, which also works as functional back end. The information – design, special geometry, material, and box load – is entered into the application. To store the user information such as calculation queue, recipes, and test results, Cosmos DB is used as a data storage. (Target Company 2021.)

Calculations are based on the FEM analysis tool called Abaqus, which was chosen as the "analysis-engine" software for FEM for its easy approach to integration with Python script. Abaqus contains simple model construction, test execution and visualization, and very simple test management. (Target Company 2021.)

Web application communicates with Abaqus through Windows Service using REST API developed for this purpose. When the calculation is ready, Abaqus outputs the result to a specified directory, which is polled by the Windows Service, and the results are read, interpreted, and sent to the Azure backend. (Target Company 2021.)

4.3 Validation

The functionality and reliability of the tool are evaluated from many perspectives before the Virtual Compression Test can be successfully deployed. In consideration of the evaluation of the Virtual Compression Test, the process can be divided into verification, validation, and user experience.

Verification is an evaluation of FEM development´s intermediary work products and reviews whether the results correlate to the conditions set at the beginning of the project. In the project, verification is performed by a software supplier, who creates the Abaqus-based FEM model and is therefore not discussed further in this study.

Validation, in turn, evaluates if the final product meets the Target Company`s user needs. It involves excessive testing of process and sub-functions which are observed and evaluated to verify the process functionalities. Evaluation is made in two different perspectives: first, the Virtual Compression Test is observed as an individual tool, and second, through comparison to the traditional product development process and physical prototyping.

In addition to verification and validation, also user experience is evaluated to ensure that the set user needs are fulfilled, and the functionality and visuality of the tool support both the design process and reliability of the results.

4.3.1 Validation process

Thacker et al. (2004, 40) define the motivation behind validation as "*to quantify confidence in the predictive capability of the model by comparison with experimental data*". The validation of the Virtual Compression Test is made with experimental validation.

The purpose of experimental validation is to document and demonstrate if the tool is modeled correctly, and operates according to set requirements. The validation process can be described in many different ways. In Figure 18 the validation is presented as an experimental validation comparison between physical and virtual processes; in Figure 19 validation steps are introduced as a validation pyramid.

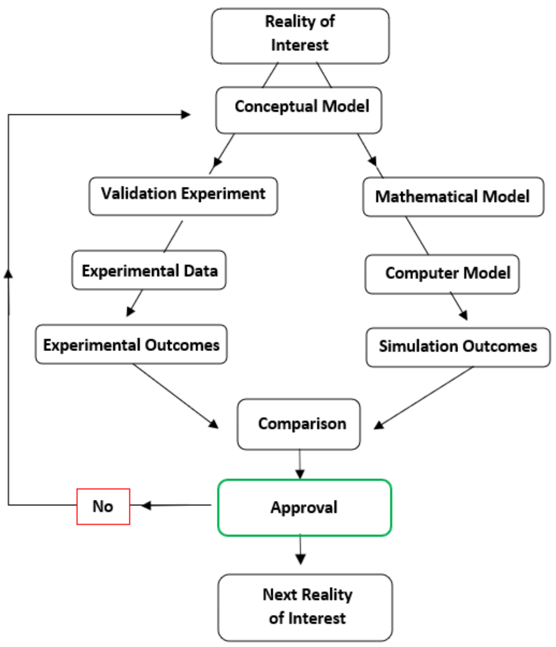


Figure 18. The experimental validation process evaluates application approval in the comparison between experimental and mathematical modeling processes.

Experimental validation compares the results of the physical and virtual prototyping outcomes; however, the process also includes evaluation of internal process steps including verification of computer model, FEM.

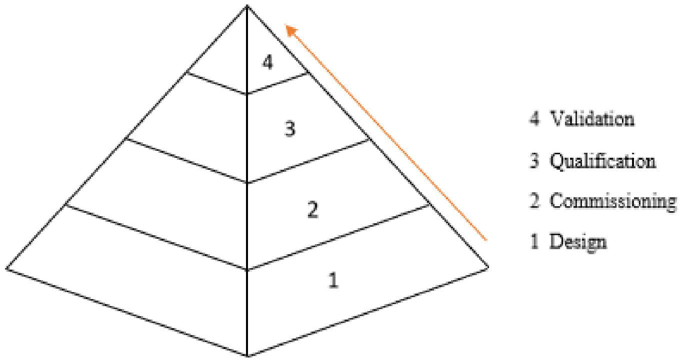


Figure 19. The validation pyramid is a four-step-process consisting of design, commissioning, qualification, and validation.

The validation pyramid is a four-step- process, which consists of the design phase, commissioning, qualification, and validation. On the design phase specifications towards functional and user requirements, and plans towards quality, project, and validation are made. In the commissioning phase, the tests measuring operability and user acceptance of the tool are made. In the qualification phase, the installation qualification (IQ) and the operational qualification (OQ) are evaluated to achieve the performance qualification (PQ). On the highest peak is the validation, which gathers all the information together for the final acceptance – or refusal. (Burkett 2021.)

4.3.2 Research methods for experimental validation

The research methods of the experimental validation acceptance are divided into quantitative and qualitative methods, though, the same design and testing processes were evaluated with different perspectives and approaches resulting in both numerical and textual information.

The qualitative methods applied in this research were individual interviews combined with behavioral observations. In practice, the everyday work of the target group was observed, and interviews were used to illustrate verbally the motivations behind actions. Due to the variation of work assignments between individuals, a shared design experiment was implemented to be able to compare the processes with similar input data. As the designer´s behavior, approach, and design process were all evaluated at the same time, both quantitative and qualitative data were achieved from the research.

In addition, the observation study was used to outline best practices better, related to the design process and physical prototyping, and especially towards possibilities of virtual prototyping. The findings of the simulation development and target group observation research were tested with user tests of developed Virtual Compression Test web application tool to ensure a high-quality user experience.

The quantitative research focused on comparative research of physical and virtual BCT testing, which was evaluated through mathematical results values and graphs. Additionally to BCT, the effect of humidity on strength properties was observed.

4.4 User Experience

User experience (UX) has an active role in whether the new applications become useful tools for everyday use and makes user-centered design and user interface design significant when implementing new tools for the design process. User Experience can be defined as the sum of emotions, sensations, and responses a person experiences when interacting with different kinds of products and services. ISO 9241-210:2019 standard defines UX as *“The collection of perceptions and reactions of a user, deriving from the use or expectation of a product, system or service.”* User Experience as the design perspective helps to gain a deeper understanding of users and their needs, abilities, values, and also limitations. The most important thing is to understand the context of use and its relation to the user’s needs.

ISO 252010:2011 defines user experience satisfaction with four attributes of the use quality: usefulness (ergo cognitive satisfaction), pleasure (ergo emotional satisfaction), comfort (ergo physical satisfaction), and trust (safety-related satisfaction). The factors influencing different User Experiences are often described as models or diagrams such as in Figure 20. For achieving a good -valuable and meaningful- user experience, a product or service must be useful, desirable, usable, valuable, accessible, credible, and findable.

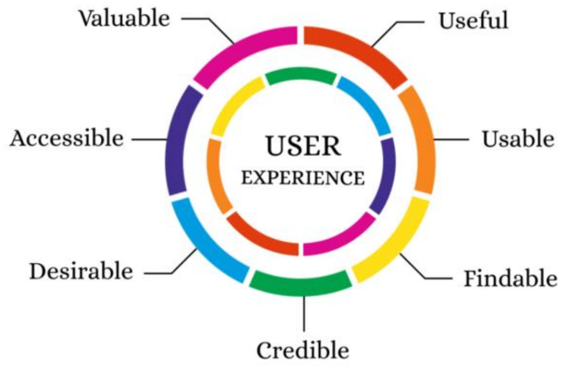


Figure 20. Valuable user experience includes several indicators. (Costa 2022).

In the means of product or service

- useful means that it needs to fulfill a defined need
- desirable evaluates that the design elements evoke emotion and appreciation
- usable means simply easy functionality
- valuable means added value both for business and the customer
- accessible involves that content is accessible to people despite any disabilities
- credible relates that the user trusts and believes what you honestly tell for them
- findable that the product or content needs to be easy to find. (Interaction Design Foundation 2021.)

The user experience of the virtual prototyping tool was evaluated through experimental user tests where the design task of designing 0201 with special geometry was given, and the process was guided verbally. The aim was to give short instructions to the user for proceeding with the virtual tool and to observe how the user finds the functionalities in the application. The functions followed the design steps presented in chapter 6.4 but the freedom to choose the design and geometry was left for the user.

Observational and verbal feedback of the usability of virtual tools is evaluated further in the following chapter through visuality and technical functionality.

The research was evaluated and analyzed not only through test reports but also by observing the test process and its development. Many changes related to the user interface and finite element model were made during the process, and this analysis reviews the ones most significant in terms of technical functionality, reliability, and user experience. Between model and layout improvements, several simulations were run but due to the relevance, not all the simulations results are not showcased in this study.

5. Results and discussion

The research aiming at the validation can be divided into four main steps: BCT testing, reliability assessment, process analysis, and user tests.

BCT testing included both physical and virtual tests for single and double flute boards, in addition, the effect of humidity conditions on strength properties was evaluated. Process analysis observed the traditional and virtual design and prototyping processes through design experiments. The user experience was evaluated to ensure the functionality of the user interface of the virtual prototyping tool, and reliability was assessed by comparing processes and outcomes of the research areas.

5.1 Compression testing

The sample matrix of BCT testing included 18 ten-piece sets of different kinds of glued boxes with varying materials and special geometry. The test matrix is presented in detail in Appendix 1, Figure 21 presents a few example boxes.

The boxes were tested in two sets: the first set included single flute boxes and the second set double flute boxes. Information received from the first test set defined the materials and designs of the second set.

The selection of the materials was based on the strength properties: both light and strong recipes were chosen, as well as virgin fiber and recycled materials were evaluated. In this thesis, recipes are named after flute and grammage.

Figure 21. The sample matrix of BCT tests included different kinds of glued boxes with varying materials and special geometry.

The motivation behind box design choices was to test both commonly used standard FEFCOs and standard FEFCOs with added special geometry. The first test set used FEFCOs from slotted 0200 and ready glued 0700 series, and the second set used only slide-type FEFCO 0501 to minimize the number of variables in the design. The matrix of the double flute boards was defined after the single board tests were executed and interpreted.

The physical testing aimed to evaluate how adding special geometry such as handles, and ventilation holes affect the results, and what is the capability of simulation to repeat results and compression behavior.

5.1.1 Physical compression strength testing

The physical BCT testing was performed according to FEFCO TM 50 / ISO12048 for the set of ten boxes of each design with Techlab Systems VAL 50 compression testing machine (Figure 22). Before testing unassembled boxes were air-conditioned for 24 hours to reach the 50% moisture level. After air-conditioning, boxes were assembled without any fitting and loaded one by one in stacking compression press between metal plates. The assembling of the box was done by one person, and the test was run by another person to ensure the similarity of the boxes and the immutability of the testing process.

Figure 22. Techlab Systems VAL 50 Box compression testing machine.

The floating upper plate was set with preload of 10N and moved down with 100 mm/min. The compression was performed until the 20 % deformation limit in height was reached, and the results were analyzed with the force-displacement curve. The test results are figured in Figure 23. In addition, photos of the assembled, crushed boxes were taken and the areas of the physical changes of the boxes were highlighted with a marker to be able to visualize the changes in the documentation.

Deformation was evaluated also visually by continuing the crushing of the last box of the set by increasing the performance limit to 80 % to observe the physical changes in design under load. To be able to compare the changes during the compression for the virtual prototyping process, the deformation of the boxes was filmed.

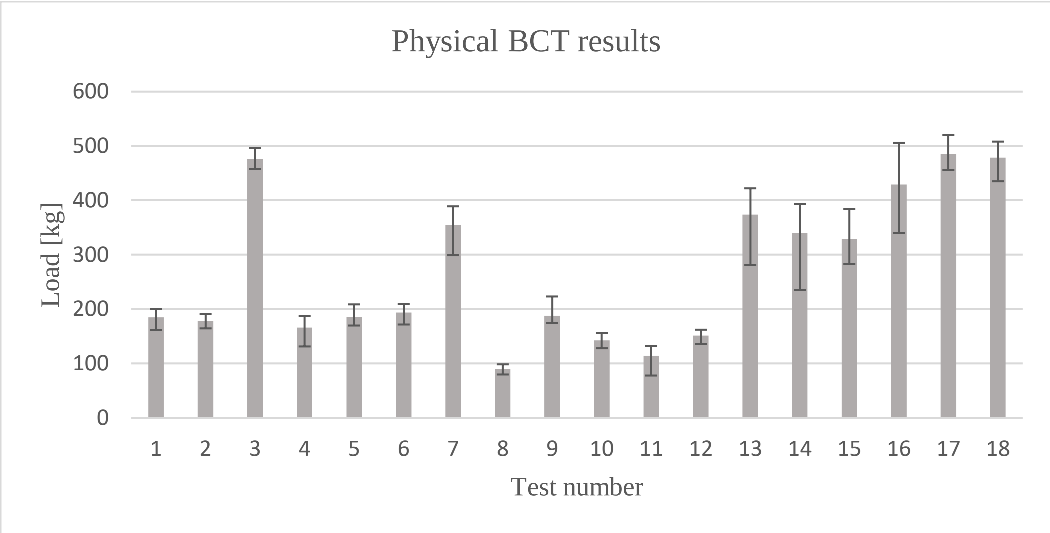


Figure 23. Physical BCT results present the mean load with an error bar indicating the minimum and maximum values of the test set.

Figure 23 presents the results with mean values and error bars indicating the minimum and the maximum values of the set. The technical drawings, individual test results, and force-displacement curves are presented in detail in Appendix 2.

5.1.2 Virtual compression strength testing

Virtual package modeling with the FEM-based application follows a four-step process. The basic information of the box is set on the first "General" stage (Figure 24) of the process. The basic information includes customer and test name, FEFCO code, inside dimensions, load on the box, and the board grade variant i.e. board grade and material recipe. The load on the box indicates the total weight on the lowest box of the pallet.

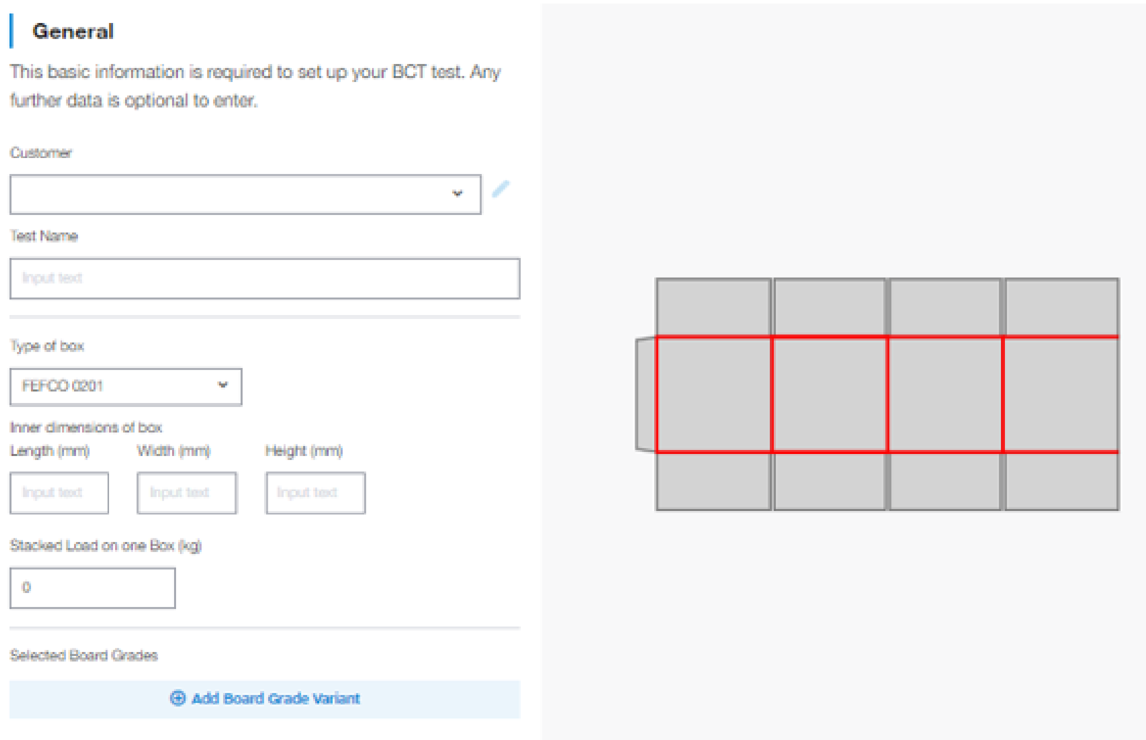


Figure 24. In the “General” tab of the virtual tool, the basic information of the box is set.

In adding a board grade there are two options: standard board and custom board. Anything from one to four recipes can be selected per simulation for material comparison. Standard board means choosing the material recipe from the existing material library; the custom board is for testing new recipes by creating the structure by choosing wanted liners and fluting(s) from the list according to the producer, ply name, and grammage.

The material library is defined through user settings and location which enables the selection of existing materials according to location but also brings an opportunity to build a custom recipe through manufacturer codes. In current applications, the plies have unit-specific shortcodes and to use a shared database, only ply manufacturer codes are used in the application´s ply identification. Despite selection, the information menu next to material selection provides calculated information such as grammage, thickness, and bending stiffness of the selected board.

In step two “Geometry” (Figure 25) the special geometry of the box can be implemented to box layout. The geometry tab includes a pre-set selection of handles, openings, and rule types to choose from and to scale to the wanted size and position.

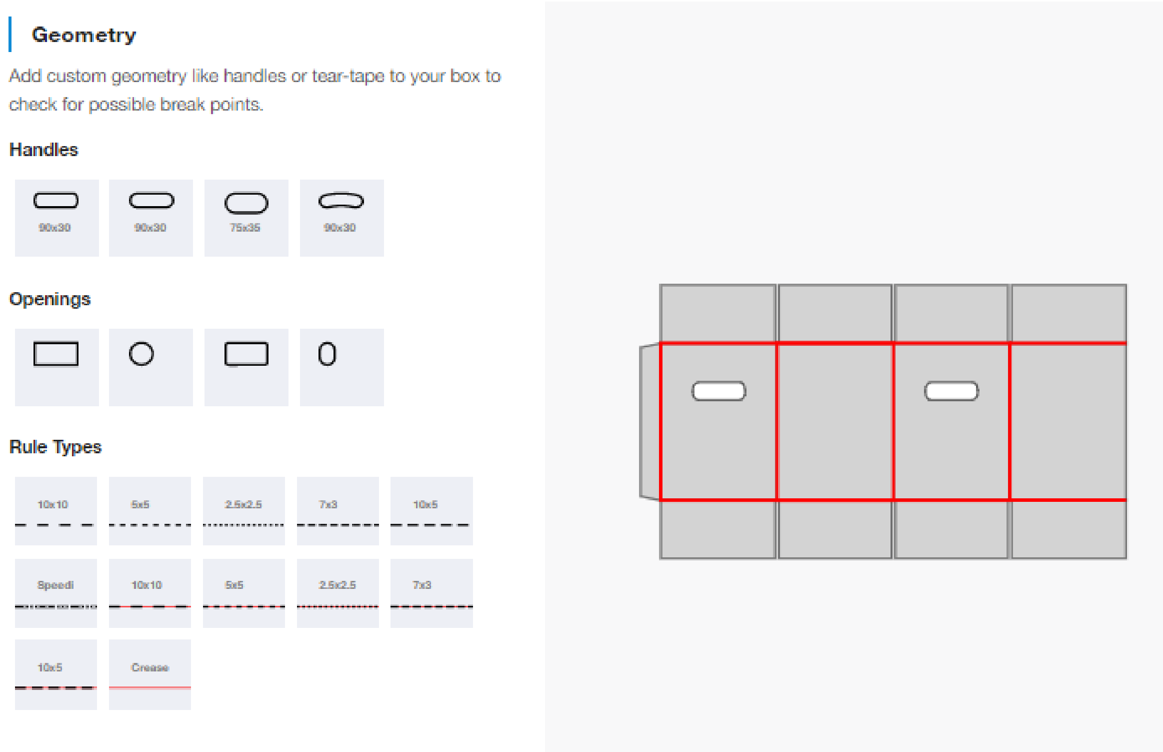


Figure 25. In the “Geometry” tab the pre-set selection of the special geometry can be implemented for the box layout.

In step three “Advanced” (Figure 26) there is a possibility to change production parameters of the analysis method and flute direction if needed.

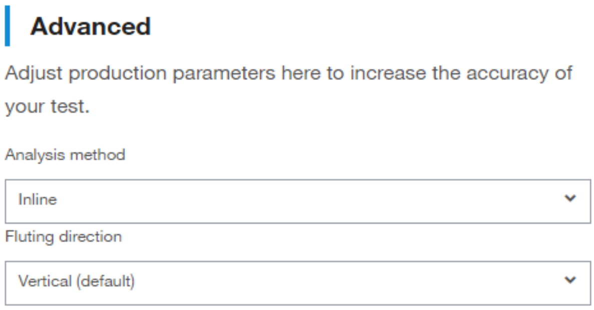


Figure 26. In the “Advanced” tab the production parameters can be controlled.

On the final “Options” step, the default settings of the safety factor and modeling approach can be changed. As a default simulation is using the elastic approach due to its shorter calculation time.

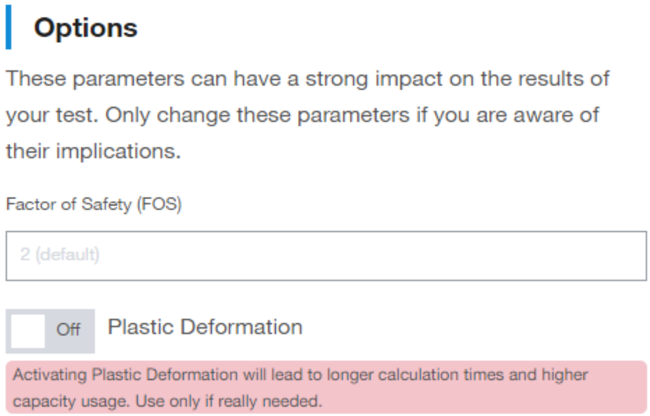


Figure 27. In the “Options” tab the default parameters of the calculation can be changed.

After the selections, the simulation is added to the calculation queue. Calculation time varies from two to ten minutes depending on the analysis method, number of comparative materials, and added geometrical details. The test results indicate if the box passes the strength requirements set for the box. The results are presented with a force-displacement curve, with mathematical figures, and with a 3D model.

The results of the first simulation test are presented in Figure 28. Figure 29 provides the information of the comparison between physical and virtual tests. The individual test results are presented in detail in Appendix 3.

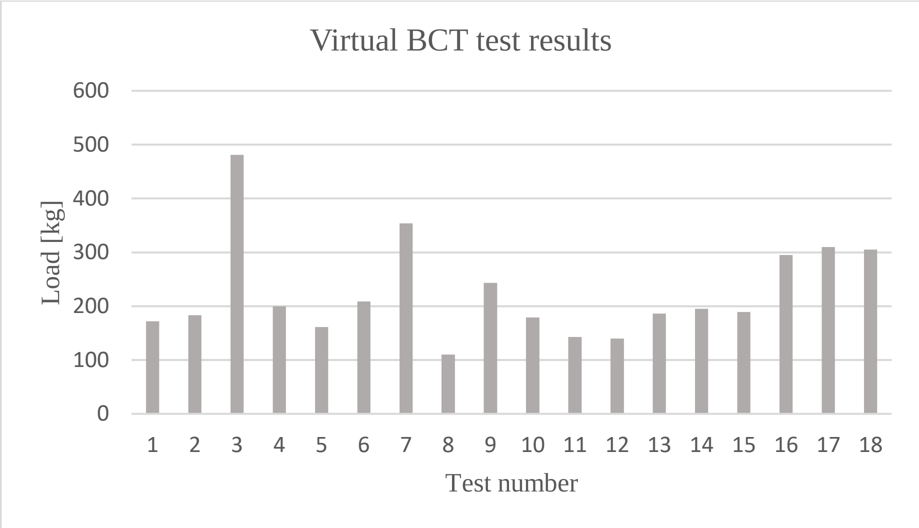


Figure 28. The virtual BCT test result presents the calculated maximum load of the box.

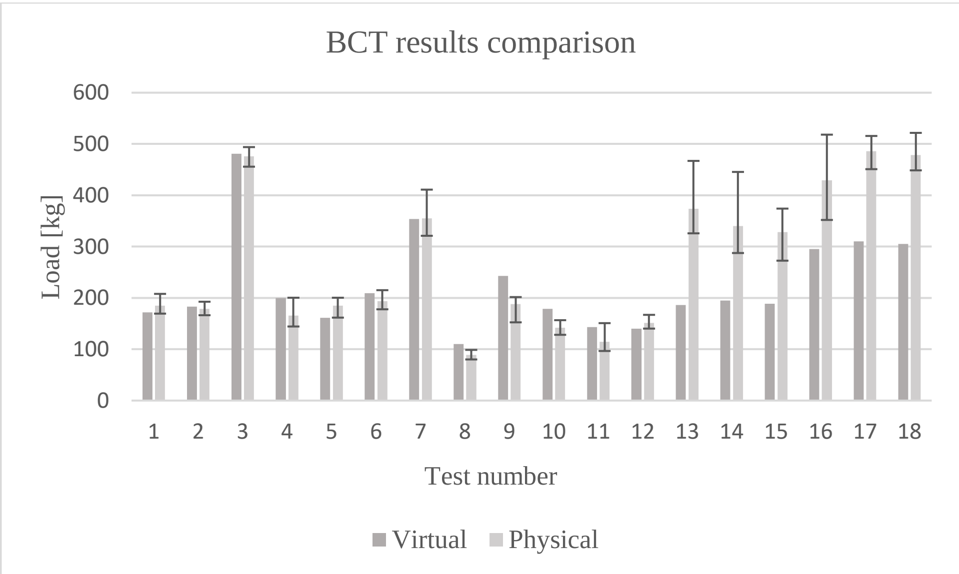


Figure 29. The comparison between physical and virtual tests indicates variation. In single flute recipes, virtual simulation overpredicts and double-board recipes underpredicts the maximum load.

The comparison between physical and virtual test results indicates variation in both single and double flute recipes. In single flute recipes, virtual simulation overpredicts the maximum load following the maximum load of the physical tests. In the double flute boxes, the maximum load virtual tool underpredicts the maximum load, providing even 40 % smaller results than a minimum load of the physical tests. Variation of the results indicates defaults both in the finite element model and in the user interface of the application.

5.1.3 Virtual compression tool development

Throughout virtual testing the predefined designs were able to replicate, though, after the first simulation tests some principle defaults in the technical functions and the layout were observed:

- in 0200 series boxes the panel order was L-W-L-W when it should have been W-L-W-L (Figure 30)
- in 0700 series boxes glue flaps were over-dimensioned (Figure 31)
- the lack of a grid or measurement tool led to the inaccurate of special geometry both in size and positioning (Figure 32)
- the positioning and calculation of crease lines was limited due to their geometry (Figure 33)
- the layout did not scale measurements according to used board types
- the material input of single flute recipes had defaults
- the transverse shear behavior of the double flute recipes was under-predicted
- the difference in strength momentum between boa boxes with flaps and without flaps was not captured correctly
- a four-step-process could be cut to three steps with rearranging selections.

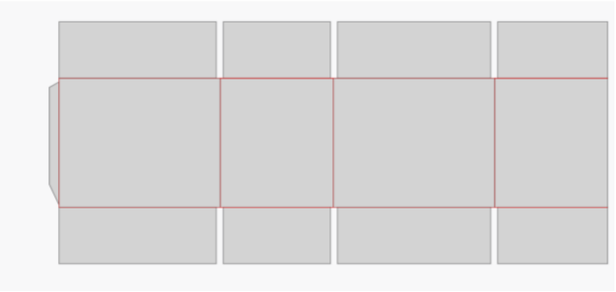


Figure 30. In the virtual tool, the length and the width measure of the layout were wrong way round.

The wrong panel order of the 0200 series boxes was fixed to follow the common design principles though it does not have a substantial effect on the BCT results. In turn, the over-dimensioned glue flap affected test results by adding the strength of the slotted sides as the flap reached over the first ventilation hole row. The glue flap width was corrected to the layout calculations.

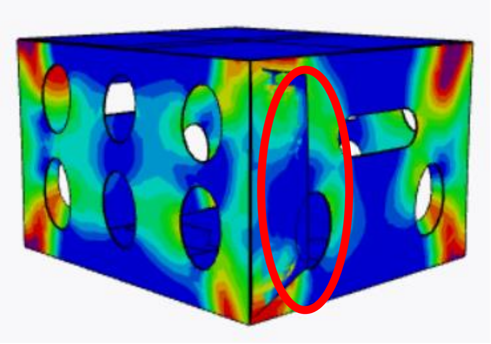


Figure 31. Over-dimensioned glue flap of the 0700 type boxes added strength properties to the box.

The biggest impact on the test results had the lack of the grid or measurement tool of the special geometry. The inaccuracy of positioning the added geometry and measuring the size of the positioned element led to the larger areas of the slotted surface in comparison to physical models. The limitation of geometry also involved the perforations, which were limited for the linear positioning without the ability to curve the shape. Perforations are often drawn to arc to increase the strength of the box under load. The measurement tool was added to the layout as seen in Figure 33 below.

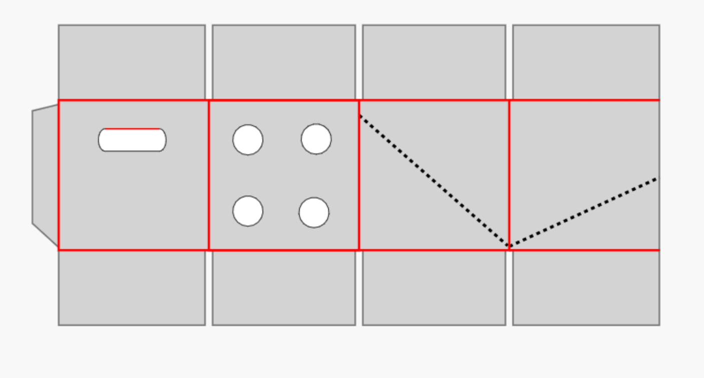


Figure 32. Limited scaling properties of the special geometry led to inaccurate positioning.

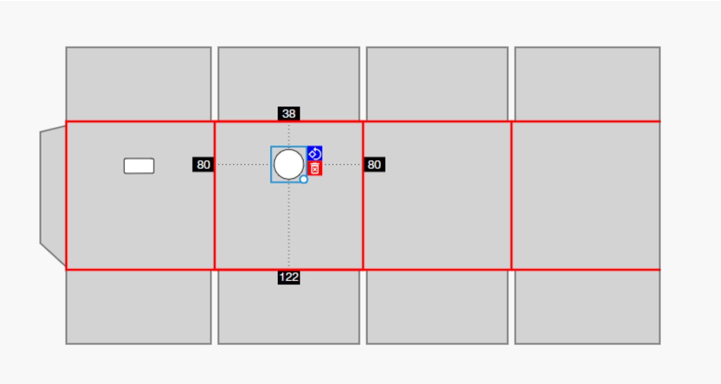


Figure 33. A measurement tool for scaling added geometry was implemented to the layout.

Due to the modeling mechanism, the measurement tool functions in panel sections instead of the overall layout. In a virtual tool, the layout dimensions do not visually change according to the used board type as the layout functions in CAD. In virtual applications, board thickness is added outside of the box in the simulation. The difference in presenting layout dimensions between simulation and CAD does not affect the test results but the designer must position the special geometry without board allowance when replicating the existing designs.

The defaults related to the single flute boxes were mainly geometry-related and easily corrected. After the first test round, some corrections also to the models in perforation and crease behavior were implemented to increase the accuracy of the model. Compared to other modeled shell elements perforations are modeled with reduced thickness, and with creases, the composite shells are allowed to rotate more freely.

Physical and virtual BCT testing outcome was compared in BCT values but also in technical functionalities. The accuracy challenges are related either to the technical layout functionalities or modeling details. The biggest variation between physical and virtual tests was observed with the double flute boxes.

The double flute boxes were tested with the 0501 boxes without flaps or added geometry to minimize the variables and to be able to capture the mechanisms related to the increasing height. The shear behavior of the double flute materials is more complex to capture than with single flutes, and after the first tests were noticed that the shear behavior of the double flutes was under-predicted. The shear behavior did not alone explain the difference in the results of physical and virtual tests, and the focus was turned to geometry. The observation and further literature research indicated that the momentum around edges between boxes with flaps and without flaps was evaluated incorrectly. The research indicates that the boxes without flaps tend to have higher strength properties than boxes with flaps due to the creases in the flaps.

After the last test round the simulation seems to predict the experimental test result behavior as seen in Figure 34.

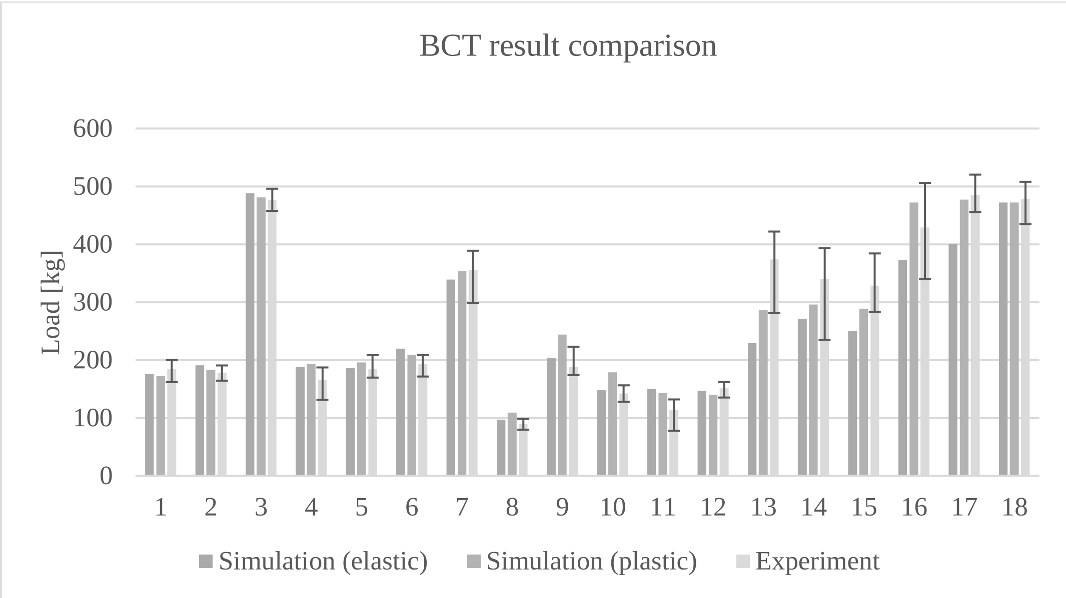


Figure 34. Final BCT test results present the results of the elastic and plastic simulation and experimental mean values with error bars indicating the minimum and maximum values of the test set.

The results indicate that the boxes from 8 to 10 overpredict the strength in the plastic approach when the double flute EB boxes underperform in the elastic approach. Though, the scale of the virtual results remains on the scale of physical experiment values.

5.2 Reliability assessment

The material behavior of the corrugated board is direction-dependent i.e. anisotropic and nonlinear. In addition, corrugated board strength value is highly dependent on environmental conditions, time strain rate, and load combinations. The more detailed the finite element model is in material behavior, the longer is the calculation time.

Jimenez et al. (2009) state that corrugated shell modeling lacks efficiency in both calculation process times but also complicated geometrical details such as flaps and creases. Jimenez et al. also state that finite element modeling is more suitable for estimating physically immeasurable material behavior instead of trying to predict the behavior of the whole packaging. The challenges in modeling are related both to the complex nature of corrugated materials but also to a wide selection of box types and their structural specialties.

Due to the unique structure of the corrugated material and complex geometry of the different designs, physical tests result in variation of 10 % to the mean is considered normal behavior. In corrugated packaging test results, the deviation will always exist also in simulation, as no absolute result can be defined with physical tests or mathematical calculations. The corrugated package design is not interested in precise strength values: the more indicative factor is a scale of result values and how the changes in design or materials affect the results. In the simulation, the primary challenge is to define the acceptable error rate in results.

The reliability is evaluated with the ECT results and with BCT values of compressive strength testing. The virtual tool uses SCT values of the plies as the basis of the strength modeling. The tool calculates an ECT value for all the materials and provides information if the SCT value is modeled correctly. The calculated value is compared to the commercially promised minimum ECT value of the material, and the measured ECT value of the physically tested boxes. The comparison is presented in Figure 35.

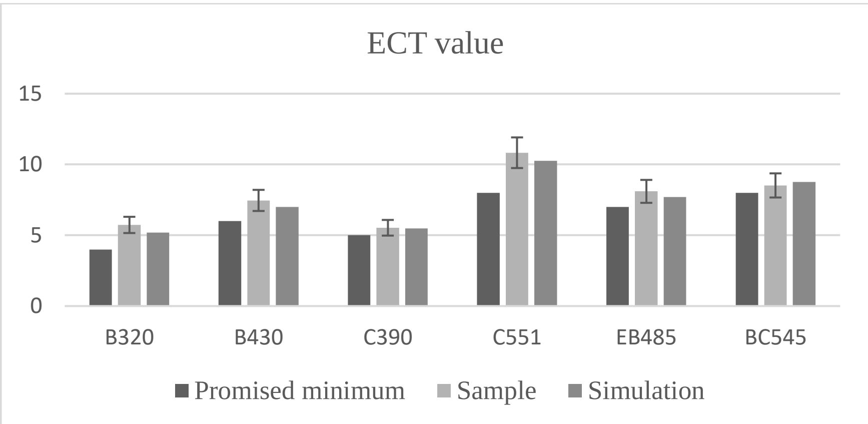


Figure 35. ECT value comparison is made between the commercially promised minimum performance value, the experimentally measured value, and the calculated value of the simulation.

The comparison indicates the variation between commercially promised and measured sample values, of which mean value the calculated ECT follows. This provides information on the accuracy of the model in predicting ECT value in the simulation calculations. In the in-house research of the target, company has been observed that growing dimensions of the box increase the relevance of the ECT value in BCT calculations. However, predicting strength properties with a virtual prototyping tool is strongly dependent on input material data and its deviation: the more data available, the more accurate the result, or in the opposite: more simplification is demanded in simulation.

The most important values in reliability assessment are the BCT results presented earlier in Figure 34. The variation between the experimental mean and simulation is less than 8 % with both elastic and plastic approaches in single flute recipes. In double flute recipes, the variation is between 15 and 35 % but the variation in the physical test results makes the comparison to mean one-sided. In double flute recipes, the differences between the minimum and maximum values in the physical tests were even 50 %.

With double flutes, the plastic approach provides more accurate results than the elastic approach, which indicates that the modeling mechanisms of the plastic approach predict the behavior of corrugated double board structure more precisely. Double flute simulation results reach the same scale as variating experiment results. Therefore, can be concluded that the simulation results reach the correct scale of compression strength with the tested geometry of 0200, 0500, and 0700 series boxes.

Force-displacement curves between elastic and plastic simulations differ visually from each other: in elastic simulation, the curve ends when the box fails; in the plastic approach the curve continues until converting stops. The plastic approach is similar to the physical testing force-displacement curve. Due to the time-consuming process, the plastic approach is recommended to use only if the curve provides added information of the box strength.

Due to the differences in scale and measurement units between simulation and experiment, the comparison of force-displacement curves is challenging and demands calculation. In the simulation, force is presented always with the fixed scale, in the experimental testing, force scales to the results. In simulation displacement is presented in percentages; the experiment provides displacement information in mm. Despite the interpreting challenges, the force-displacement curves between physical and virtual tests are similar in shape and provide identifying information of compression behavior.

The visual results of the simulation are presented in a 3D model. In the web application, the script extracts both Tsai-Wu stress and plastic strain: the elastic approach provides only the Tsai-Wu-criteria model when the plastic approach presents both. The Tsai-Wu-criteria was chosen over plastic strain as it provides information of stresses just before failure. In Figure 36 the stresses with Tsai-Wu are presented with the stress criterion bar.

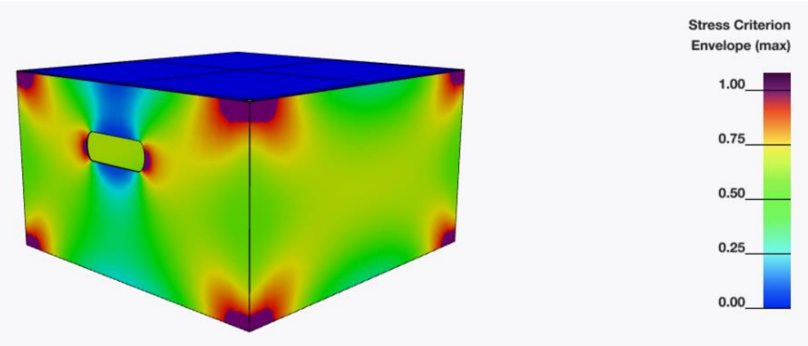


Figure 36. The 3D model of the virtual tool is based on Tsai-Wu-criteria and it describes stresses on the box just before failure.

The comparison between the physical and the virtual 3D model is complex for multiple reasons. First, simulation provides information of one individual box and is not exposed to any external variables. In experimental testing, there are at least ten boxes tested to provide mean values. Every box provides individual strength value and might differ also in the deformation behavior. Another variable is the material memory: under load, the box crushes 20 % in height during the experiment but usually returns to its original shape after the load is released making deformation evaluation challenging.

Strength modeling properties were prioritized over deformation results in modeling; thus mm values of deformation do not follow reality. Deformation behavior will be developed in further development steps of the project. From the reliability perspective, the variation in value will always exist as the detailed crush behavior of the individual box is challenging to predict, and the value is always more indicative than exact. The Tsai-Wu stresses provide and compensate for the information the deformation value lacks.

Overall, the simulation results are in good agreement with experimental test results, however, in chapter 5.2.3 some minor changes for the shell model are proposed to increase the accuracy further.

5.2.1 Effect of humidity on strength properties

The BCT value represents the strength and stress behavior of the packaging, however, it does not consider the conditions affecting the material properties in real life. One of the significant factors is the effect of humidity. The compressive strength of the packaging is good in dry conditions, but as the moisture increases, the stacking strength decreases due to the softening of the lignin in the wood fibers. With smaller packages, the effect of humid conditions is usually not significant, but with larger transport packages high moisture can cause serious failure along the adhesive lines or in the bonds between fibers. The moisture content of the board is highly connected to the relative humidity (RH) as the corrugated fibers absorb and release moisture following the surrounding environmental conditions. (Frank 2013)

The effect of humidity on material properties has been observed with testing compressive strength and modulus of elasticity in both at 50% RH and 90% RH according to FEFCO TM 50. The studies show that compressive strength and modulus of elasticity are highest in the machine direction at 50% RH, which is explained with principal fiber orientation in the machine direction in the manufacturing process. The lowest strength and elasticity values are in the cross direction, parallel to the fluting, at 90% RH. The results are similar between virgin and recycled fibers; though, the virgin materials seem to withstand water absorption better than recycled fibers. (Navaranjan et al. 2013.)

According to Van Hung et al. (2010), the strength properties are subject to the cardboard flute type: the higher the flute, the weaker the strength in high humidity conditions. The rigidity of corrugated boards is better with higher flute types, but so are the absorption properties of the material. The residual strength of the experiments varied from 55 to 65 % depending on the material and the environmental conditions predisposed.

Besides literature review, the effect of humidity for strength properties was evaluated through material trial test data of Target Company. The matrix of 420 boxes with similar outer dimensions and design structure, but with different E-, B-, C- and BC-flute recipes was observed through grammage, ECT-value, and BCT-value. The mean residual strength in ECT between 50% RH and 90% RH was 53%, and BCT 64%. The results between flute types are presented in Figures 37 and 38 below.

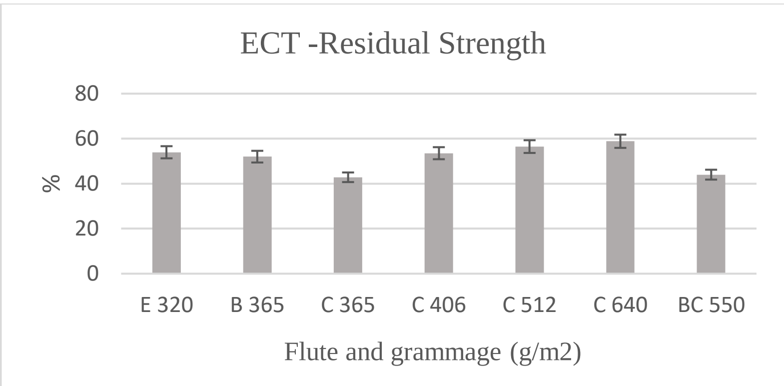


Figure 37. Residual ECT strength in 90% RH conditions.

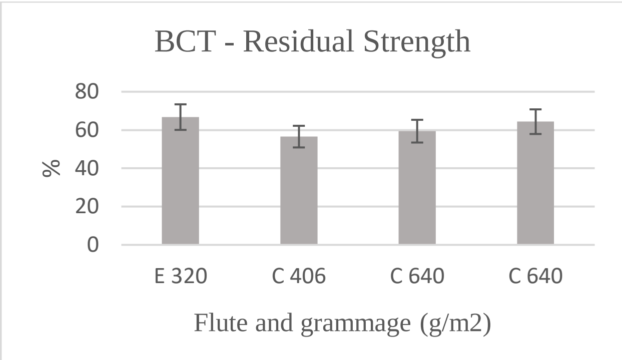


Figure 38. Residual BCT strength in 90% RH conditions.

With single flute recipes, there were not noticed big differences between grammage and residual strength: despite the grammage or flute type, the residual strength remained on the same level. However, inside C flute recipes there was variation between C365 and other C flute recipes: C365 consists of virgin liners and recycled fluting while the other C flute recipes are manufactured with 100% virgin fiber. Despite a small number of samples could be estimated that the recipes made of recycled fibers have smaller residual strength than virgin fiber recipes.

The comparison of the double flute recipe to the single flute recipes indicates that the residual strength decreases even with 20 %. Though, the number of tested double flute boxes and recipes is too small to make conclusions, although the test results agree with previous research. In addition, needs to be reminded that despite all the boxes being tested in ECT RH90%, not all boxes were tested in BCT RH90%. However, as the results and mathematical formulas indicate, ECT is directly connected to BCT, which makes the material behavior parallel.

The research of the University of Karlstad (Strömberg 2016, 40-41) provides more detailed testing results of liners and flutings. The results state that the residual tensile stiffness of RH90% retain in 65-70% in MD while the recycled fibers retain 50-60% of their original stiffness. In CD the variation is smaller, retaining in stiffness retention from 50 to 55 %. In compression stiffness, the residual strength reduction was even 50% in 90% RH conditions.

5.2.3 Factor of Safety

The result of the virtual prototyping is proportional to the mean values of the experimental tests but does not provide any information of variation. The traditional way to ensure the strength capacity is to determine a safety ratio to the formula. To cover the absence of variation and the possible simulation error, the use of the safety ratio is recommended also in a virtual compression test.

The traditional way to consider strength capacity is to provide a factor of safety (FoS). FoS defines the ratio between total and intended load that the package must conform or exceed. Traditionally FoS has been indicated with integers 1, 2, 3, and so on. Though, the challenge is not to provide overrated safety factors: one of the main purposes of virtual prototyping is to provide a tool for material optimization to reduce the overprediction of the box strength. Thus, the possibility to use one decimal after integers would reduce the possibility of over-dimensioning the FoS and the demanded strength properties.

As the current version of the simulation model does not consider special environmental conditions such as high RH, the recommendable safety factor to high humidity conditions is 2 as the strength properties decrease approximately 50 % when the humidity rises. Besides humidity safety factor 2, the normal ratio wanted to ensure the strength properties need to be added to the FoS.

5.2.3 Finite element model development

An S4R thick-shell with solid consideration transverse shear forces has been considered also in previous research (Jimenez et al. 2009) for the most cost-effective solution for finite element modeling. Despite the modeling method, building a material model means principle simplification of material behavior and its prediction.

Due to the lack of specific measured data, some of the basic information of the model is based on previous research on the subject. The strength data of the simulation is based on the SCT value in both for liners and flutings as not all carton manufacturers provide CCT value of the fluting, though using SCT with measuring flutings has been criticized. SCT is measured of the carton and CCT is measured of corrugated carton: fluting reaches its true strength properties after warming up. The continuous in-house quality follow-up using the Maltenford method for calculation indicates that using the SCT value for flutings leads to approximately 5 % better ECT value when compared to the calculation with the CCT value. Therefore, the consideration towards implementing measured CCT values and modification impact for simulation results should be evaluated.

As measured board bending stiffness value is not utilized in the model but the thickness, tensile stiffness, corrugation period, and shear behavior are used for determining the bending stiffness, there is a possibility that the thicknesses under the manufacturing process load such as flexographic printing are thinner than expected. In further steps, the evaluation of implementing bending stiffness to the model could be justified if the prediction of the bending stiffness lacks accuracy.

Modeling overlapping individual planes such as folding laps with box sides for the same plane raises concerns towards simulation´s ability to predict strength behavior of intersecting boards despite the model observing the material thickness in the model. Especially with folder-type boxes, this can cause serious strength underprediction as there cannot be different flute directions inside one plane. Therefore, reconsideration of plane locations about each other is highly recommended especially if the simulation results of complex geometry designs tend not to follow experimental test results.

Currently, the application can simulate over 20 standard FEFCOs from the 0200, 0500, and 0700 series with added geometry. The simulation development need will be more definite when the varying geometries are added to the application. Any unforeseen challenges in added box types in above mentioned or in 0300 series boxes should not exist as the technical functionalities are similar to the tested box types, however, 0400 boxes vary in geometry from the tested ones. Further research will show if the model can also predict the strength behavior of the unglued, geometrically complex solutions, especially with double-board recipes.

The most important features to add for the simulation are related to modifying standard FEFCOs. In design, it is common to combine for example 0201 and 0203 designs, and the ability to change the width of the dust flaps would allow simulation for the wider range of designs. The possibility for CAD file importing and existing design file simulation would be the most significant step to get the most out of the application and to establish the application for everyday use.

5.3 Experimental process observation

The design process was evaluated through the controlled observational experiment, where the traditional design process - including designing, material selection, physical prototyping, and possible redesign - was compared to the modern design process, where the virtual prototyping was used to support material selection and to ensure the product quality. Both physical and virtual design processes are described in more detail already in previous chapters.

The design problem chosen followed the typical packaging design product development process. The experiment involved six designer participants, who all have more than five years' experience in corrugated product designing.

Participants were individually proposed to design a transport packaging for a domestic e-commerce company, which manufactures different kinds of homeware and textiles. The detailed information including inner dimensions, FEFCO code, and special features such as handles, and printing method was given as in Table 4. The figure of the FEFCO layout is presented in Figure 39. The material selection was left for participants to do based on the design brief and on the information of the variation of products to be packed.

Table 4. Model information

FEFCO	Glued	Special features	Inner length	Inner width	Inner height	Printed	Number of colors
0201	Yes	U handles	350	350	200	Flexo	1

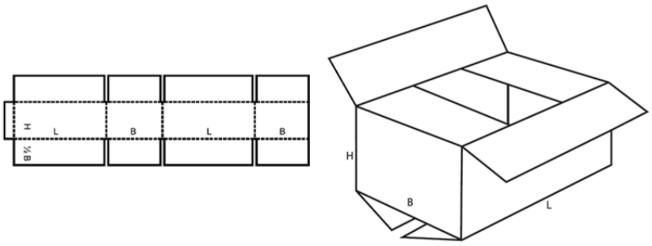


Figure 39. FEFCO 0201 (FEFCO Corrugated Packaging 2021b).

After the first completed design stage, the FEFCO code of the box was changed from 0201 to 0203, in Figure 40, with overlapping flaps, as the model information otherwise remained the same. In the second design stage, the motivation was to find out whether the change in box design after prototyping also necessitates consideration towards material change, or does the knowhow resulting from the first design affect the material selection and consideration about re-testing the physical prototypes of the second version of the product.

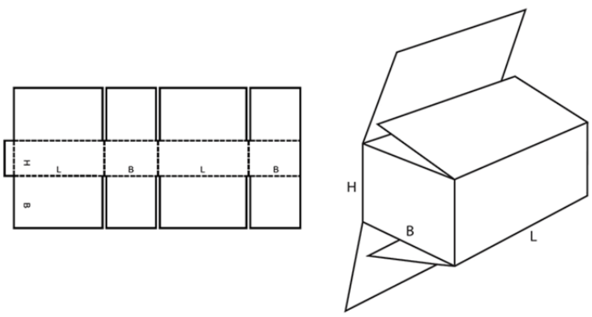


Figure 40. FEFCO 0203 (FEFCO Corrugated Packaging 2021b).

After designing, the participants produced ten physical prototypes in the workshop to be sent to the in-house laboratory for physical BCT testing. Testing was done according to FEFCO Method no 50, explained in detail already in the previous chapter 5.1.1. The overall design process and phase times were measured and observed. The timeline of the traditional design process is presented both with the stage times and overall process time in Table 5. Presented times are means of the evaluated process stages

Table 5: Duration of design phases in the traditional design process.

Operation	**Persons involved**	**Operation time (h)**	**Ready on day**
Design brief	2	0,1	1
Designing	1	0,5	1
Material procurement	3	0,5	1
10 physical models	1	2,6	2
Conditioning	1	24	3
BCT tests	2	2,35	3
Result review	2	0,18	3
Redesign	1	0,5	4
Total hours		**30,25**	x
Total time in working days		**1,26**	**4**

In the traditional product development process, the actual operation time is relatively small but as it involves also other employees, inhouse transport, and queuing time, the overall process time increases by almost 70%. The processing time increases even more if the need for another test round is considered necessary after design changes.

The experiment indicates that considering material choices and physical BCT testing, the material availability affects material decision: if the material is one of the stored materials and available at once, it will be chosen over another recipe even it might not be a designer´s first choice for the product. If the material is not one of the stored ones, the time for material delivery is approximately 14 workdays, meaning an increase of process time to 18 working days.

The virtual BCT testing of designs was performed simultaneously with physical tests with the Virtual Compression Test tool. The timeline of virtual process is presented in Table 6.

The result of the virtual prototyping was introduced to designers after design changes from 0201 to 0203 after the material choices towards physical models and testing were done. Through this was avoided that the information of virtual testing would have any impact on the traditional design process.

One of the biggest benefits of the virtual prototyping assisted design process from the process perspective is that virtual prototyping is not dependent on testing equipment, material availability, or work queues which makes it quick and adaptable. The simplified process of virtual prototyping assisted design process was presented earlier in this study in Figure 15.

The research indicates that using virtual prototyping instead of physical prototyping, more than 80 % of the time per product can be saved in the number of workdays, and only one person is involved in the process. As the process is not dependent on the designer´s physical location, using virtual prototyping allows testing and developing multiple designs and material options simultaneously.

Table 6: Duration of design phases in the virtual prototype design process.

Operation	**Persons involved**	**Operation time (h)**	**Ready on day**
Design brief	2	0,1	1
Designing	1	0,3	1
Virtual tool: designing	1	0,25	1
Virtual tool: BCT test	1	0,35	1
Result review	1	0,22	1
Redesign	1	0,2	1
Total time hours		**1,42**	x
Total time in working days		**0,06**	**1**

After the first design, the results of the physical prototyping were introduced to designers to provide information on deformation, maximum load of kilograms, and a physical box with slightly crushed top corners. Two out of six designers chose recipe A and the other four had stronger recipe B. When presenting the results, the designers were told that the customer would like to change the design to the FEFCO 0203 with overlapping flaps, and designers were asked if they would reconsider the material choice about the facts they were provided from the first set.

None of the designers was willing to run another test round, as it was considered time-consuming and unnecessary despite the product developed might be over-dimensioned related to the material after the design change. Due to the time-consuming procedure, demand for fast product development processes, and the strong knowhow of the industry, for example with experiment box in real life all of the designers said they would not have run physical tests for the box but instead choose the material that – for sure – is strong enough for the product. Due to this reason, the designers who did not choose recipe B for the first design changed the recipe from A to higher strength category recipe B. The design change for overlapping flaps was considered to provide more strength for the corners of the packaging which deformed first in the test boxes.

After the material decision towards the physical box was made, the results from virtual testing in Figure 41 were provided of the first test box, and designers were asked if the results would change their opinion of the final material or would they find it important to compare the results between two recipes before making the final decision. None of the participants were immediately ready to do the material change related to the virtual prototyping result of box 0201 as it did not provide new information referred to physical tests. However, all the participants identified the possibility for effective and fast virtual comparison of materials, and the virtual test was run for design 0203 with both material recipes.

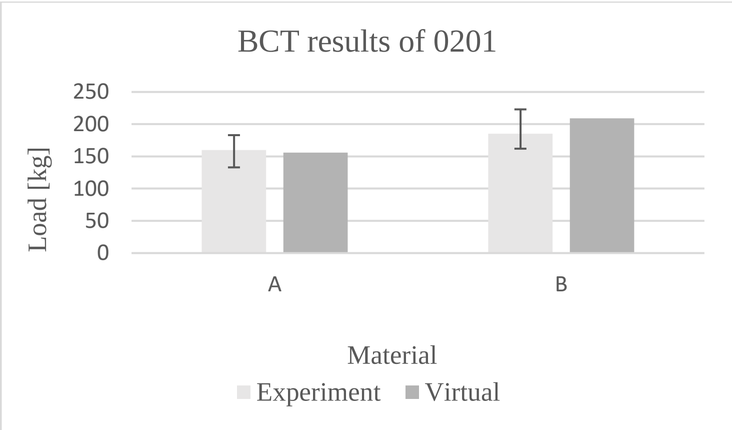


Figure 41. Results of the load-carrying capacity of the box design 0201.

After the virtual prototyping result comparison, presented in Figure 42, was evaluated that for the designed box with 0203 structure recipe A would have been strong enough. The change in the design improved maximum BCT strength only by 5 % as the overlapping flaps provide more strength to the content bearing capacity but due to creasing lines of the flaps, it does not provide a significant advantage in stacking strength. Due to the creases, 0203 as a structure is just slightly stronger than 0201 and the stresses under compression are similar between boxes. Overpredicting material selection does not only affect the capability to withstand loads but only for the weight and price of the package

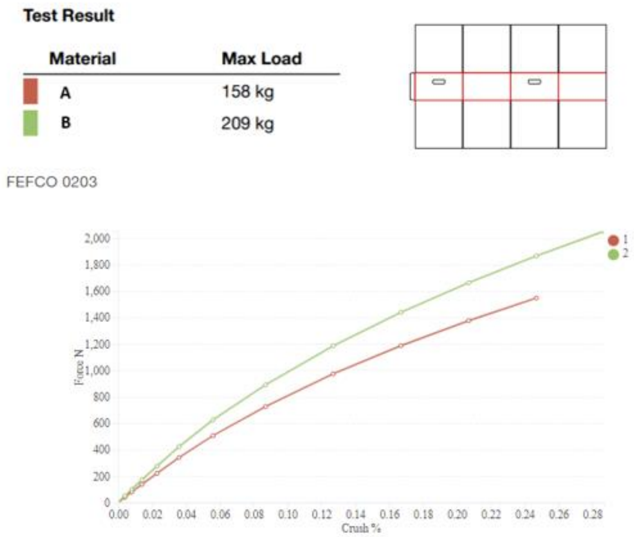


Figure 42: Virtual simulation results of the load-carrying capacity of box design 0203.

The truckload height with pallet is usually 2200 mm in maximum, meaning that 200 mm boxes would be stacked 10 boxes on top of each other. The BCT value of 0203 was approximately 158 kg. With maximum compression load for the lowest packaging of the pile, this would mean 15,8 kg contents per upper box, which is more than sufficient value for the intended use. If the purpose of the use is considered, with 15,8 kg content it would be possible to include for example 50 coffee cups or 15 duvet cover sets inside the box which is far more than you can fit into 350x350x200 mm inner dimensions.

5.4 User experience observation

The user behavior and UX of the application were evaluated with an experiment where the instructions of the design details and proceeding were given verbally but the navigation and functionalities were implemented self-directed. The motivation was to observe if the functionalities were logical and easy to use. The experiment was carried out with personnel from sales, designing, product management, and quality management to ensure a comprehensive user perspective.

In general, the navigation, technical functionalities, and layout were remarked well designed, logical, and easy to operate. The color-coding of the application was used logically as red indicated errors, green indicated passed testing and blue has been used to point out the following steps on selections. Though, some development targets were also pointed out and deduced through user behavior and feedback.

The most common challenge occurred with selections, which had not a headline or established color-coding to point out the selection. Also a headline with the expression “add” indicated for users an optional field instead of compulsory selection. Another confusing expression was the “Load on the box” (Figure 43) which was understood as the load inside of the box instead of load on the lowest box on a pallet according to the BCT testing principles.

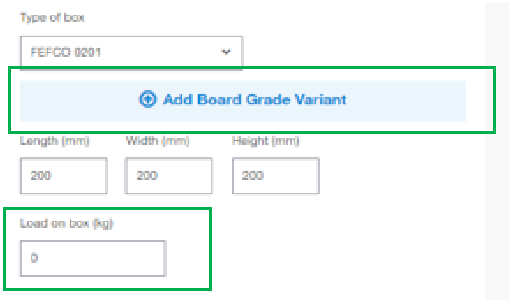


Figure 43. In the “General” tab the selections of adding the board grade and the load on the box confused users.

The compulsory fields were marked with headlines and positioned for the more user-friendly selection order. In addition, the pop-up windows indicating missing selections were added. Navigation between tabs and functions was improved by utilizing color-coding and creating shortcuts.

On the “Geometry” tab deficiencies in the measurement tools were observed as presented in Figure 44. The measurement tool was also pointed out to be inadequate: despite the ability to measure, turn and delete the position on the box panel, the ability to scale the object according to set measurement was missing. User test results indicate the challenge to scale the object on the layout: the tool tends to sometimes "jump" over exact measurement if the layout was not zoomed in. In addition, the users tried to drag the special geometry on the layout instead of clicking the buttons.

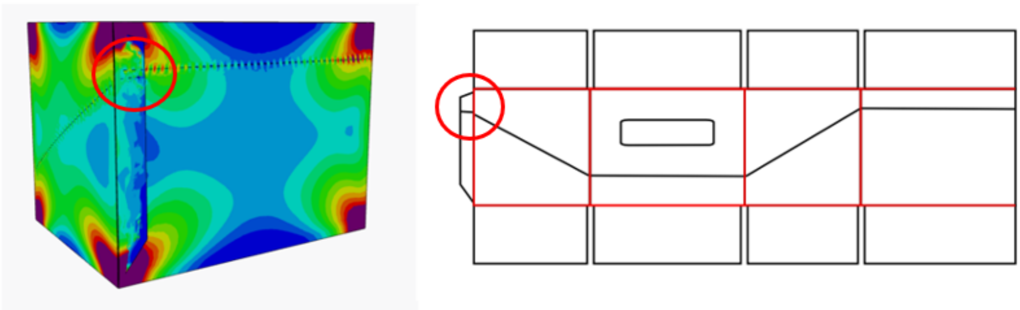


Figure 44. Inaccuracy in the measuring tool indicates mispositioning of the added geometry of the box.

On the "Advanced" tab the selections indicated discussion about the meaning of the analysis method as the terminology is not familiar for the average user. Besides, in applications only two approaches are implemented: elastic and plastic, and the selection between analysis approaches is done in separate fiel on the last tab. By re-arranging the fluting direction selection to general settings and by deleting analysis method selection, the process was able to cut to a three-step-process.

Test results (Figure 45) awoke conversation of result interpretation. Due to the modeling technique, which positions flaps for the same plane with side panels, the 3D looks like flaps are outside of the box and the order of dust flaps is incorrect. Change of the image would involve significant changes in model behavior and would be complex to fix. Therefore the importance of fundamental user training is essential as using modeling techniques requires some compromises in usability.

Easy design and material comparability and ability to modify tested material or add another material without the need to start the test all over for comparison were appraised. Also, the possibility to delete and hide tested materials, and export separate report files of results were commended. However, the lack of opportunity to modify the existing design and interpret the force-displacement curve with crush % was evaluated as displeasing as it brings no added value to the results without mathematical calculations. The expression of FoS also confused some of the users.

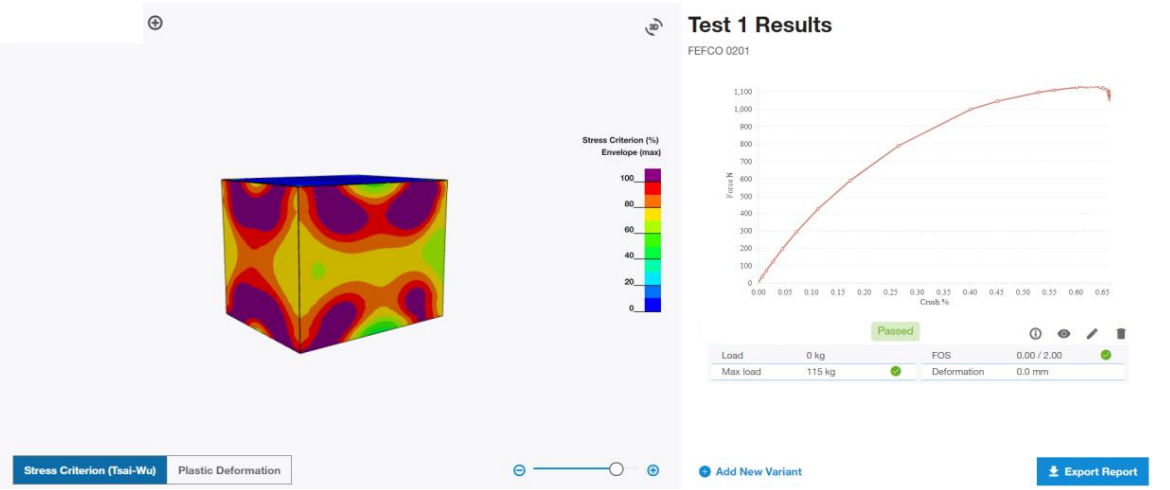


Figure 45. The user tests indicate that the result interpretation of the virtual tool requires distinct user trainining.

The exported test report summarizes the testing details for a single page file with the wanted details. The test reports can be used either for in-house documentation or as an external document for customers with a legal disclaimer.

The purpose of the external test report is to provide a separate file to save the results as a file or to present the testing results for the customer. It is possible to exclude for example unwanted materials and detailed material information meant for the in-house use only of the report. The layout of the report received its only negative comment regarding the 3D objects. The object is scalable, and its size and position are reliant on the scaling of the test results before exporting a file. It was proposed to set a default size for the object already on the test result page to 70 % scaling of the object to improve the user experience.

The comments after user tests were mainly positive and the possibilities provided by simulation technology were praised. Customers` growing demand to decrease packaging price by changing constructions or material without strength reduction is a common challenge but the tools for testing are deficient. Self-explanatory layout and easy functionalities were appraised, though, guidance for result interpreting was mentioned to be essential.

Designers mentioned that due to the limited constructions the application would not apply for everyday use and the possibility to import existing design files would be a primary development step from their perspective. Despite the lack of constructions the possibilities and advantages of the application were identified, and especially the possibility for strength comparison between materials was pointed out as an important feature.

In consideration of good user experience, the application fulfills a defined need for modern and agile design tools for virtual prototyping and material optimization. It is easy to operate and provides added value both for the Target Company and customers with its process efficiency and visual reports. Application is online based tool and does not demand separate licenses or installed programs. The reliability is proved to be on the right scale through comparison with experimental testing, though further experiments could show the possible development targets with more complex corrugated designs. However, the approach of modeling has been considered to be congruous and able to follow the corrugated behavior despite variation inaccuracy.

The advanced, final version of the application interface is presented in Appendix 4.

5.5 Discussion

The advantage of the FEM-assisted package design process is the cost-effectiveness which provides significant savings in labor, materials, and process time. The FEM-assisted tool enables modern, fast, and agile ways to test both new designs and materials to ensure product quality and material optimization. The internal and external documents provided by the application support the communication and development process between designer, sales, and customer. The shared database of plies brings the application available for different business units despite the variation in material combinations and recipe names used.

However, as the application is not connected to the material database the simulation results are highly dependent on manual updating of material properties and constant testing and development regarding complex geometry of designs and the ability of simulation to repeat them. The reliability of the application has been proved to be on the right strength scale, though, the presence of possible error and effect of environmental conditions needs to be considered in using safety factors. Like in physical test results, variation always exists, and the users should be emphasized to avoid black and white result interpretation. Despite the testing method, the results are always more indicative than exact. Therefore, simulation provides a tool for fast product development, but the significance of physical models increases when communication between model and designer is necessary.

The user interface of the simulation tool is logical, self-guiding, pleasant, and easy to use. Defaults noticed in user tests were improved with minor layout changes, though some of the details such as result interpreting require user training. The biggest disadvantage of the application is the limited selection of standard FEFCOs available restraining the possibilities to use the application with custom designs and limiting the use for directive purposes instead of actual customer cases. The ability to modify and import designs would increase the value of the application in designing and utilizing an everyday tool for strength optimization. In a further development step, there would also be a possibility to add for example calculation of recycling and plastic rate, and carbon footprint calculation to the simulation as the values are material component-based and already available in current material management systems.

Before applying any additional functionalities to the application, further research towards the functionality of 0400 series boxes is essential. As the virtual model in glued structures has been proved to function on an acceptable level, the next indicative step is to ensure the functionality of folder-type boxes of which geometry is much more complex relative to the other standard structures.

From a validation perspective user interface is considered accepted despite suggestions of improvements for special design handling. Though the evaluated designs and materials resulted in an acceptable range in values, there are still some uncertainties that prevent the release of the tool for unlimited user groups or customer cases. However, there is no such indicative reason for preventing publishing the application for a limited user group to generate data for both user and application provider.

6. Conclusions

The results indicated that using virtual prototyping-assisted processes reduces the product development time by up to 80 %. This encourages designers to make fast and effective material and design comparisons leading to material optimization. Even though the design example in the experiment was simple and limited concerning standard FEFCO design, it is a possible design problem also in real-life industry and has no impact on the overall differences in process or the additional benefit the virtual prototyping provides to product development.

A literature review illustrated that there is always a distribution in physical BCT testing due to complex factors of corrugated design, and interpreting results demands a deeper understanding of materials, products, and testing process. A similar approach applies also to virtual prototyping, as the calculated value only yields one result instead of ten in physical prototyping. Virtual prototyping is a process of continuous improvement in which the calculation model is updated based on material updates and substantial test results. Safety factors are used to ensure the durability of the product in various conditions and to consider the possibility of an error rate in simulation. Despite the literature review´s criticism towards composite shell modeling technique aptitude for interpreting the behavior of the whole packaging, the results proved that by implementing elaborated ply data and predicting material behavior under load through shear, modulus, and stiffness analysis, it is possible to attain an acceptable accuracy with virtual strength simulation.

The reliability assessment indicated that the variation between the experimental mean and simulation is less than 8 % with both elastic and plastic approaches in single flute recipes. In double flute recipes, the variation is between 15 and 35 % but the variation in the physical test results makes the comparison to mean one-sided as the difference between experimental results in a double flute can be even 50 % between the minimum and maximum value. The results interpretation indicates that the virtual model can predict the behavior of the corrugated board on the acceptable level when considering the natural behavior of the corrugated board. In addition, the force-displacement curve provides similar information as the physical test, though, the added value of the virtual tool is the 3D model providing information of the stresses under the load.

The primary limitation of the research is that due to time and resource constraints, the experiments concentrated on the limited number of materials and glued FEFCO designs with added geometry. More complex design geometries might have created more distribution in simulation results indicating mechanisms that might not be captured with the model.

Customers` growing demand to decrease packaging price by changing design or material without strength reduction is a common challenge but the tools for testing are deficient. The user tests indicate that the simulation tool is logical, self-guiding, and easy to use, though the result interpreting requires user training. The disadvantage of the application is the limited selection of standard FEFCOs available restraining the possibilities to use the application. The ability to modify and import designs would increase the value of the application in designing and provide an everyday tool for strength optimization. In addition, the limitations in the special design features and lack of design import set development challenges for the application. To utilize the full potential of the tool, the possibility for design import should be prioritized in development targets.

Despite accepted validation of the application, further studies of the model behavior with more complex design geometry are needed to ensure the feasibility and reliability of the Virtual Compression Test for everyday use. The development of the virtual tool provides endless possibilities for utilizing the simulation properties also for recycling rate, carbon footprint, and product price calculations. However, the simulation results are dependent on manual updating of material properties and constant testing and development regarding complex geometry of designs and the ability of simulation to repeat them. Publishing the application for the limited user group to generate data for both user and application provider is essential for the application development besides further investigation of the model behavior and development

References

ABB AB. 2017. L&W 4-Point Bending Stiffness Tester. Datasheet. [Referred 04.12.2021.] Available: https://new.abb.com/pulp-paper/abb-in-pulp-and-paper/products/lorentzen-wettre-products/laboratory-paper-testing/paper-strength-testing/l-w-4-point-bending-tester

Andersson, T. 2022. Software supplier. About Virtual Compression Test and test boxes [private email]. Receiver Susanna Heposalmi. Sent 25.1.2022, 13.07 o'clock (GMT +0200).

Atticus Poetry. 2017. Love Her Wild. First edition. London: Headline Book Publishing. P. 18.

Biancolini, M.E. & Brutti, C. 2003. Numerical and Experimental Investigation of the Strength of Corrugated Board Packages. Packaging Technology and Science, 16:2. Pp. 47–60.

Borqvist, E., Wallin, M., Tryding, J., Ristinmaa, M. & Tudisco, E. 2016. Localized Deformation in Compression and Folding of Paperboard. Packaging technology & science, 29:7. Pp. 397–414.

Brandberg, A. & Kulachenko, A. 2020. Compression failure in dense non-woven fiber networks. Cellulose, 27:10. Pp. 6065–6082.

Burkett, T. 2021. Incorporating Validation Concepts into the Biotechnology Curriculum. The Community College of Baltimore County. [Referred 11.01.2022.] Available: https://slideplayer.com/slide/6005603/

Clifford Packaging. 2015. Performance packaging. [Referred 05.12.2021.] Available: https://www.cliffordpackaging.com/products/performance-packaging/

Costa, D. 2020. The 7 factors that influence user experience. UX Collective. [Referred 01.02.2022.] Available: https://uxdesign.cc/the-7-factors-that-influence-user-experience-2805282616f9

Coutts, E.R. & Pugsley, C. 2018. Physical versus virtual prototyping and their effect on design solutions. The ICDC2018, Fifth International Conference on Design Creativity. Pp. 1–2.

FEFCO Corrugated Packaging. 2021a. The Corrugator. [Referred 31.10.2021.] Available: https://www.fefco.org/technical-information/production-process

FEFCO Corrugated Packaging, 2021b. FEFCO Code. [Referred 26.10.2021.] Available: https://www.fefco.org/technical-information/fefco-code

FEFCO Corrugated Packaging. 2022. How corrugated is made? [Referred 17.03.2022.] Available: https://www.fefco.org/sites/default/files/How_corrugated_is_made-2.pdf

FEFCO Corrugated Packaging. TM 50. Introduction to the development of FEFCO Testing Methods for corrugated board and boxes. Determination of compression resistance. Pp. 24–25. Available in PDF-file: https://www.fefco.org/sites/default/files/documents/import_anglais.pdf

Finnish corrugated board association. 2018. Aaltopahvi – Käyttäjän käsikirja. 42 p. Available in PDF-file: https://www.aaltopahvi.fi/_files/ugd/b4bed9_6089073f08d14ff89fa0c1793fe3678a.pdf

Frank, B. 2013. Corrugated Box Compression—A Literature Survey. Packaging Technology and Science, 27:2. Pp. 105–128.

Interaction Design Foundation. 2021. The 7 Factors that Influence User Experience. [Referred 24.01.2021.] Available: https://www.interaction-design.org/literature/article/the-7-factors-that-influence-user-experience

ISO 2759:2014. Board — Determination of bursting strength. 4th edition. Geneva: International Organization of Standardization, 2014. 13 p.

ISO 9241-210:2019. Ergonomics of human-system interaction — Part 210: Human-centered design for interactive systems. 2nd edition. Geneva: International Organization of Standardization, 2019. 33 p.

ISO 12048:1994. Packaging — Complete, filled transport packages — Compression and stacking tests using a compression tester. 1st edition. Geneva: International Organization of Standardization, 1994. 5 p.

ISO 25210:2011. Systems and software engineering — Systems and software Quality Requirements and Evaluation (SQuaRE) — International Organization of Standardization.

System and software quality models. 1st edition. Geneva: International Organization of Standardization, 2011. 34 p.

iStock, 2021. Corrugated stock illustrations, Aaltopahvin paksuus. [Referred 24.10.2021.] Available: https://www.istockphoto.com/fi/vektori/aaltopahvin-paksuus-gm607759180

Jimenez, M.A., Conde, I., Garcia, B. & Liarte E. 2009. Design of Different Types of Corrugated Board Packages Using Finite Element Tools. Simula Customer Conference. 15 p.

Lähteenmäki, M. 2018. Elementtimenetelmän perusteet. Pp. 1–11. Available in PDF-file: https://mlahteen.fi/arkistot/elpe_pdf/johdanto.pdf

Mecmesin. 2020. Edge Crush Test (ECT) of corrugated cardboard. [Referred 28.10.2021.] Available: https://www.mecmesin.com/publications/edge-crush-test-ect-corrugated-cardboard

Navaranjan, Dickson, A., Paltakari, J. & Ilmonen, K. 2013. Humidity effect on compressive deformation and failure of recycled and virgin layered corrugated paperboard structures. Composites Part B: Engineering, 45:1. Pp. 965–971.

Robertson, B.F & Radcliffe, D.F. 2009. Impact of CAD tools on creative problem-solving in engineering design. Computer-aided design, 2009, 41:3. Pp. 136–146.

SCAN P 42:81. Paper and Board – CCT value and CCT index – Corrugated crush test, 42:81. Scandinavian Pulp, Paper and Board Testing Committee Methods. Kemesta, 2013. 3 p.

Shebab, E., Yatta, D., Hamed, M., & Wasim, A. 2013. Finite Element Analysis Process in Design Engineering: Best Practice. Concurrent Engineering Approaches for Sustainable Product Development in a Multi-Disciplinary Environment. Springer-Verlag London. Pp. 327–328.

Strömberg, F. 2016. Humidity´s effect on strength and stiffness of containerboard materials. A study in how the relative humidity in the ambient air affects the tensile and compression properties in linerboard and fluting mediums. Master Thesis. Karlstad University, Faculty of Health, Science and Technology, Department of Engineering and Chemical Science. Karlstad. 73 p.

Sustainable Packaging News. 2021. Metsä Board minimizes the environmental impact of packaging with Dassault Systèmes' simulation platform. [Referred 12.12.2021.] Available: https://spnews.com/metsaboard-minimises-environmental-impact/

Syrjä, M. 2019. Elementtimenetelmään perustuvan ohjelman käytön perusteet. Master Thesis. Aalto University, School of Engineering, Building Technology. Espoo. 153 p.

TAPPI T 825. Flat crush test of corrugated board (rigid support method). Technical Association of the Pulp and Paper Industry, 2014. 4 p.

Target Company. 2019. Production of corrugated board. [Referred 26.10.2021.]. Available at the Company Share Point, limited access.

Target Company. 2021. Proof of Concept documentation. [Referred 26.10.2021.] Available at the Company Share Point, limited access.

Thacker, B., Doebling, S., Hemez, F., Anderson, M., Pepin, J. & Rodriguez, E. 2004. Concepts of Model Verification and Validation. U.S. Department of Energy Office of Scientific and Technical Information. 27 p.

Van Hung, D., Nakanoa, Y., Tanakab, F., Hamanakab, D. & Uchino, T. 2010. Preserving the strength of corrugated cardboard under high humidity condition using nano-sized mists. Composites Science and Technology, 70:14. Pp. 2123–2127.

Zienkiewicz, O. C., Taylor, R. L. & Zhu, J. Z. 2013. The finite element method: its basis and fundamentals. 7th edition. Oxford, UK : Butterworth-Heinemann. 714 p.

Appendix 1: Test matrix

Test number	FEFCO	Glued	Handles	Ventilation holes	Crease (in height)	Perferation	Flute	Grammage	Minimum ECT	Length	Width	Height	Sample size
1	201	G	U				B	320	4	700	500	500	10
2	201	G	U		x		B	320	4	700	500	500	10
3	201	G	U		x		C	551	8	700	500	500	10
4	205	G	P	x			B	430	6	500	350	400	10
5	205	G	P	x			C	390	5	500	350	400	10
6	215	G		x			B	430	6	600	400	400	10
7	215	G		x			C	551	8	600	400	400	10
8	711	G	P	x			B	320	4	280	250	180	10
9	711	G	P	x			C	551	8	280	250	180	10
10	713	G					B	320	4	350	300	250	10
11	713	G				x	B	320	4	350	300	250	10
12	713	G				x	C	390	5	350	300	250	10
13	501	G					EB	485	7	200	200	195	10
14	501	G					EB	485	7	200	200	300	10
15	501	G					EB	485	7	200	200	500	10
16	501	G					BC	545	8	200	200	195	10
17	501	G					BC	545	8	200	200	300	10
18	501	G					BC	545	8	200	200	500	10

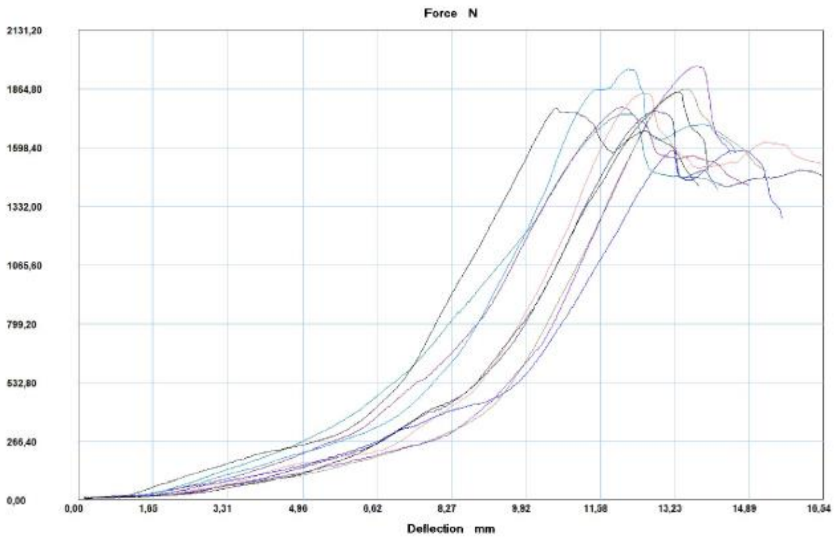
Appendix 2: Physical BCT testing results

BOX 1

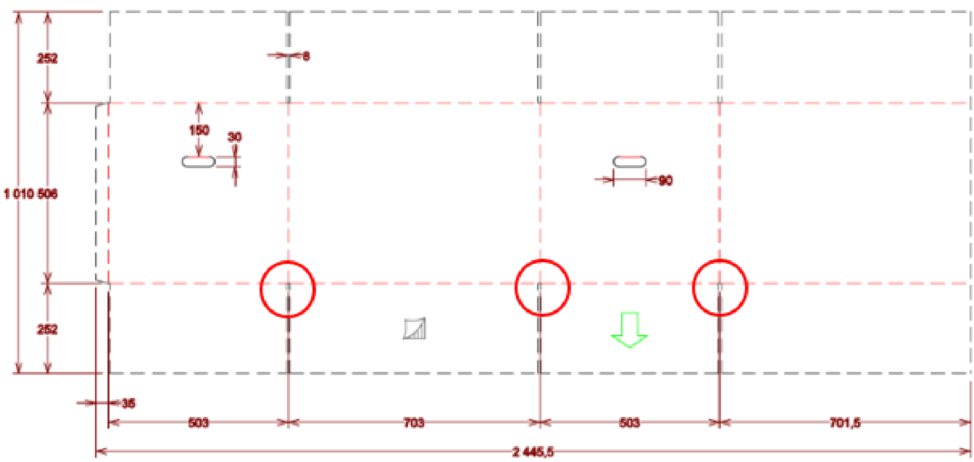
Inner dimensions: 700x500x500 mm

Material: B320

FEFCO / Special geometry: 0201 / Glued, U handle



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1750,00	12,10	178,33
2	1765,00	12,78	179,85
3	1966,00	13,68	200,34
4	1783,00	12,03	181,69
5	1955,00	12,19	199,21
6	1844,00	12,58	187,90
7	1588,00	13,17	161,82
8	1864,00	13,50	189,94
9	1852,00	13,24	188,72
10	1776,00	10,58	180,97
Mean	1814,300	12,584	184,877
Desv. Std	109,446	0,917	11,153
Coef. V.	0,060	0,073	0,060

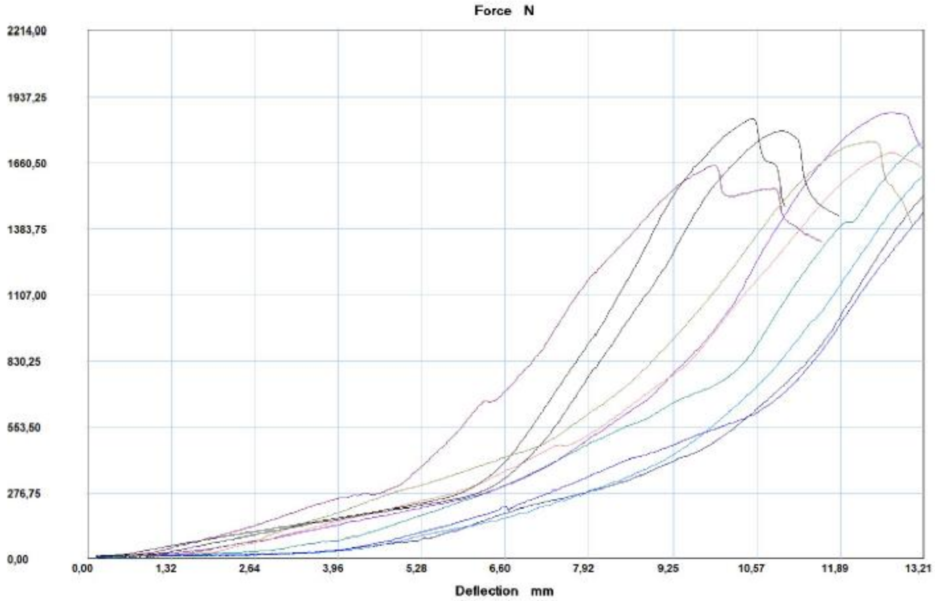


BOX 2

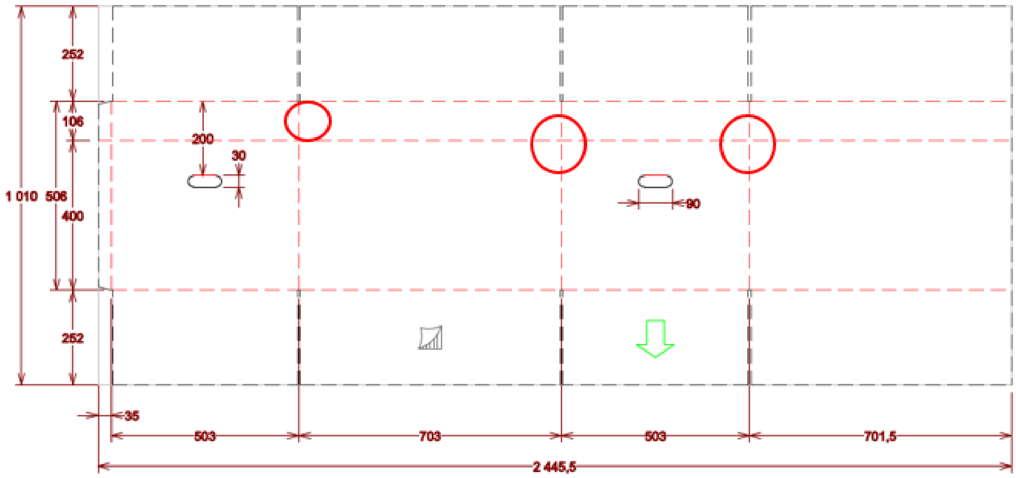
Inner dimensions: 700x500x500 mm

Material: B320

FEFCO / Special geometry: 0201 / Glued, U handles, Crease in height



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1766,00	13,32	179,96
2	1614,00	13,67	164,47
3	1872,00	12,65	190,76
4	1649,00	9,91	168,03
5	1815,00	14,36	184,95
6	1704,00	12,71	173,64
7	1711,00	14,42	174,35
8	1751,00	12,37	178,43
9	1795,00	10,99	182,91
10	1845,00	10,48	188,01
Mean	1752,200	12,488	178,549
Desv. Std	83,468	1,577	8,505
Coef. V.	0,048	0,126	0,048

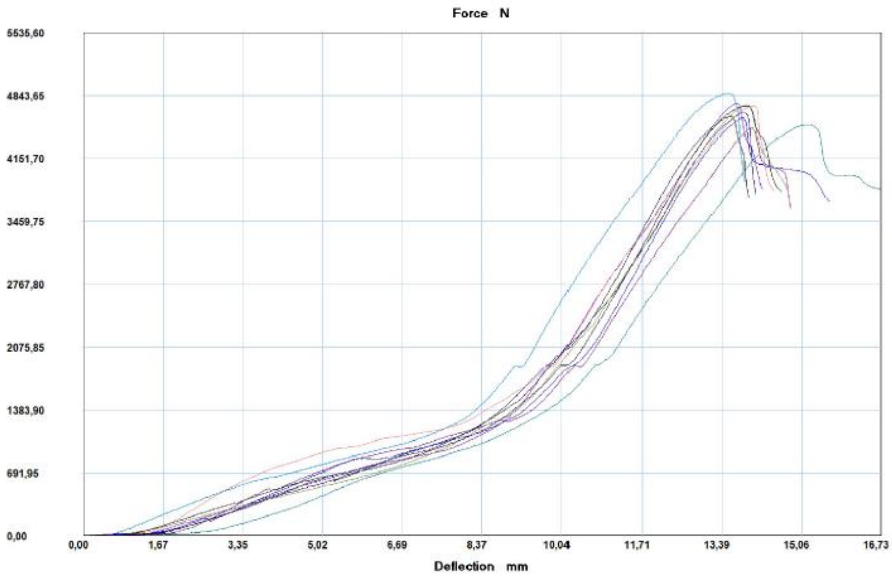


BOX 3

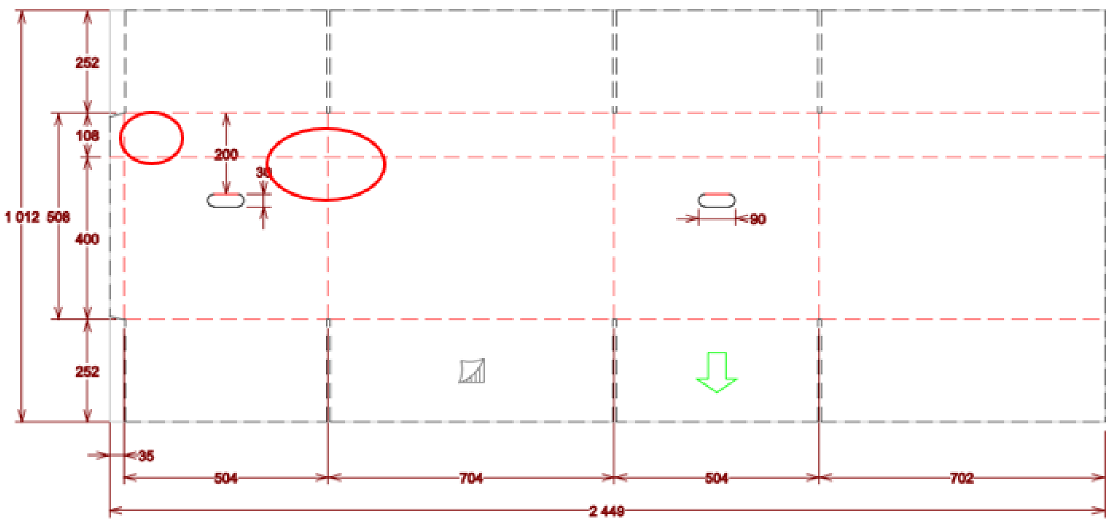
Inner dimensions: 700x500x500 mm

Material: C551

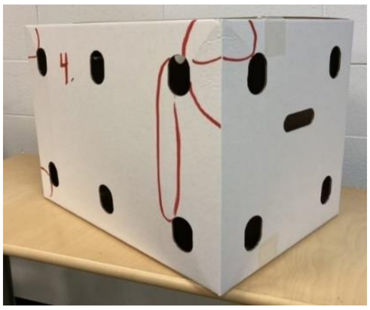
FEFCO / Special geometry: 0201 / Glued, U handles, crease in height



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	4525,00	15,22	461,10
2	4654,00	13,81	474,24
3	4751,00	13,68	484,13
4	4493,00	14,00	457,84
5	4868,00	13,51	496,05
6	4730,00	14,04	481,99
7	4598,00	13,81	468,54
8	4738,00	13,87	482,80
9	4733,00	13,90	482,29
10	4613,00	13,57	470,06
Mean	4670,300	13,940	475,904
Desv. Std	114,988	0,482	11,717
Coef. V.	0,025	0,035	0,025



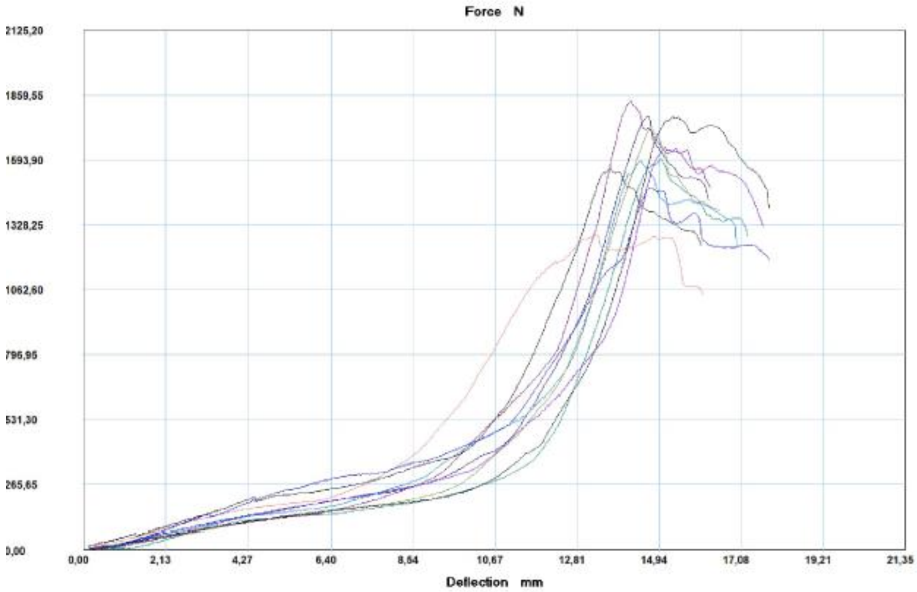
BOX 4



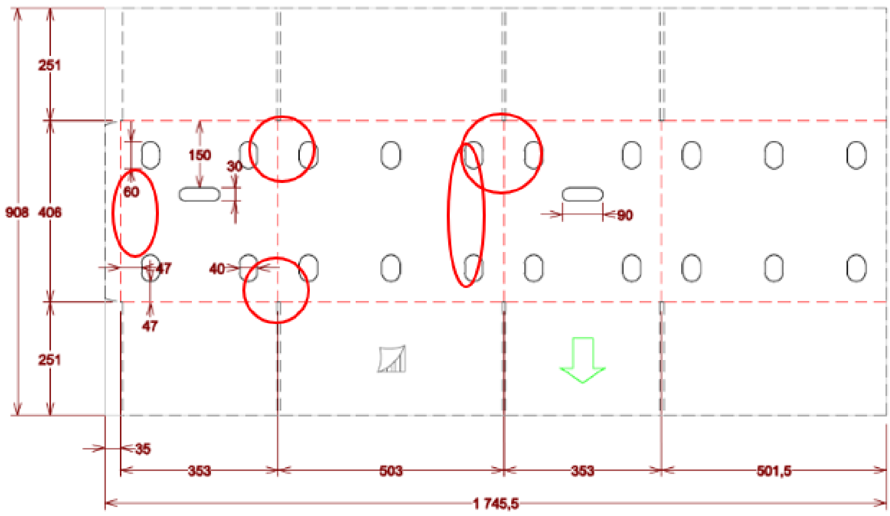
Inner dimensions: 500x350x400 mm

Material: B430

FEFCO / Special geometry: 0205 / Glued, P handles, ventilation holes



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1596,00	14,99	162,63
2	1773,00	14,63	180,67
3	1647,00	15,09	167,83
4	1838,00	14,20	187,29
5	1590,00	14,46	162,02
6	1288,00	13,26	131,25
7	1480,00	14,73	150,81
8	1730,00	14,74	176,29
9	1561,00	13,67	159,07
10	1771,00	15,30	180,46
Mean	1627,400	14,508	165,832
Desv. Std	163,570	0,640	16,668
Coef. V.	0,101	0,044	0,101

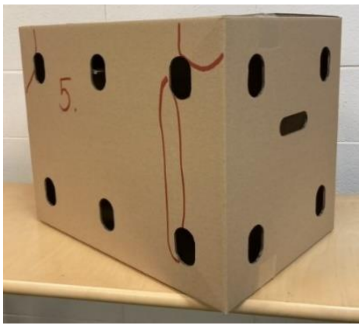


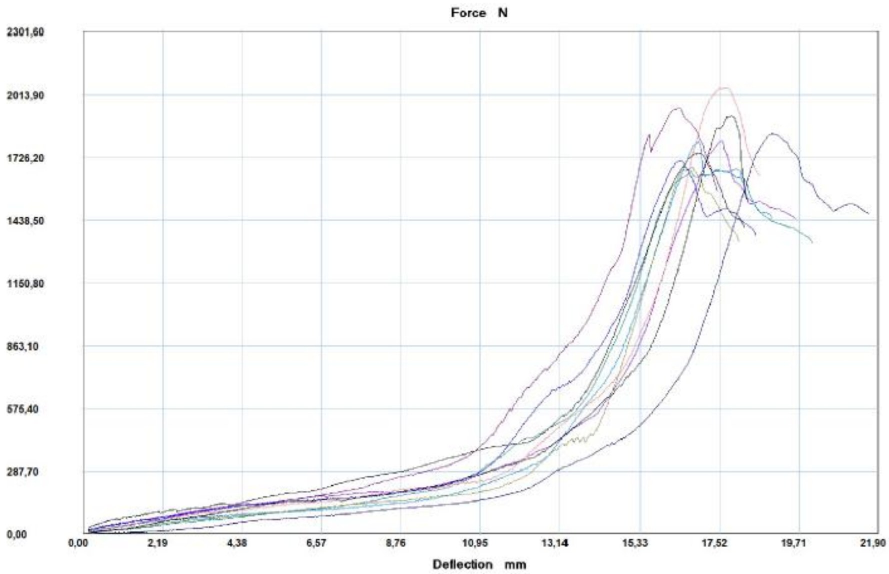
BOX 5

Inner dimensions: 500x350x400 mm

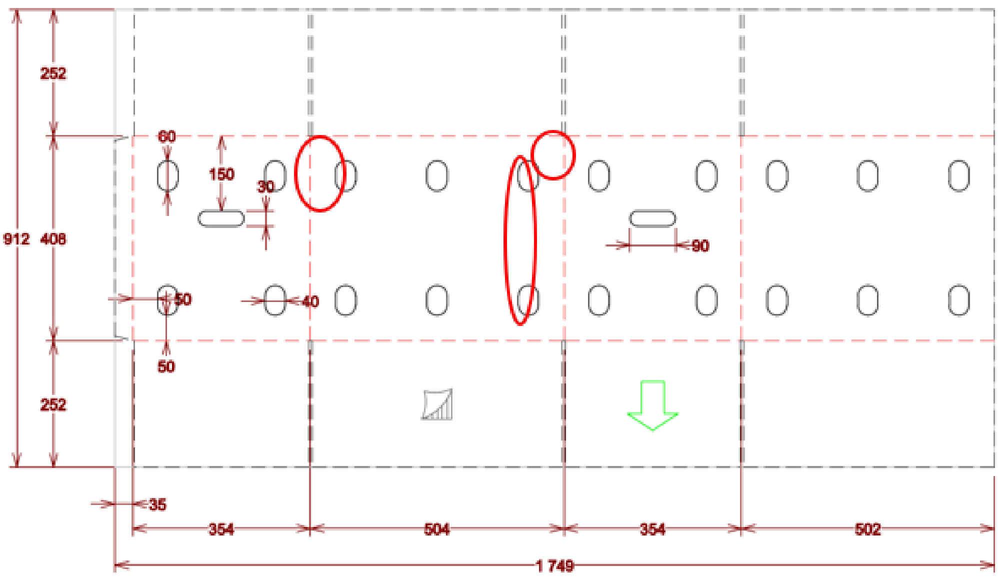
Material: C390

FEFCO / Special geometry: 0205 / Glued, P handles, ventilation holes





Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1666,00	17,55	169,77
2	1837,00	18,98	187,19
3	1804,00	17,59	183,83
4	1953,00	16,42	199,01
5	1800,00	16,94	183,42
6	2047,00	17,63	208,59
7	1714,00	16,46	174,66
8	1681,00	16,75	171,29
9	1746,00	16,89	177,92
10	1918,00	17,83	195,44
Mean	1816,600	17,304	185,112
Desv. Std	124,455	0,778	12,682
Coef. V.	0,069	0,045	0,069

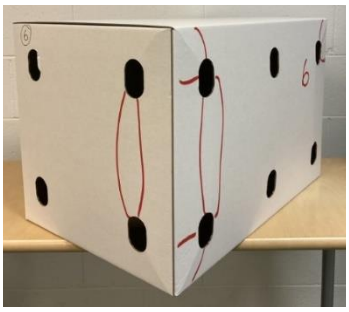


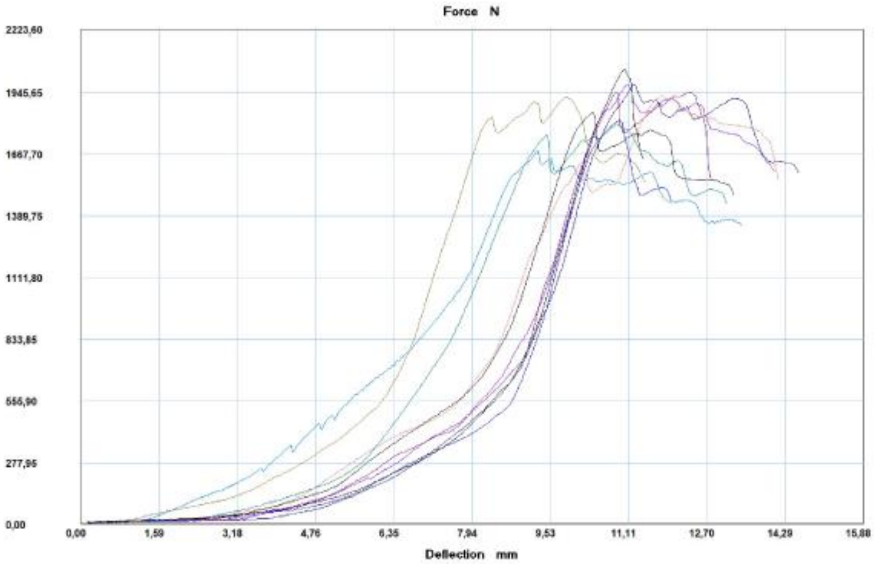
BOX 6

Inner dimensions: 600x400x400 mm

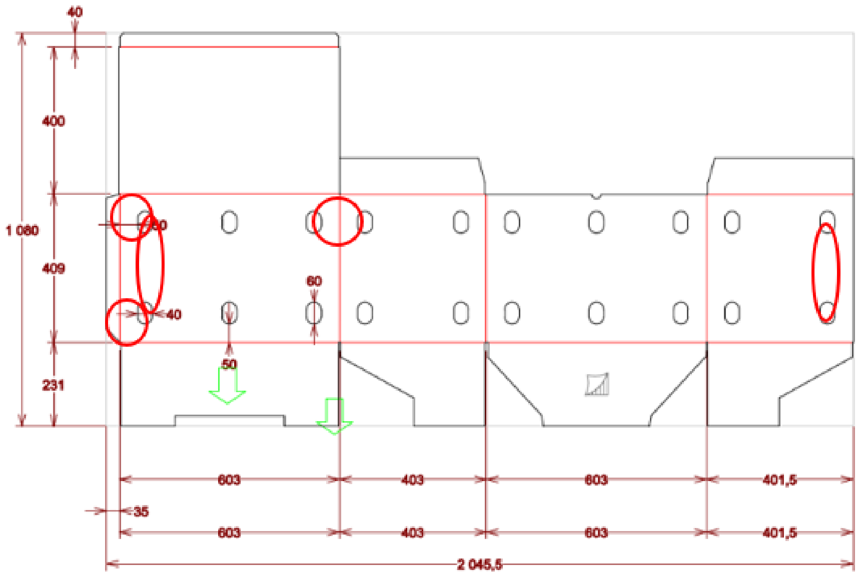
Material: B430

FEFCO / Special geometry: 0215 / Glued, ventilation holes





Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1805,00	10,86	183,93
2	1980,00	11,24	201,76
3	1983,00	11,10	202,07
4	1949,00	10,86	198,60
5	1684,00	9,27	171,60
6	1930,00	11,78	196,67
7	1820,00	10,92	185,46
8	1923,00	9,86	195,95
9	2050,00	11,03	208,90
10	1853,00	10,38	188,82
Mean	1897,700	10,729	193,376
Desv. Std	107,422	0,720	10,946
Coef. V.	0,057	0,067	0,057

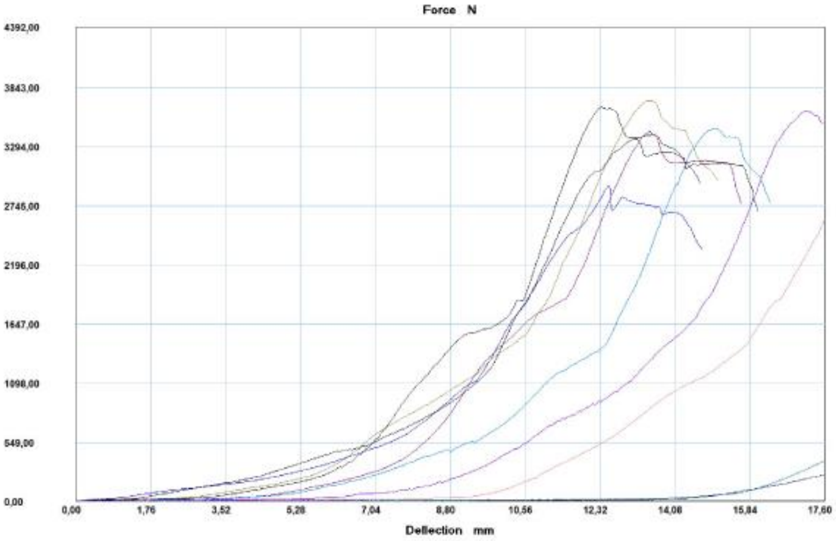


BOX 7

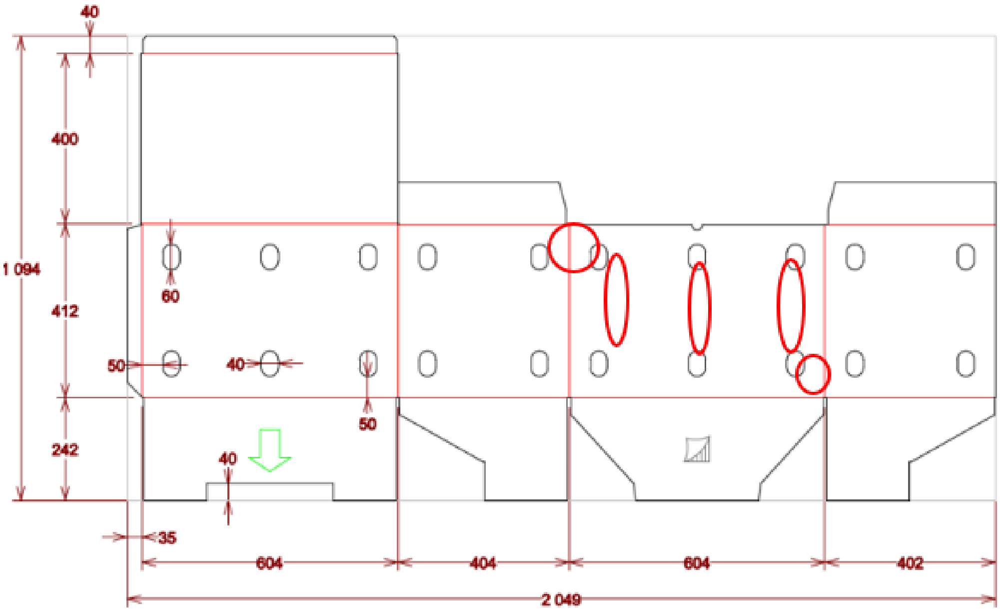
Inner dimensions: 600x400x400 mm

Material: C551

FEFCO / Special geometry: 0215 / Glued, ventilation holes



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	3212,00	24,27	327,30
2	3610,00	25,75	367,86
3	3628,00	17,14	369,69
4	3433,00	13,48	349,82
5	3462,00	15,01	352,78
6	3817,00	19,20	388,95
7	2934,00	12,53	298,97
8	3718,00	13,40	378,86
9	3367,00	13,16	343,10
10	3660,00	12,34	372,95
Mean	3484,100	16,628	355,030
Desv. Std	263,837	4,927	26,885
Coef. V.	0,076	0,296	0,076

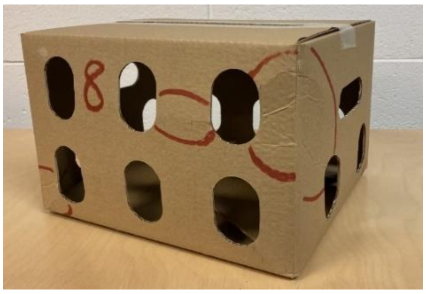


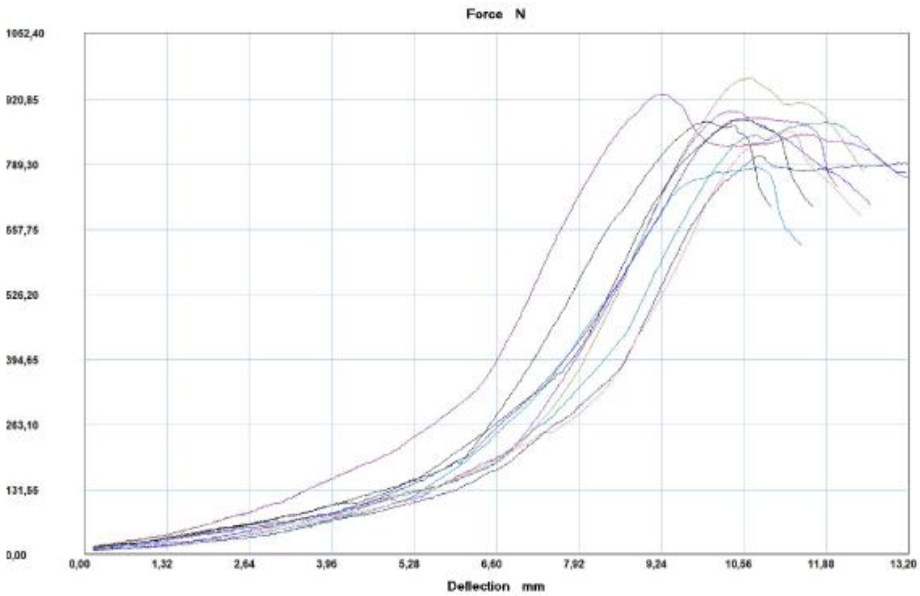
BOX 8

Inner dimensions: 280x250x180 mm

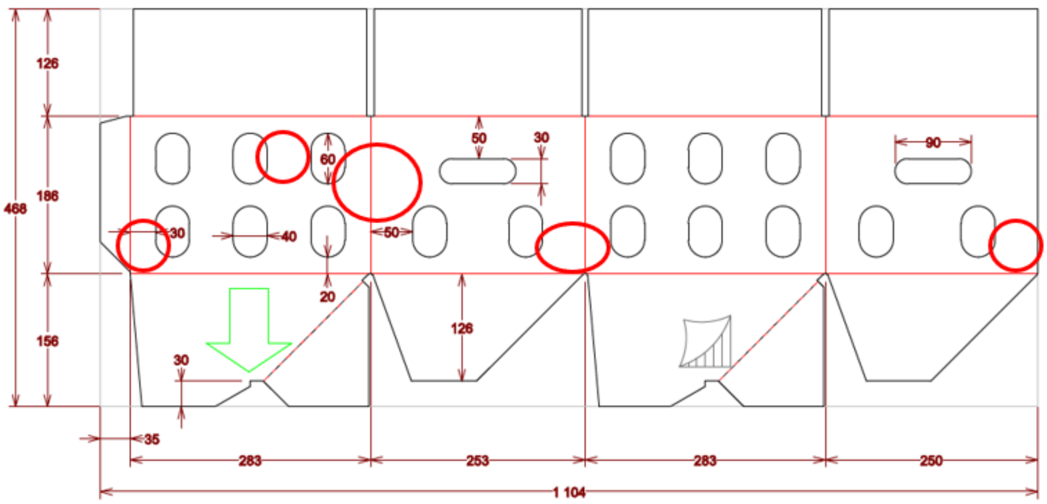
Material: B320

FEFCO / Special geometry: 0711 / Glued, P handles, ventilation holes





Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	875,00	11,84	89,16
2	806,00	10,77	82,13
3	897,00	10,32	91,40
4	932,00	9,25	94,97
5	782,00	10,71	79,69
6	858,00	11,19	87,43
7	883,00	10,61	89,98
8	965,00	10,68	98,33
9	880,00	10,42	89,67
10	877,00	9,96	89,37
Mean	875,500	10,574	89,213
Desv. Std	53,357	0,688	5,437
Coef. V.	0,061	0,065	0,061



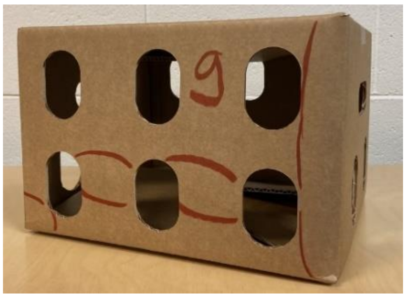
BOX 9

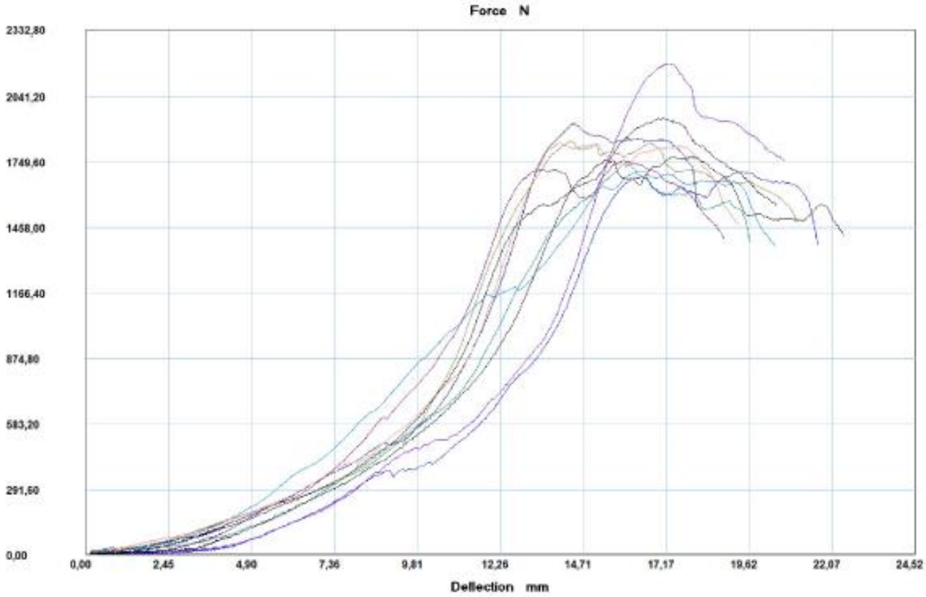
Inner dimensions: 280x250x180 mm

Material: C551

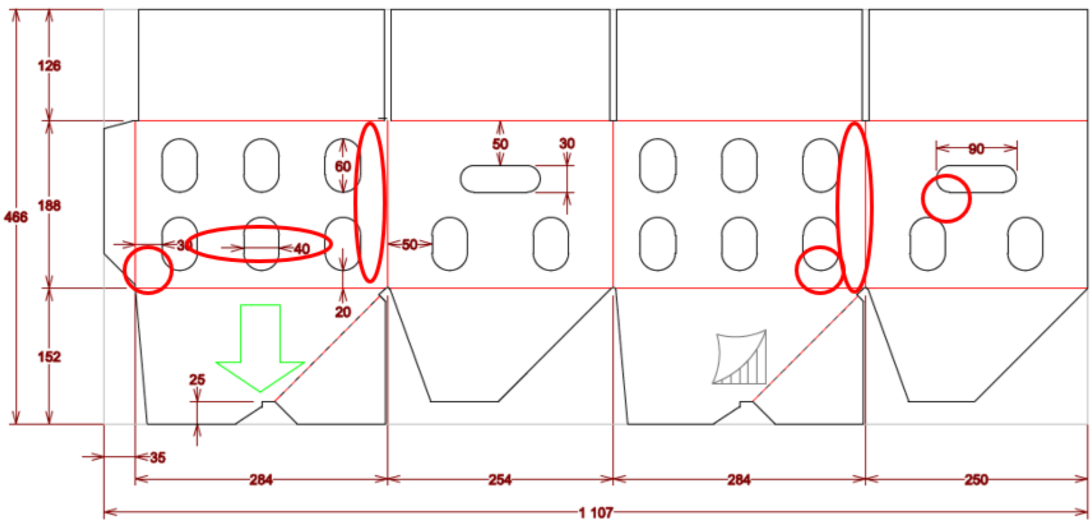
FEFCO / Special geometry:

0711 / Glued, P handles, ventilation holes





Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1744,00	15,95	177,71
2	1921,00	14,38	195,75
3	2190,00	17,24	223,16
4	1756,00	15,89	178,94
5	1710,00	16,38	174,25
6	1836,00	14,03	187,09
7	1707,00	19,31	173,94
8	1845,00	14,34	188,01
9	1778,00	17,86	181,18
10	1944,00	16,91	198,09
Mean	1843,100	16,231	187,812
Desv. Std	147,017	1,687	14,981
Coef. V.	0,080	0,104	0,080

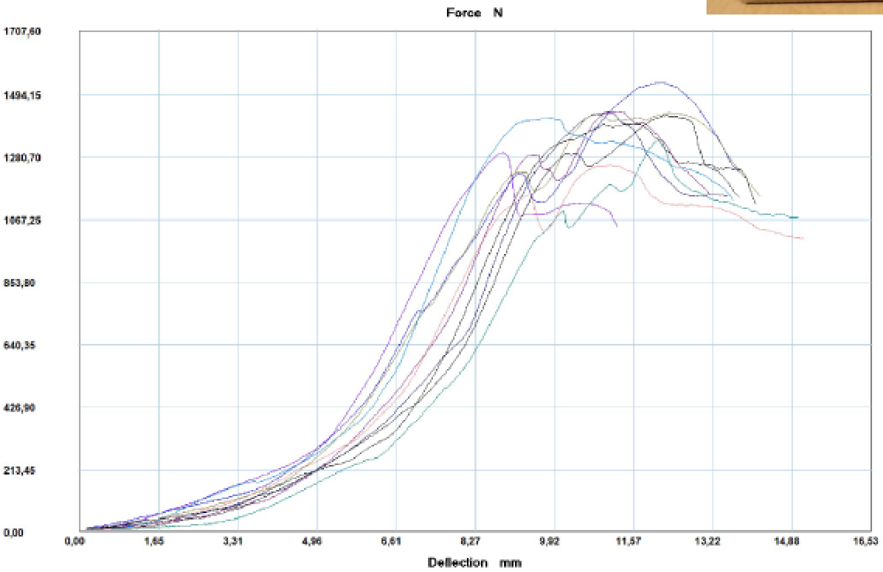


BOX 10

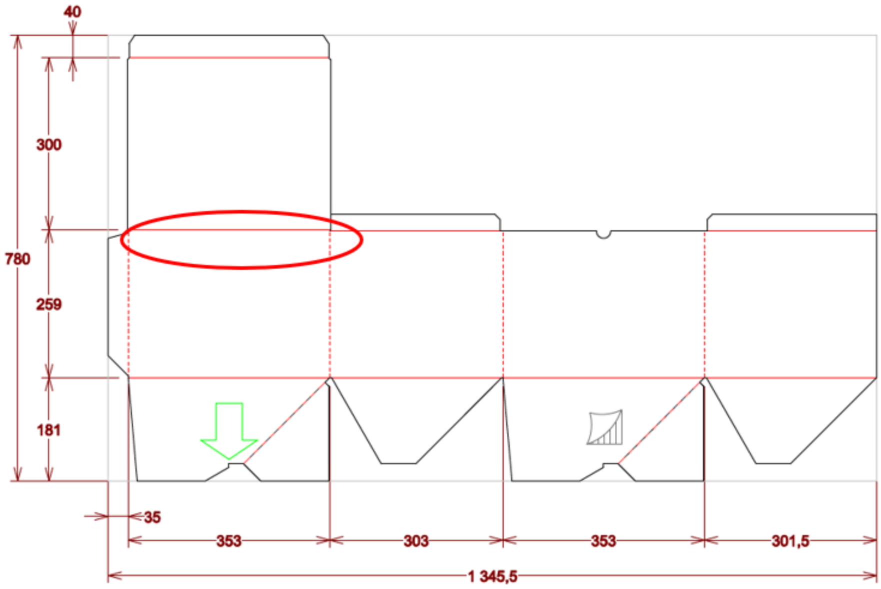
Inner dimensions: 350x300x250 mm

Material: B320

FEFCO / Special geometry: 0713 / Glued



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1342,00	12,10	136,75
2	1432,00	11,03	145,92
3	1296,00	8,84	132,06
4	1438,00	11,06	146,53
5	1414,00	9,83	144,09
6	1255,00	11,04	127,88
7	1535,00	12,05	156,42
8	1432,00	12,30	145,92
9	1395,00	11,55	142,15
10	1423,00	12,19	145,00
Mean	1396,200	11,200	142,273
Desv. Std	79,950	1,123	8,147
Coef. V.	0,057	0,100	0,057



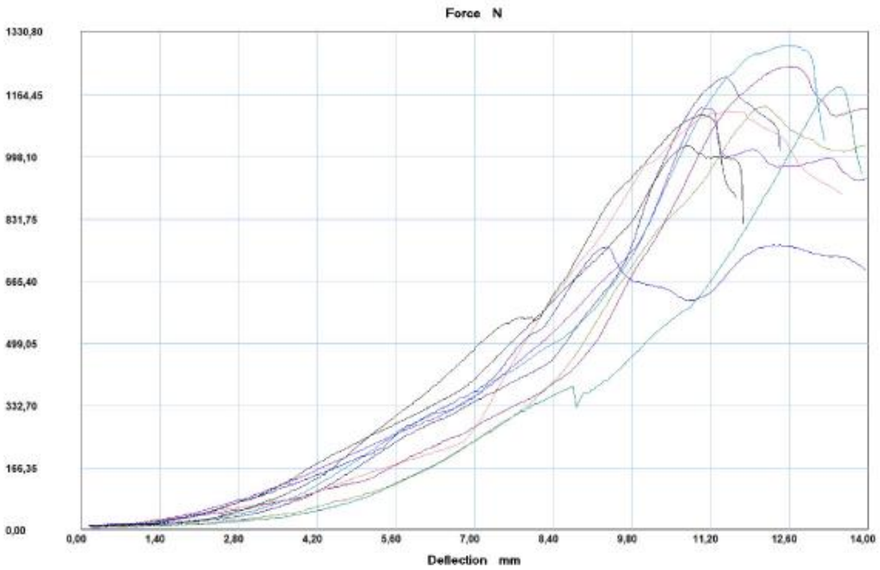
BOX 11

Inner dimensions: 350x300x250 mm

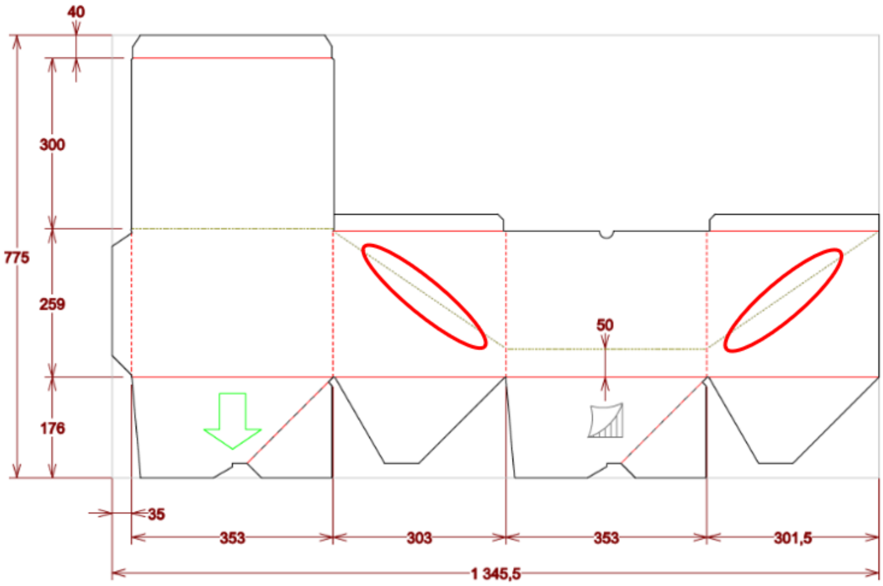
Material: B320

FEFCO / Special geometry:

0713 / Glued, perforation



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1186,00	13,51	120,85
2	1212,00	11,45	123,50
3	1130,00	11,03	115,15
4	1242,00	12,57	126,56
5	1296,00	12,46	132,06
6	1121,00	11,51	114,23
7	763,00	12,31	77,75
8	1133,00	12,12	115,45
9	1028,00	10,79	104,75
10	1109,00	10,99	113,01
Mean	1122,000	11,875	114,332
Desv. Std	147,175	0,865	14,997
Coef. V.	0,131	0,073	0,131



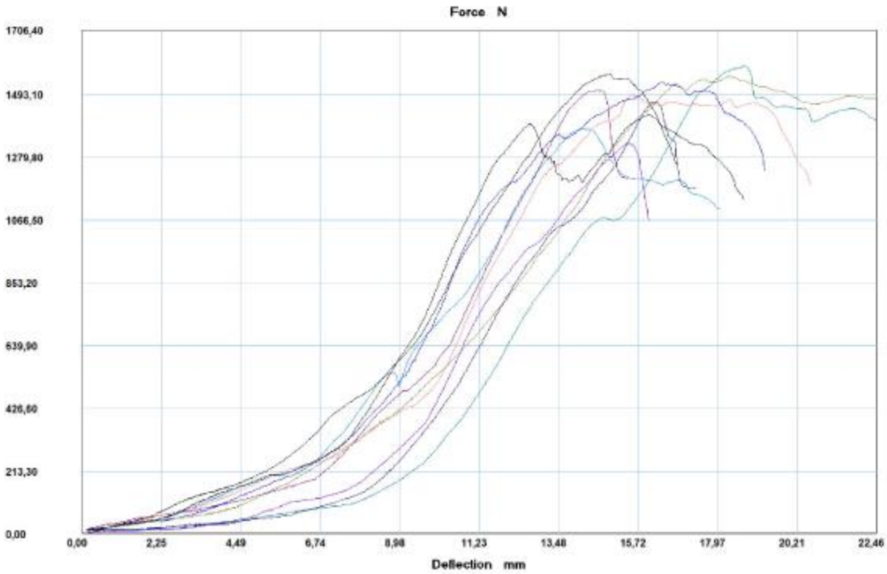
BOX 12

Inner dimensions: 350x300x250 mm

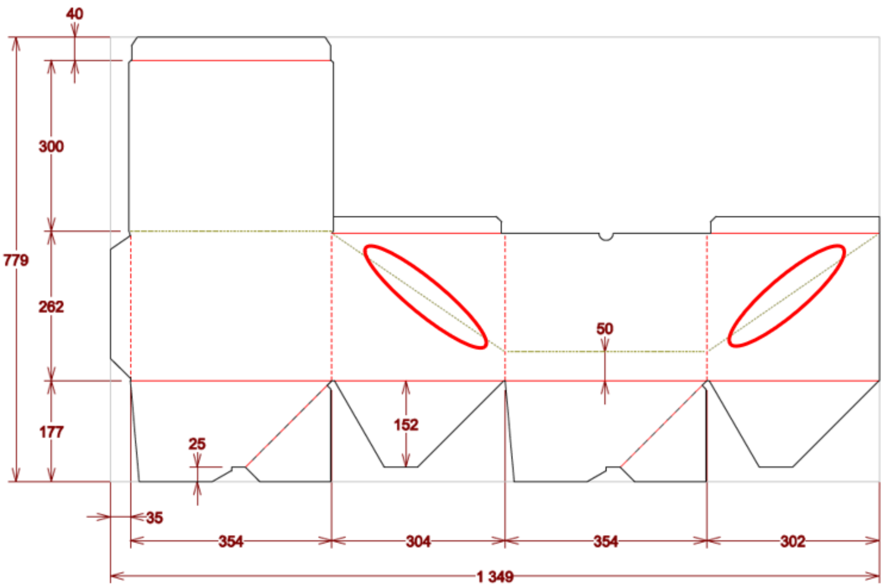
Material: C390

FEFCO / Special geometry:

0713 / Glued, perforation



Specimen	MaxF N	Def.MaxF mm	MaxF kg
1	1591,00	18,73	162,12
2	1466,00	16,12	149,39
3	1328,00	15,44	135,32
4	1508,00	14,57	153,67
5	1377,00	14,19	140,32
6	1490,00	15,53	151,83
7	1535,00	16,41	156,42
8	1556,00	18,31	158,56
9	1563,00	14,93	159,27
10	1422,00	15,96	144,90
Mean	1483,600	16,020	151,179
Desv. Std	85,660	1,489	8,729
Coef. V.	0,058	0,093	0,058

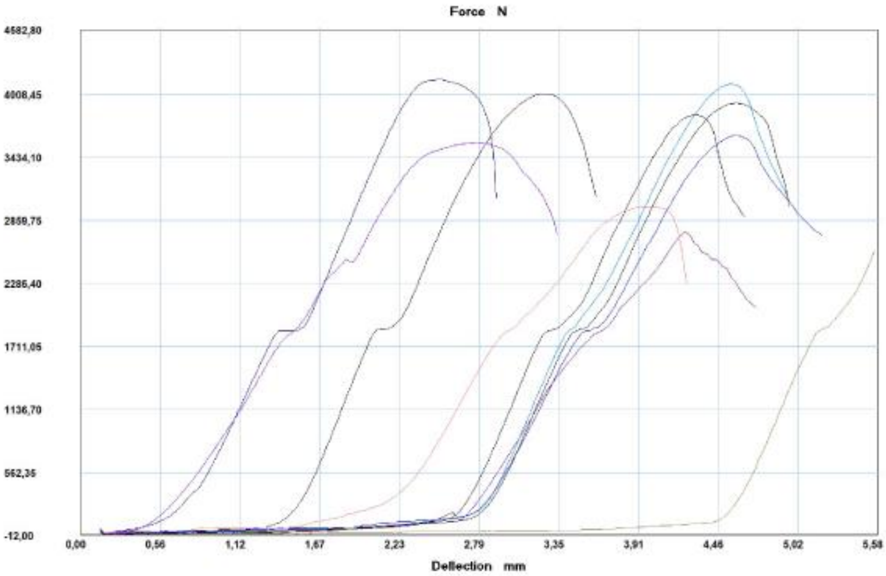


BOX 13

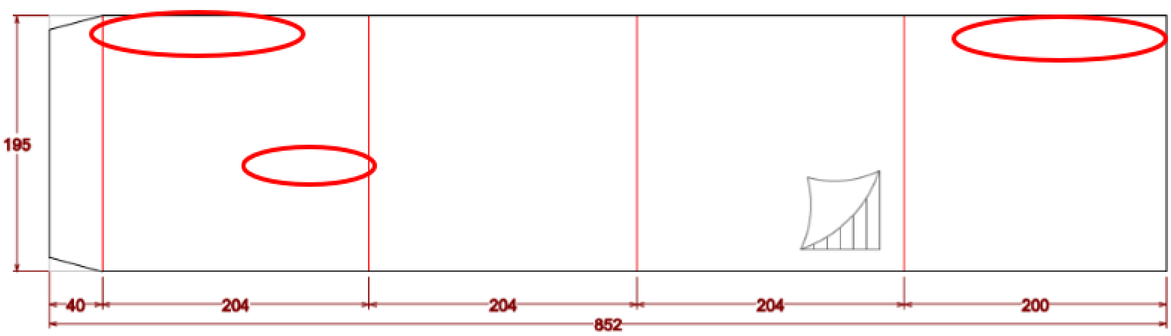
Inner dimensions: 200x200x195 mm

Material: EB485

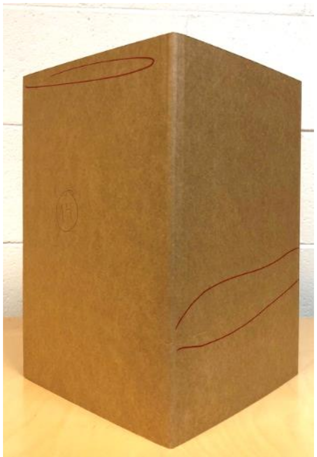
FEFCO / Special geometry: 0501 / Glued



Specimen	MaxF N	Def.MaxF mm	MaxL kg/mm2	MaxF kg
1	4015,00	3,25	0,01	409,13
2	4142,00	2,50	0,01	422,07
3	3568,00	2,74	0,01	363,58
4	2757,00	4,23	0,01	280,94
5	4101,00	4,55	0,01	417,89
6	2980,00	4,01	0,01	303,66
7	3637,00	4,57	0,01	370,61
8	3754,00	6,15	0,01	382,53
9	3929,00	4,59	0,01	400,37
10	3819,00	4,29	0,01	389,16
Mean	3670,200	4,088	0,009	373,993
Desv. Std	464,886	1,057	0,001	47,372
Coef. V.	0,127	0,259	0,127	0,127



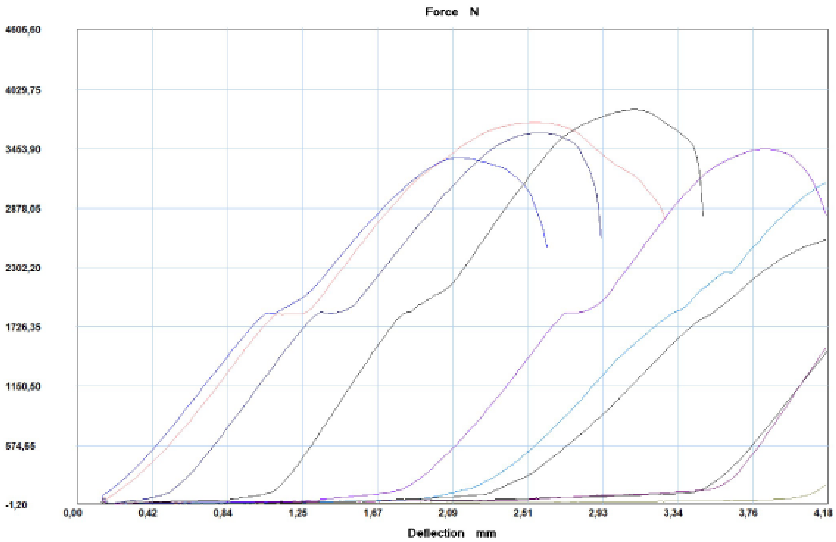
BOX 14



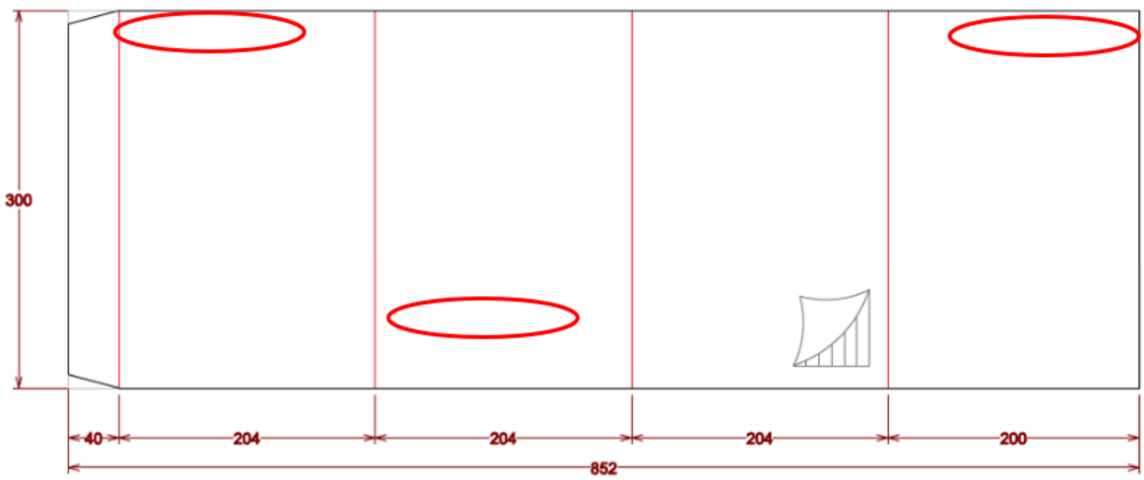
Inner dimensions: 200x200x300 mm

Material: EB485

FEFCO / Special geometry: 0501 / Glued



Specimen	MaxF N	Def.MaxF mm	MaxL kg/mm2	MaxF kg
1	3463,00	5,59	0,01	352,88
2	3610,00	2,55	0,01	367,86
3	3453,00	3,82	0,01	351,86
4	3858,00	5,54	0,01	393,13
5	3180,00	4,30	0,01	324,04
6	3708,00	2,55	0,01	377,85
7	3373,00	2,13	0,01	343,71
8	2307,00	5,83	0,01	235,08
9	2608,00	4,27	0,01	265,76
10	3838,00	3,09	0,01	391,09
Mean	3339,800	3,968	0,009	340,326
Desv. Std	514,474	1,374	0,001	52,425
Coef. V.	0,154	0,346	0,154	0,154

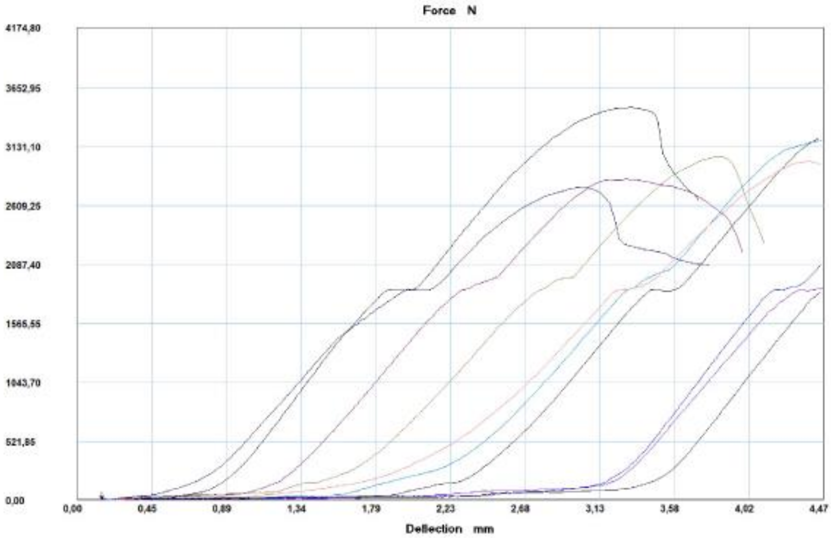


BOX 15

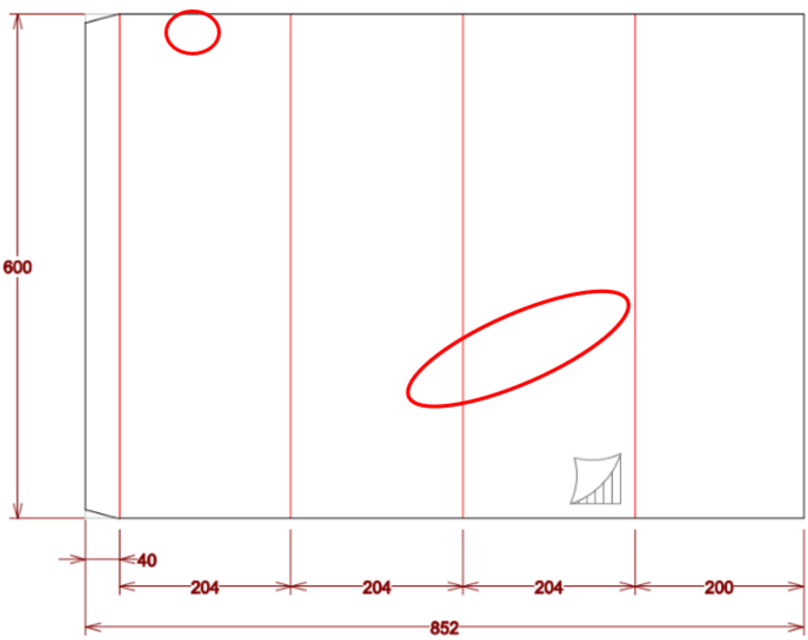
Inner dimensions: 200x200x500 mm

Material: EB485

FEFCO / Special geometry: 0501 / Glued



Specimen	MaxF N	Def.MaxF mm	MaxL kg/mm2	MaxF kg
1	3271,00	4,69	0,01	333,31
2	2775,00	3,02	0,01	282,77
3	3344,00	5,83	0,01	340,75
4	2844,00	3,29	0,01	289,80
5	3198,00	4,51	0,01	325,88
6	3003,00	4,37	0,01	306,01
7	3507,00	5,63	0,01	357,36
8	3040,00	3,83	0,01	309,78
9	3771,00	6,07	0,01	384,26
10	3479,00	3,31	0,01	354,51
Mean	3223,200	4,455	0,008	328,444
Desv. Std	314,519	1,109	0,001	32,049
Coef. V.	0,098	0,249	0,098	0,098

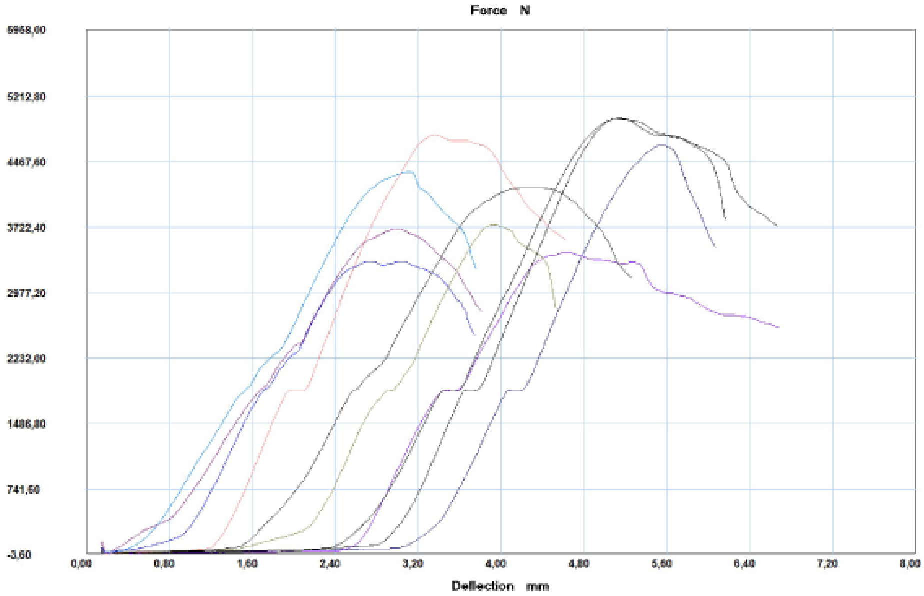


BOX 16

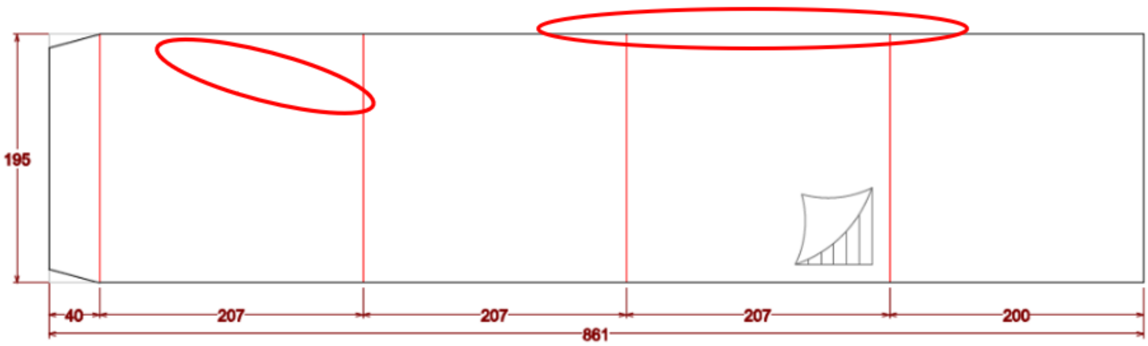
Inner dimensions: 200x200x195 mm

Material: BC545

FEFCO / Special geometry: 0501 / Glued



Specimen	MaxF N	Def.MaxF mm	MaxL kg/mm2	MaxF kg
1	4960,00	5,12	0,01	505,42
2	4652,00	5,55	0,01	474,04
3	3434,00	4,63	0,01	349,92
4	3700,00	2,99	0,01	377,03
5	4352,00	3,12	0,01	443,47
6	4773,00	3,35	0,05	486,37
7	3334,00	2,72	0,03	339,73
8	3750,00	3,91	0,04	382,13
9	4176,00	4,25	0,04	425,53
10	4965,00	5,13	0,05	505,93
Mean	4209,600	4,076	0,027	428,958
Desv. Std	624,271	1,012	0,018	63,613
Coef. V.	0,148	0,248	0,655	0,148

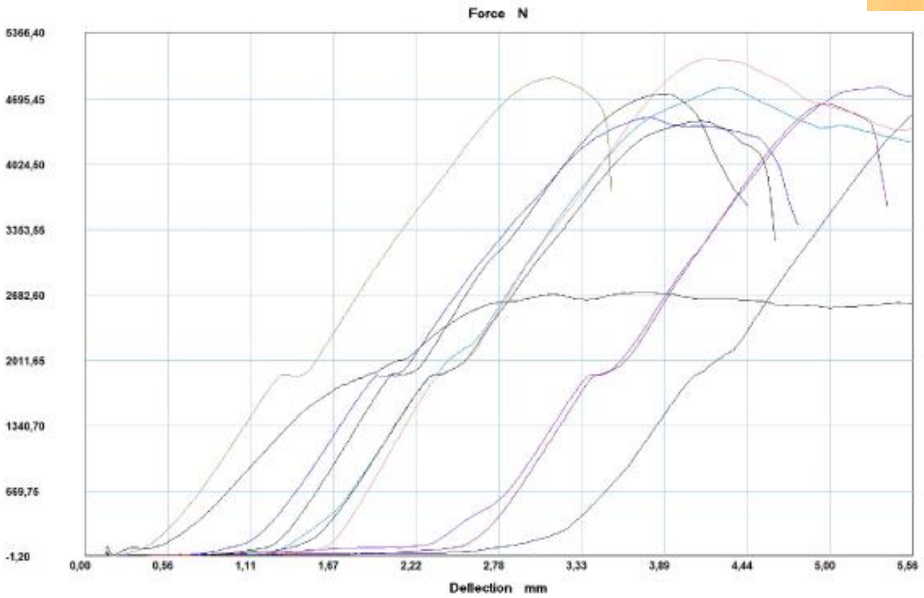


BOX 17

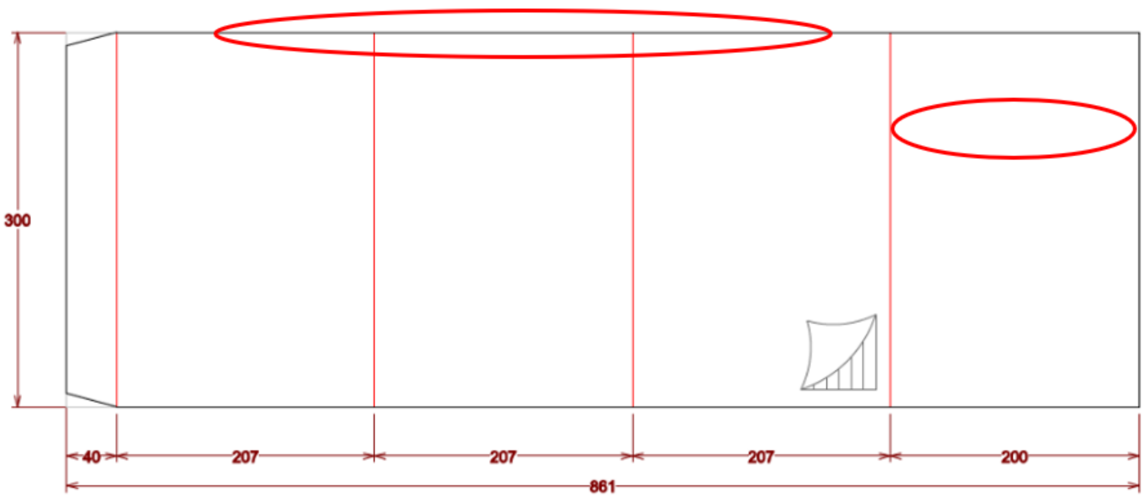
Inner dimensions: 200x200x300 mm

Material: BC545

FEFCO / Special geometry: 0501 / Glued



Specimen	MaxF N	Def.MaxF mm	MaxL kg/mm2	MaxF kg
1	4601,00	12,02	0,01	468,84
2	5019,00	6,14	0,01	511,44
3	4820,00	5,32	0,01	491,16
4	4649,00	4,97	0,01	473,73
5	4814,00	4,30	0,01	490,55
6	5107,00	4,20	0,01	520,40
7	4509,00	3,77	0,01	459,47
8	4921,00	3,14	0,01	501,45
9	4750,00	3,86	0,01	484,03
10	4472,00	4,13	0,01	455,70
Mean	4766,200	5,185	0,012	485,676
Desv. Std	211,657	2,549	0,001	21,568
Coef. V.	0,044	0,492	0,044	0,044

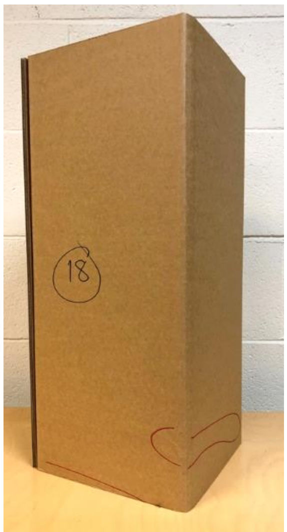


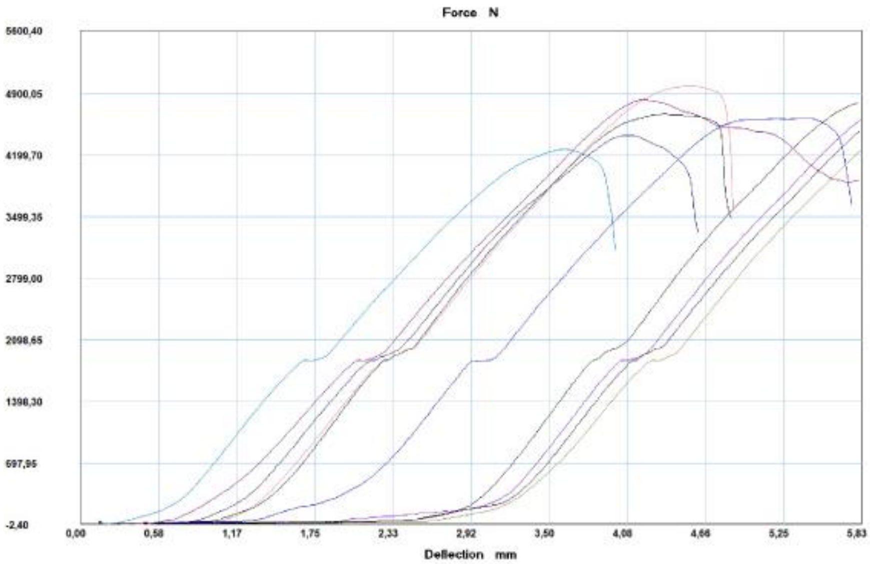
BOX 18

Inner dimensions: 200x200x500 mm

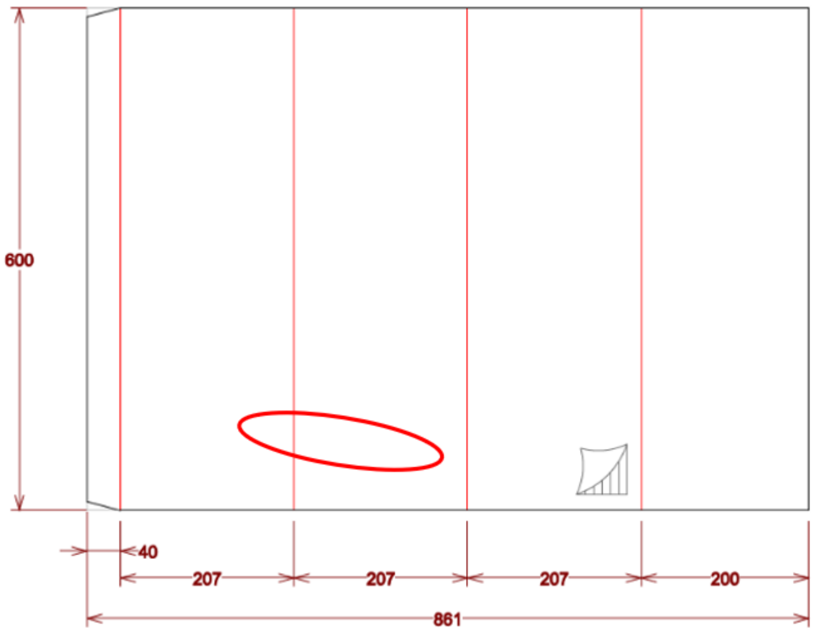
Material: BC545

FEFCO / Special geometry: 0501 / Glued





Specimen	MaxF N	Def.MaxF mm	MaxL kg/mm2	MaxF kg
1	4834,00	5,92	0,01	492,58
2	4426,00	4,09	0,01	451,01
3	4811,00	6,16	0,01	490,24
4	4829,00	4,20	0,01	492,08
5	4269,00	3,61	0,01	435,01
6	4986,00	4,54	0,01	508,07
7	4619,00	5,43	0,01	470,68
8	4527,00	6,15	0,01	461,30
9	4975,00	6,39	0,01	506,95
10	4667,00	4,34	0,01	475,57
Mean	4694,300	5,084	0,012	478,349
Desv. Std	236,274	1,034	0,001	24,076
Coef. V.	0,050	0,203	0,050	0,050



Appendix 3: Virtual BCT testing results

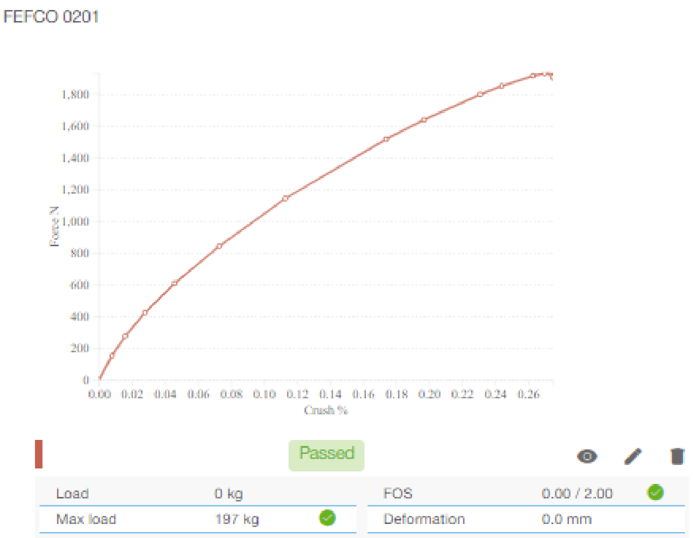
BOX 1

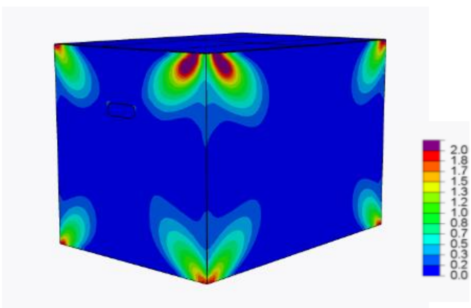
Inner dimensions: 700x500x500 mm

Material: B320

FEFCO / Special geometry: 0201 / Glued, U handles

Test 1





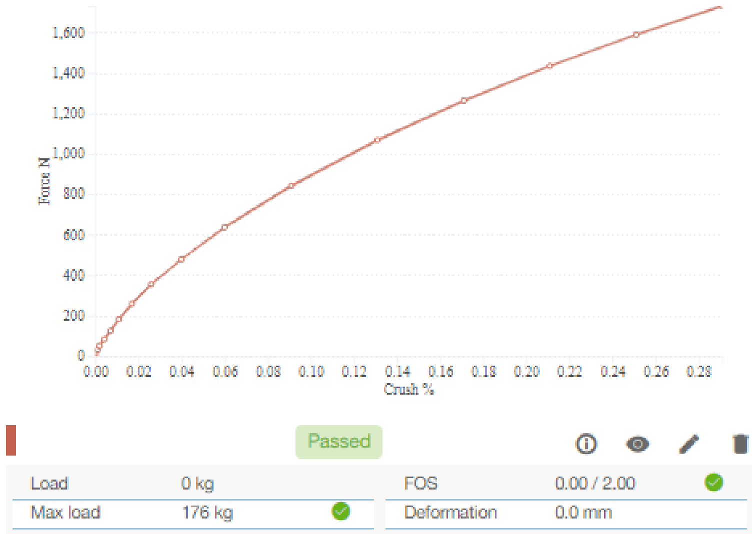
BOX 1

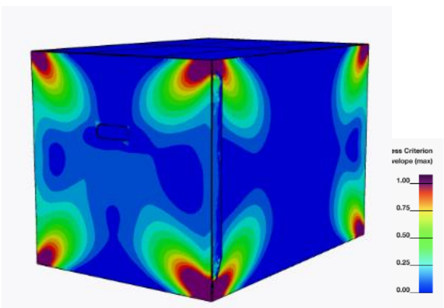
Inner dimensions: 700x500x500 mm

Material: B320

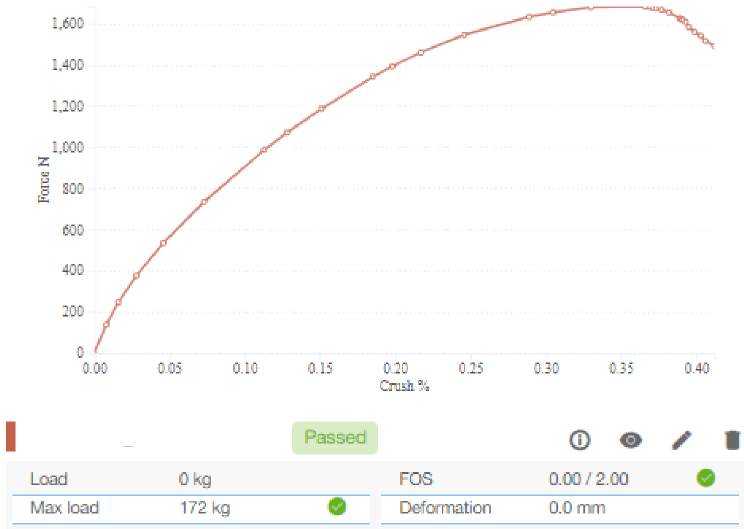
FEFCO / Special geometry: 0201 / Glued, U handles

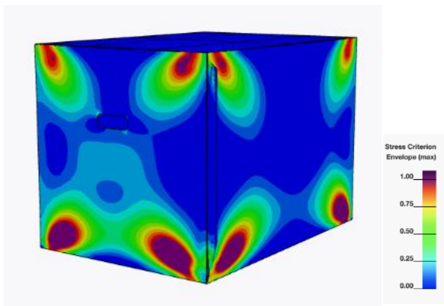
Test with fixed material data, elastic





Test with fixed material data, plastic





BOX 2

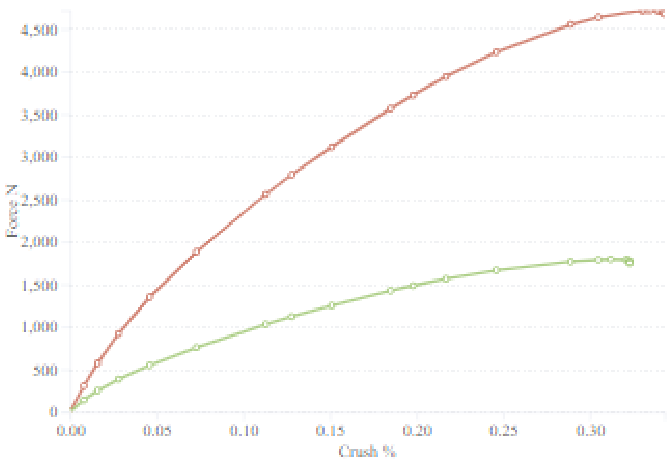
Inner dimensions: 700x500x500 mm

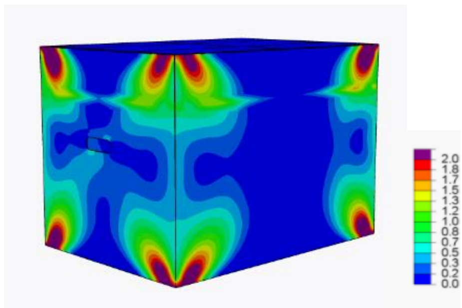
Material: B320

FEFCO / Special geometry: 0201 / Glued, U handles, Crease in height

Test 1

FEFCO 0201





Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	183 kg	Deformation	0.0 mm

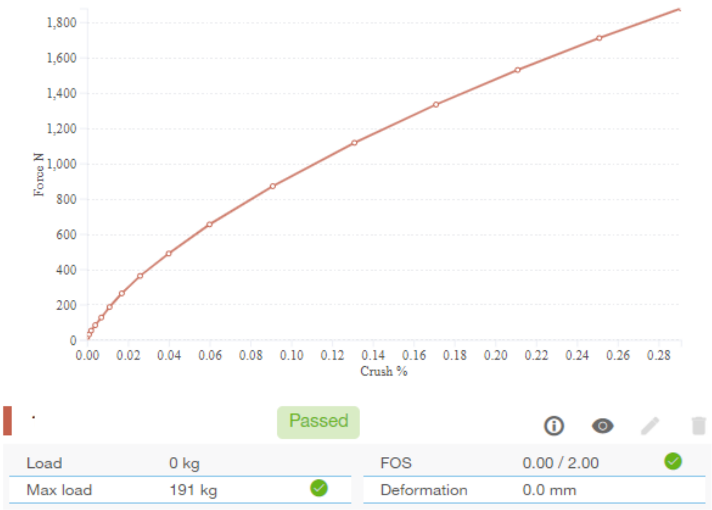
BOX 2

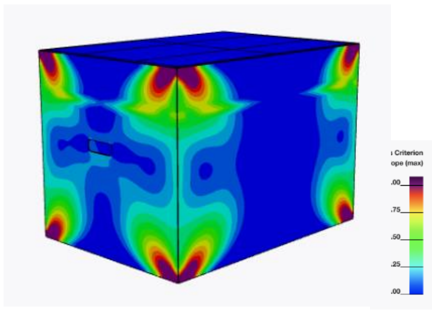
Inner dimensions: 700x500x500 mm

Material: B320

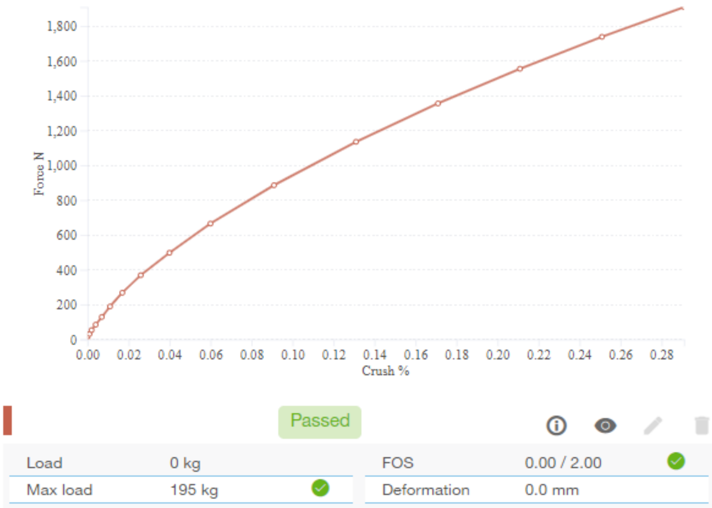
FEFCO / Special geometry: 0201 / Glued, U handles, Crease in height

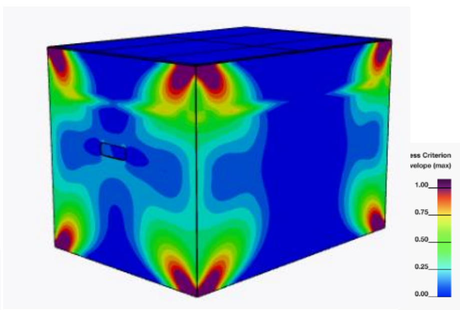
Test with fixed material data, elastic





Test with fixed material data, plastic





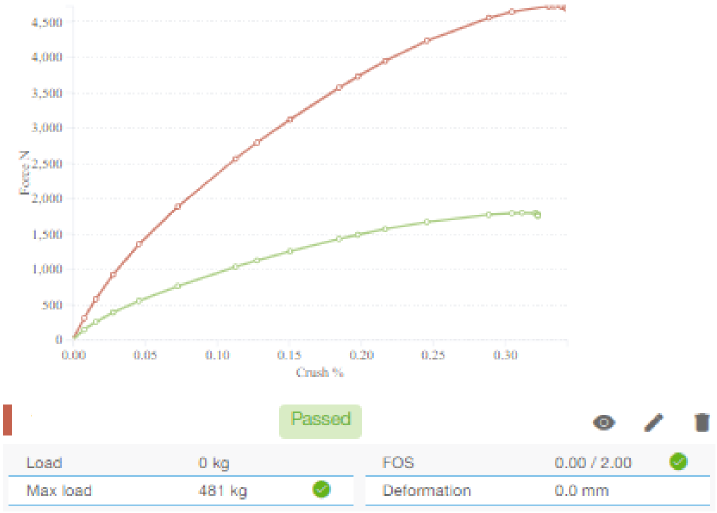
BOX 3

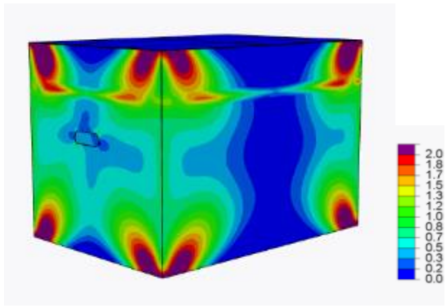
Inner dimensions: 700x500x500 mm

Material: C551

FEFCO / Special geometry: 0201 / Glued, U handles, crease in height

Test 1





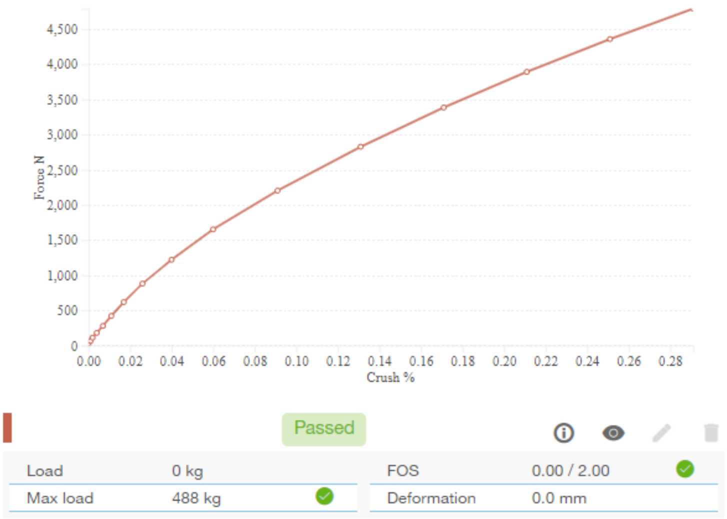
BOX 3

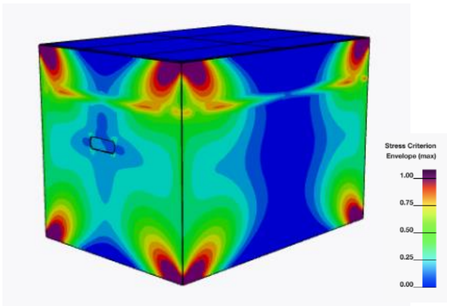
Inner dimensions: 700x500x500 mm

Material: C551

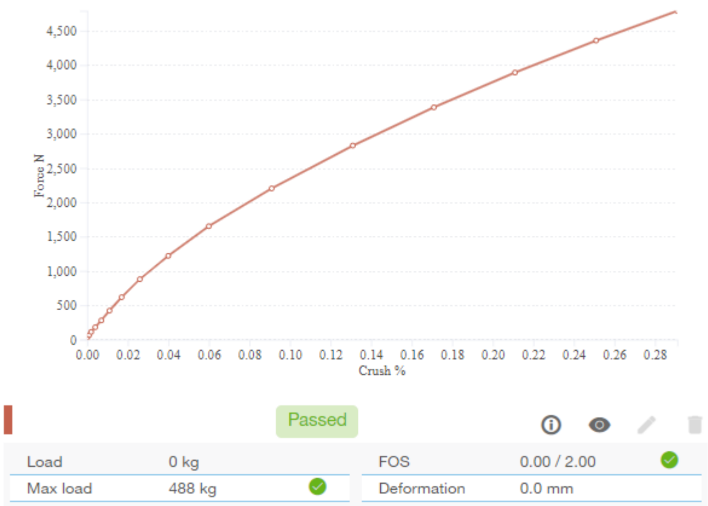
FEFCO / Special geometry: 0201 / Glued, U handles, crease in height

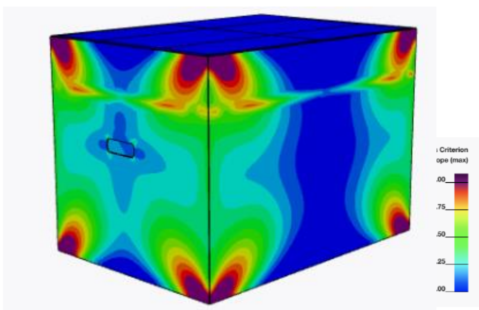
Test with fixed material data, elastic





Test with fixed material data, plastic





BOX 4

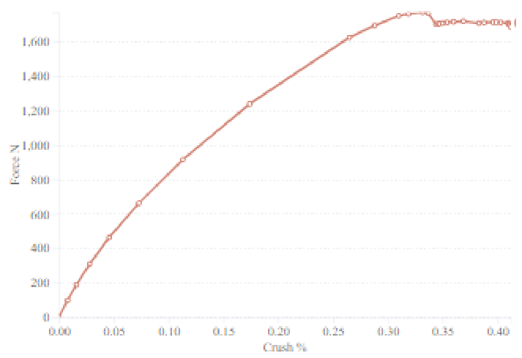
Inner dimensions: 500x350x400 mm

Material: B430

FEFCO / Special geometry: 0205 / Glued, P handles, ventilation holes

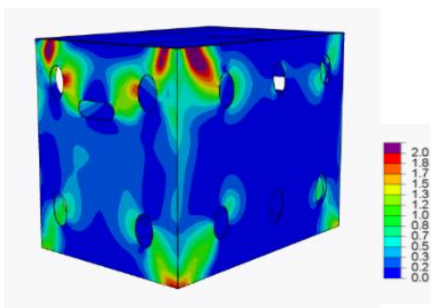
Test 1

FEFCO 0205



Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	180 kg	Deformation	0.0 mm



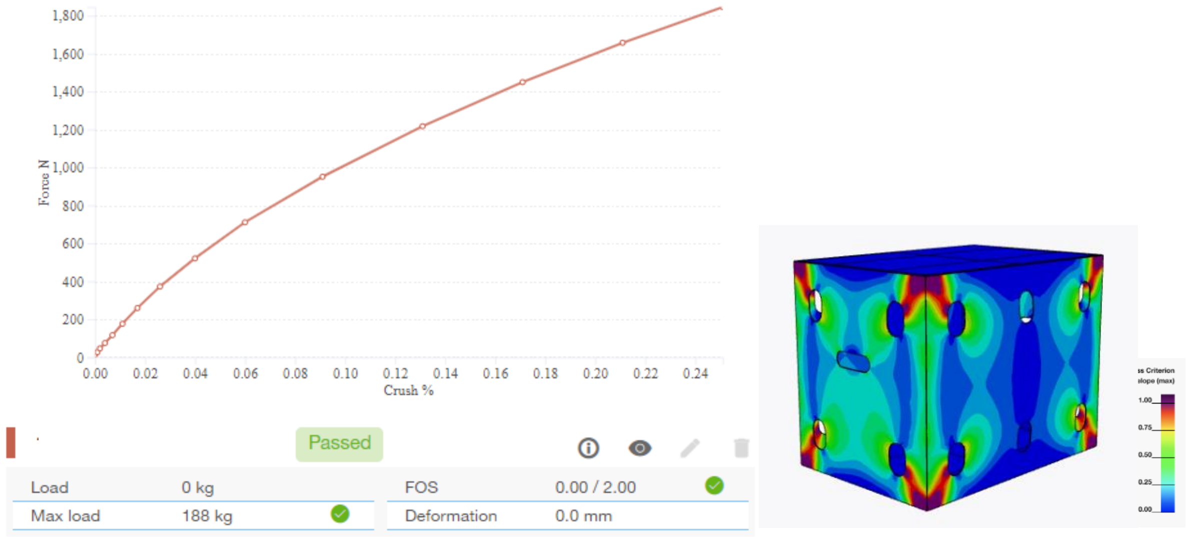
BOX 4

Inner dimensions: 500x350x400 mm

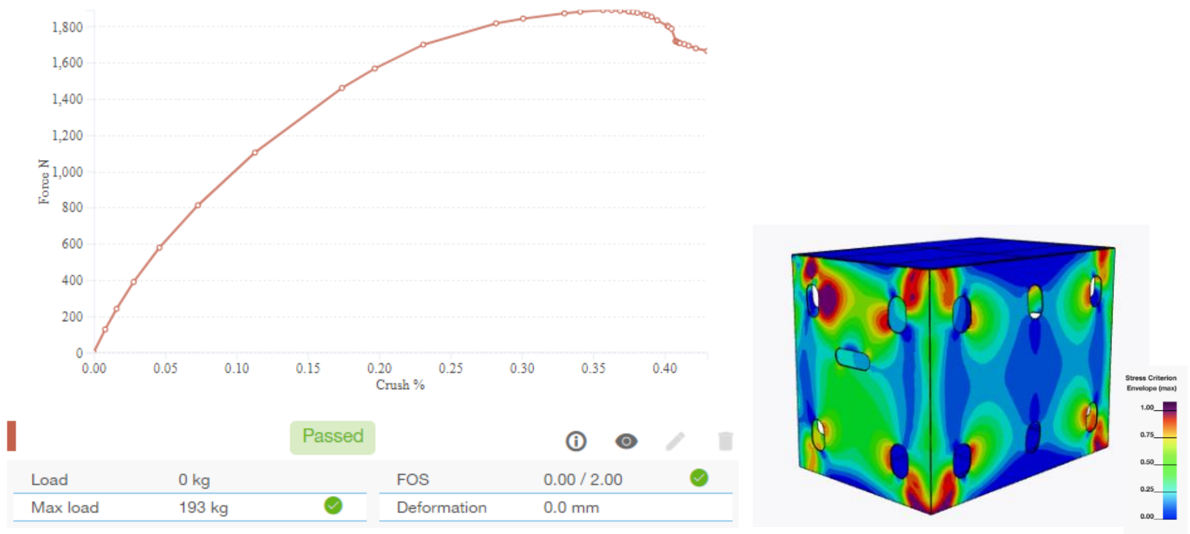
Material: B430

FEFCO / Special geometry: 0205 / Glued, P handles, ventilation holes

Test with fixed material data, elastic



Test with fixed material data, plastic



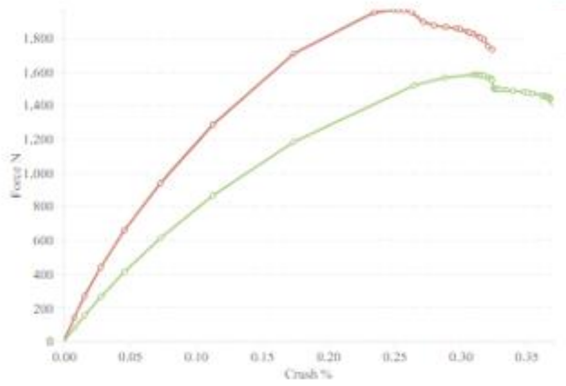
BOX 5

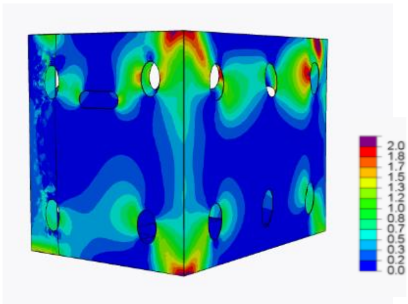
Inner dimensions: 500x350x400 mm

Material: C390

FEFCO / Special geometry: 0205 / Glued, P handles, ventilation holes

Test 1





Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	161 kg	Deformation	0.0 mm

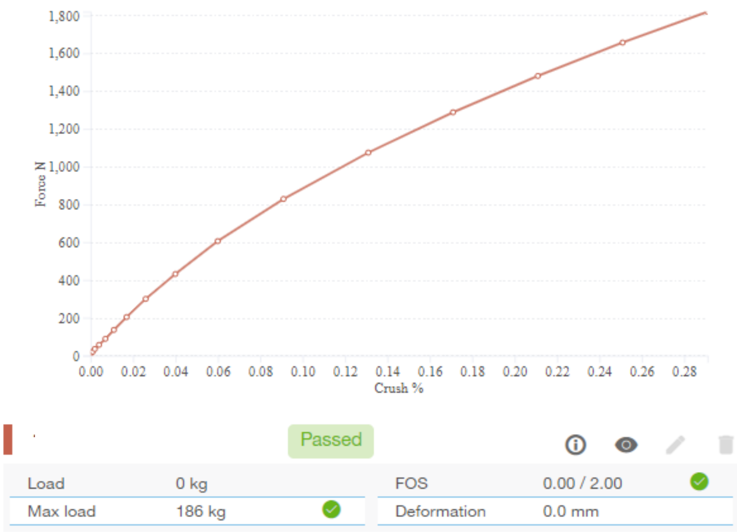
BOX 5

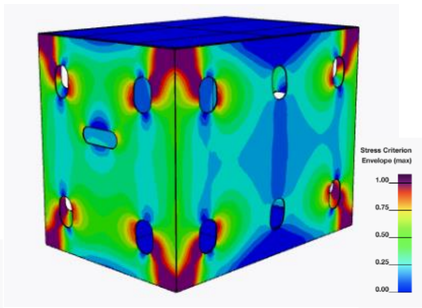
Inner dimensions: 500x350x400 mm

Material: C390

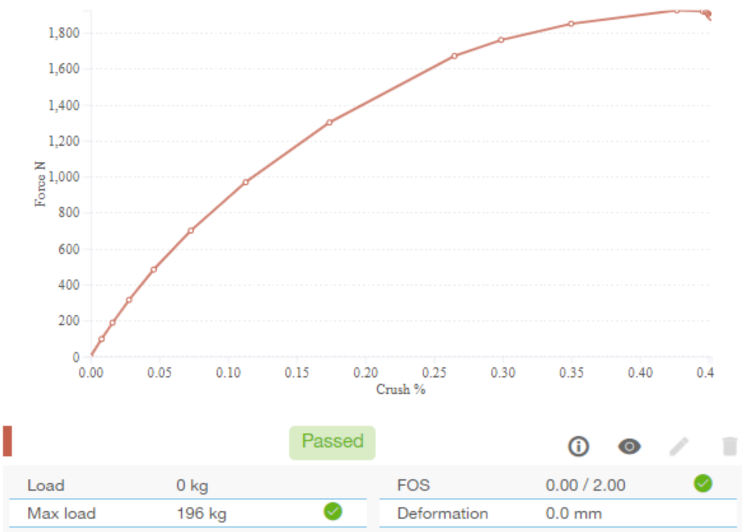
FEFCO / Special geometry: 0205 / Glued, P handles, ventilation holes

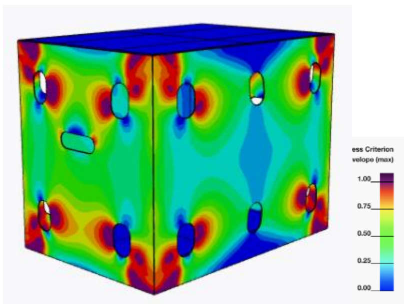
Test with fixed material data, elastic





Test with fixed material data, plastic





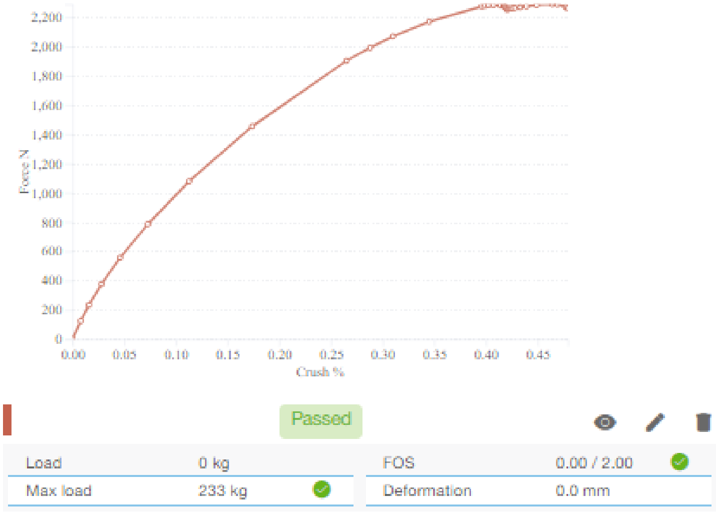
BOX 6

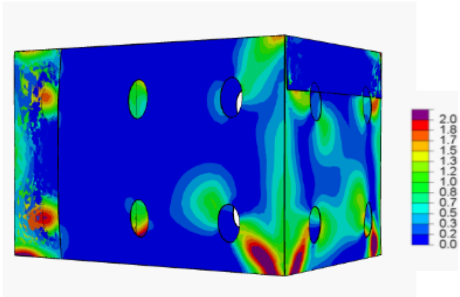
Inner dimensions: 600x400x400 mm

Material: B430

FEFCO / Special geometry: 0215 / Glued, ventilation holes

Test 1





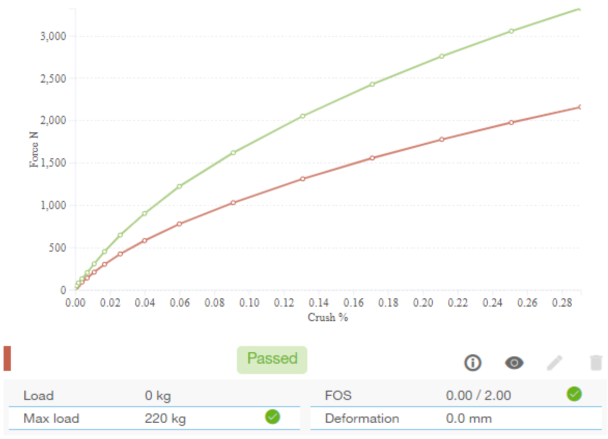
BOX 6

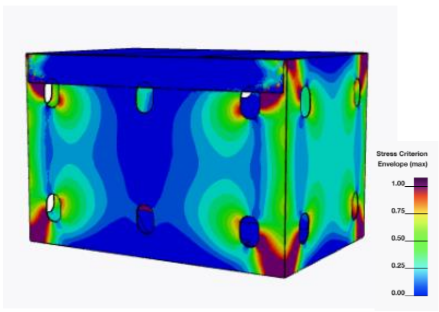
Inner dimensions: 600x400x400 mm

Material: B430

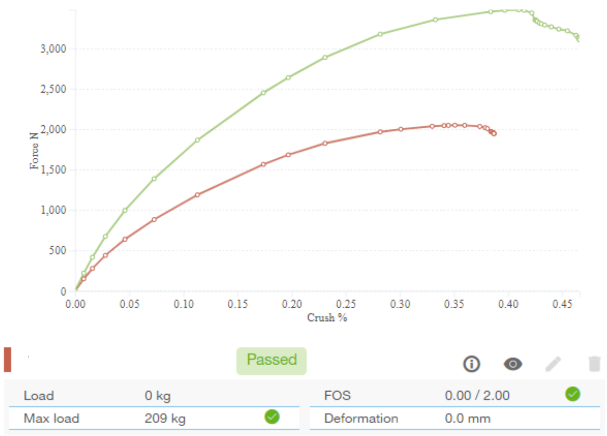
FEFCO / Special geometry: 0215 / Glued, ventilation holes

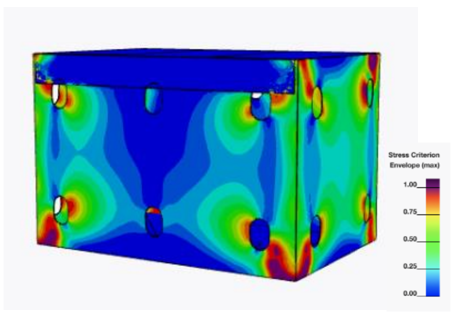
Test with fixed material data, elastic





Test with fixed material data, plastic





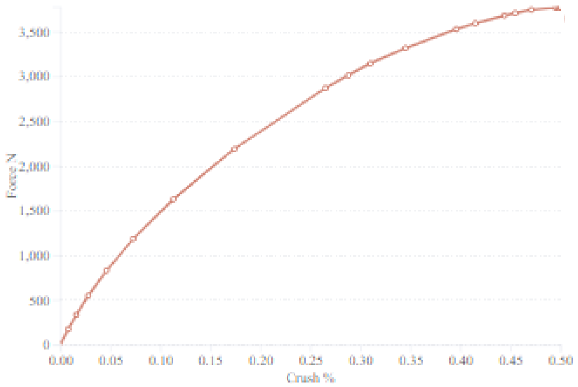
BOX 7

Inner dimensions: 600x400x400 mm

Material: C551

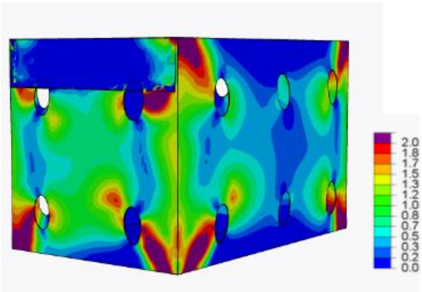
FEFCO / Special geometry: 0215 / Glued, ventilation holes

Test 1



Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	385 kg	Deformation	0.0 mm



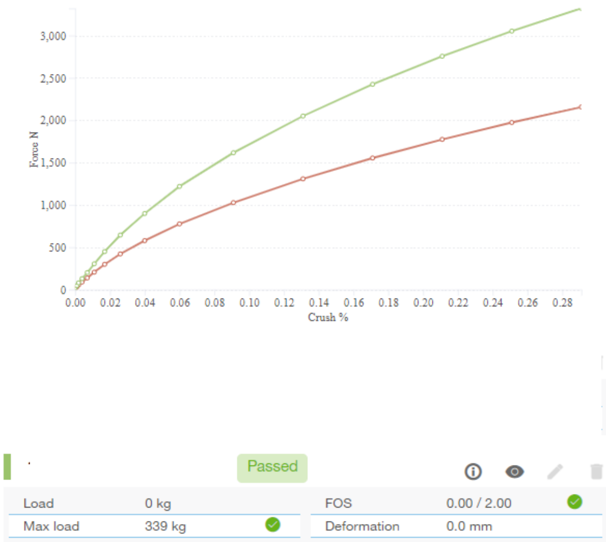
BOX 7

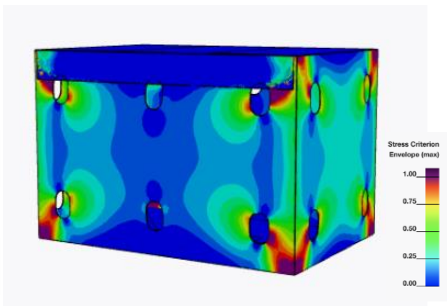
Inner dimensions: 600x400x400 mm

Material: C551

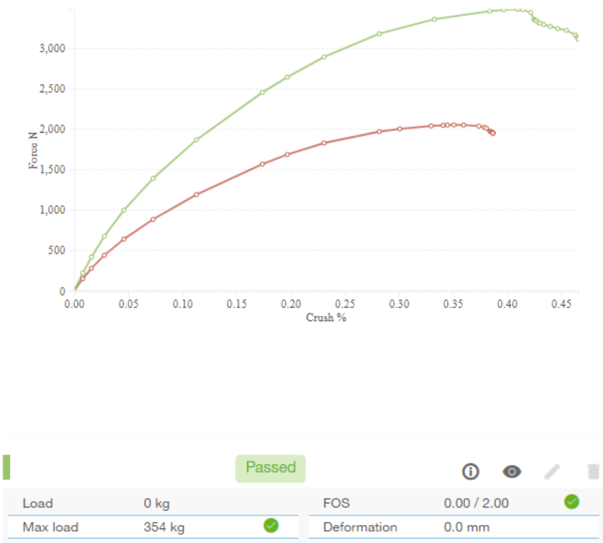
FEFCO / Special geometry: 0215 / Glued, ventilation holes

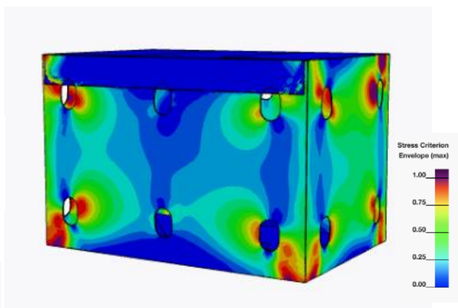
Test with fixed material data, elastic





Test with fixed material data, plastic





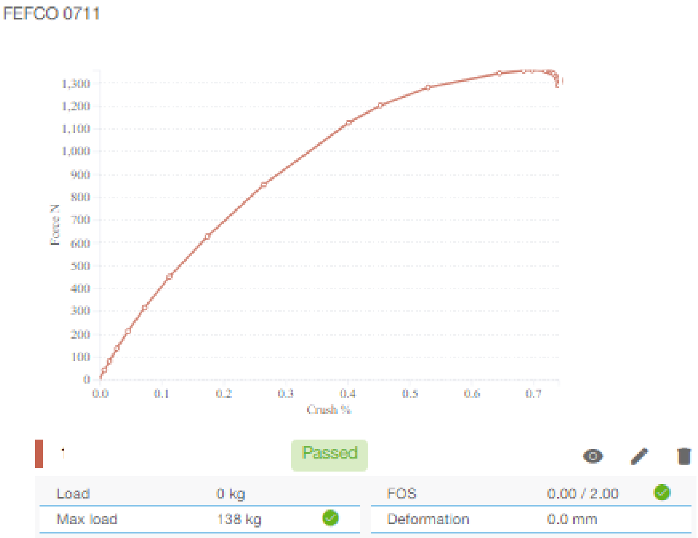
BOX 8

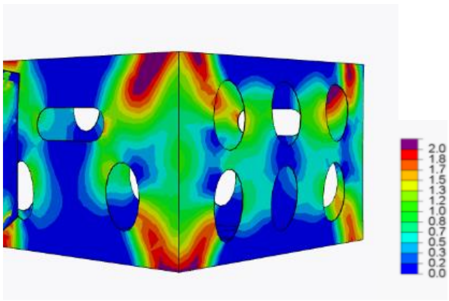
Inner dimensions: 280x250x180 mm

Material: B320

FEFCO / Special geometry: 0711 / Glued, P handles, ventilation holes

Test 1





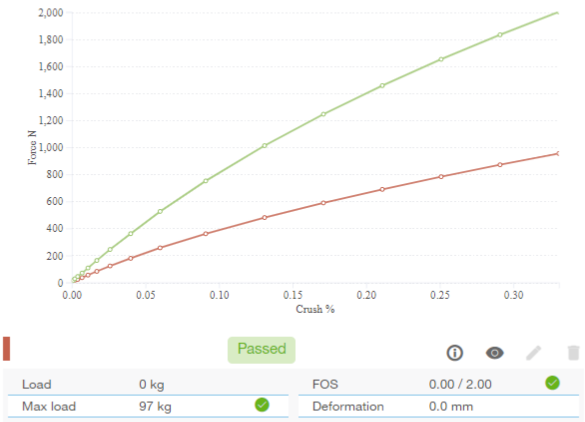
BOX 8

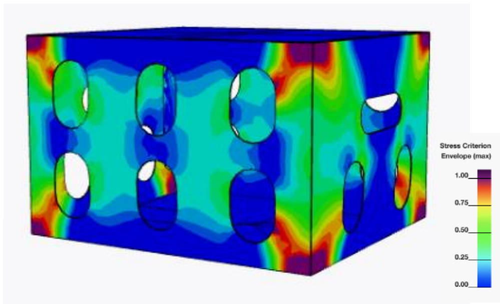
Inner dimensions: 280x250x180 mm

Material: B320

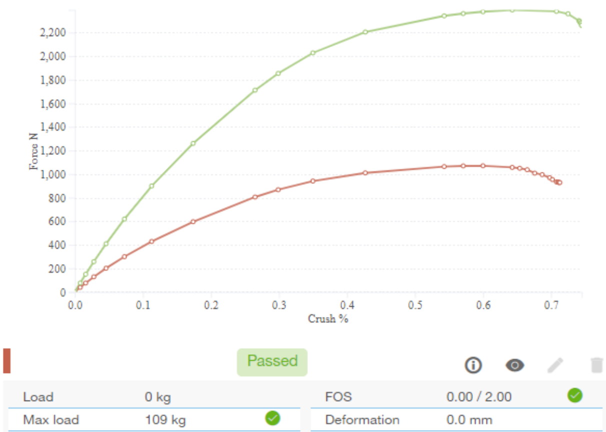
FEFCO / Special geometry: 0711 / Glued, P handles, ventilation holes

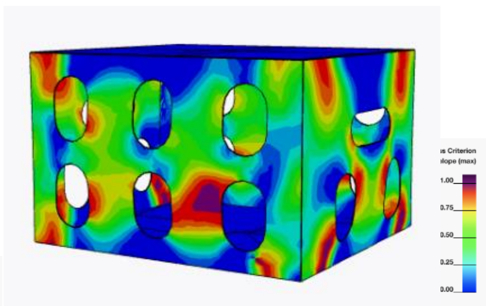
Test with fixed material data, elastic





Test with fixed material data, plastic





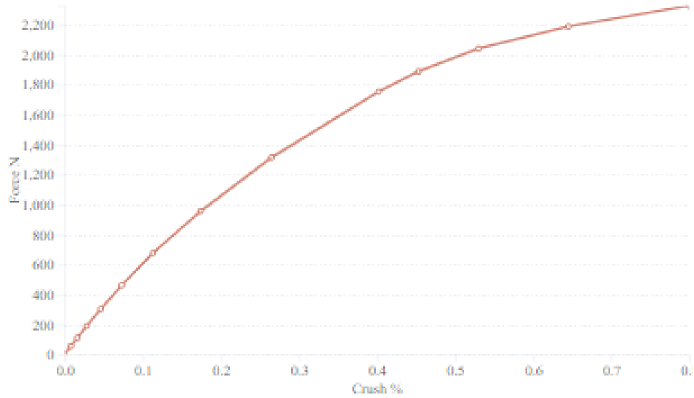
BOX 9

Inner dimensions: 280x250x180 mm

Material: C551

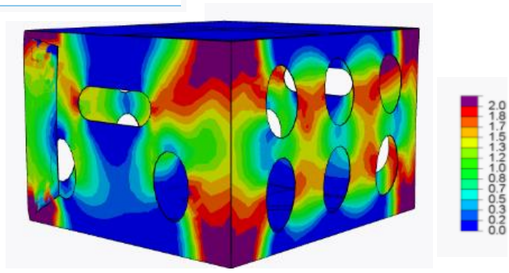
FEFCO / Special geometry: 0711 / Glued, P handles, ventilation holes

Test 1



Passed

Load	0 kg		FOS	0.00 / 2.00	✓
Max load	237 kg	✓	Deformation	0.0 mm	



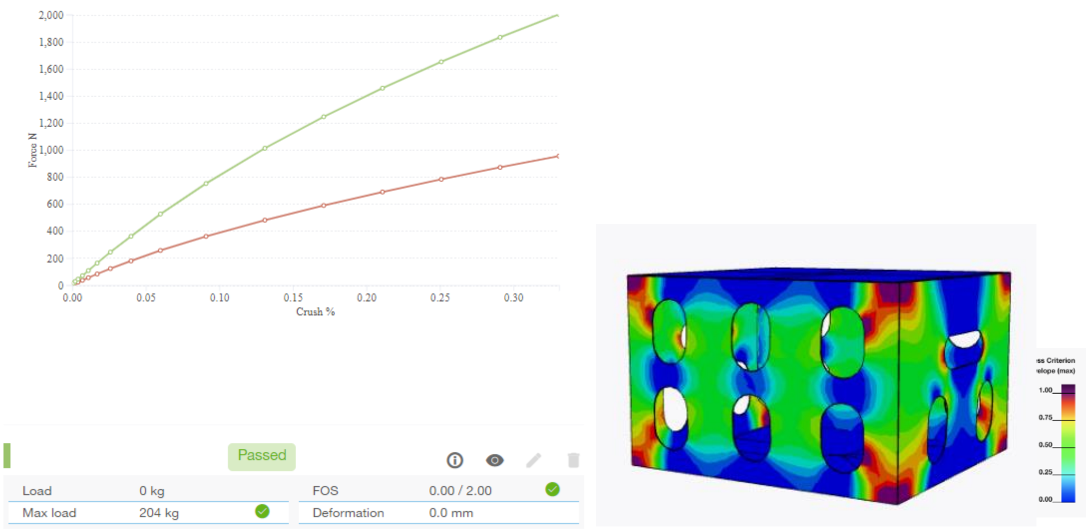
BOX 9

Inner dimensions: 280x250x180 mm

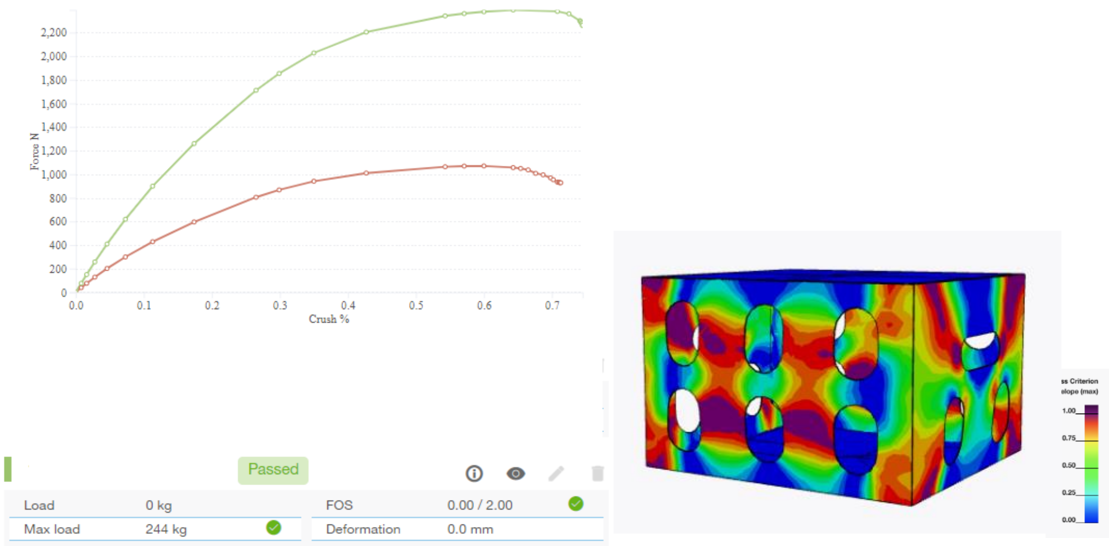
Material: C551

FEFCO / Special geometry: 0711 / Glued, P handles, ventilation holes

Test with fixed material data, elastic



Test with fixed material data, plastic

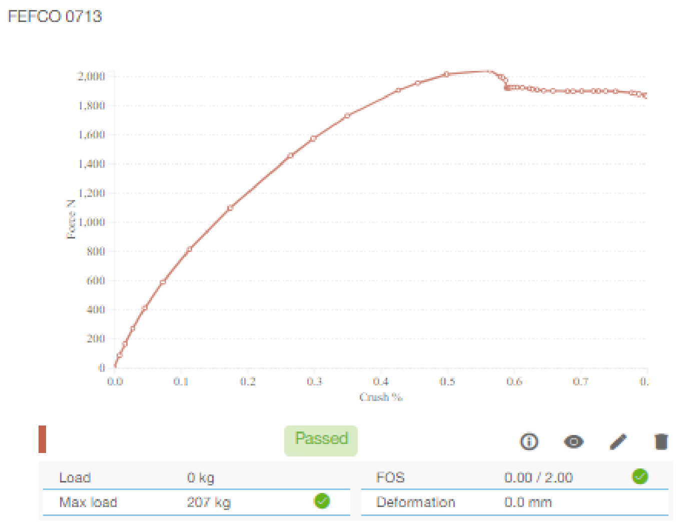


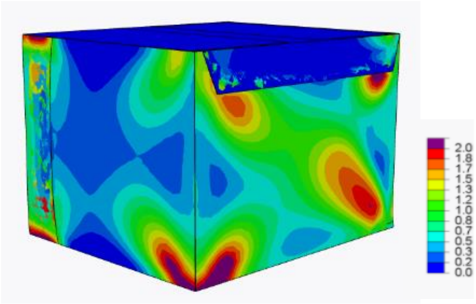
BOX 10

Inner dimensions: 350x300x250 mm

Material: B320

FEFCO / Special geometry: 0713 / Glued





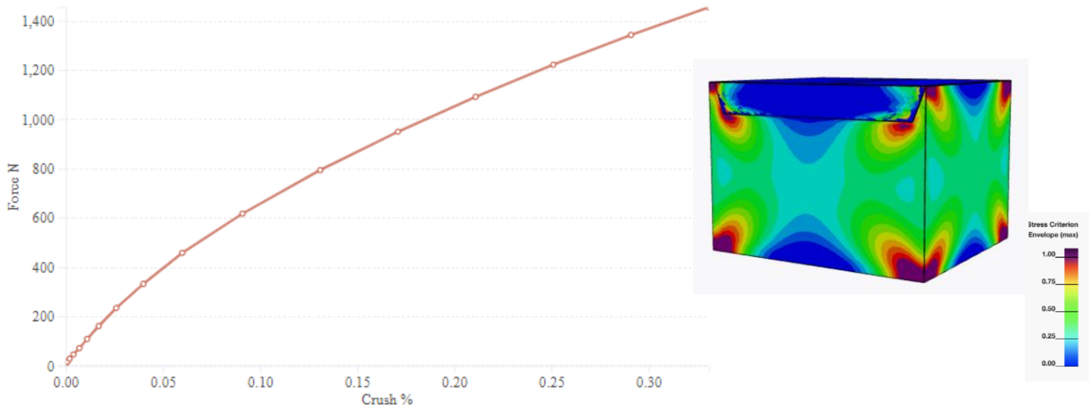
BOX 10

Inner dimensions: 350x300x250 mm

Material: B320

FEFCO / Special geometry: 0713 / Glued

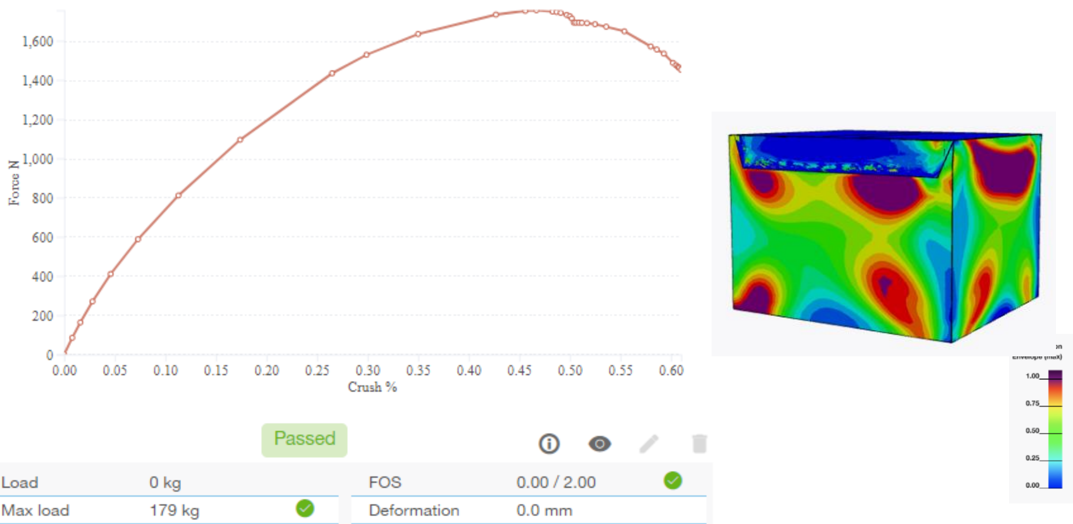
Test with fixed material data, elastic



Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	148 kg	Deformation	0.0 mm

Test with fixed material data, plastic



Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	179 kg	Deformation	0.0 mm

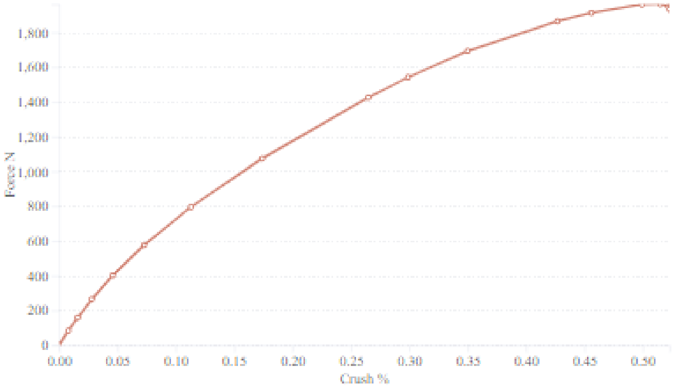
BOX 11

Inner dimensions: 350x300x250 mm

Material: B320

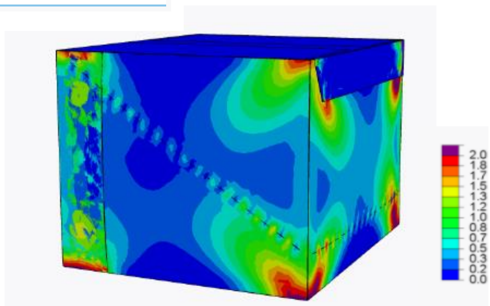
FEFCO / Special geometry: 0713 / Glued, perforation

Test 1



Passed

Load	0 kg	FOS	0.00 / 2.00
Max load	200 kg	Deformation	0.0 mm



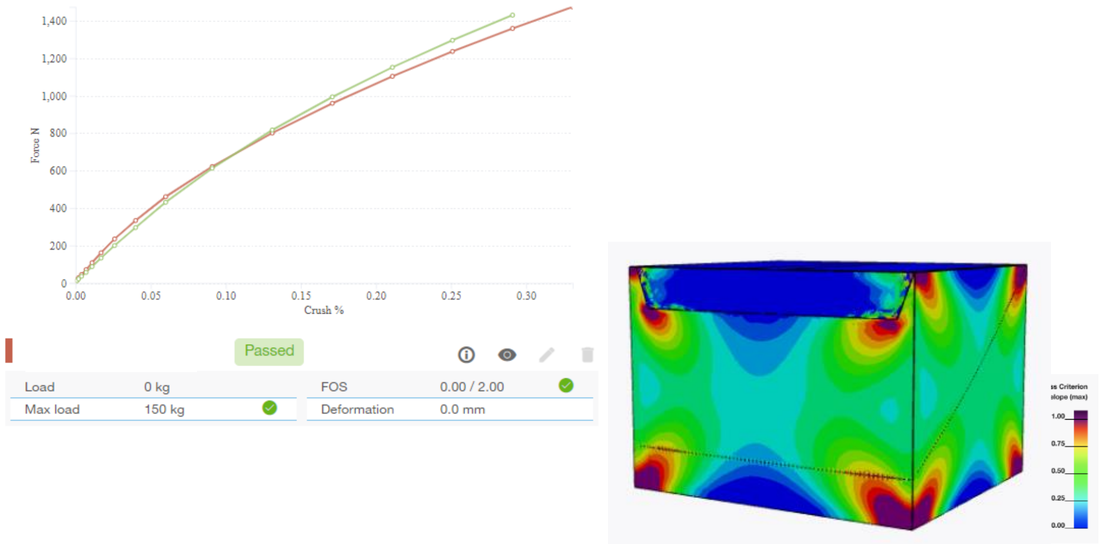
BOX 11

Inner dimensions: 350x300x250 mm

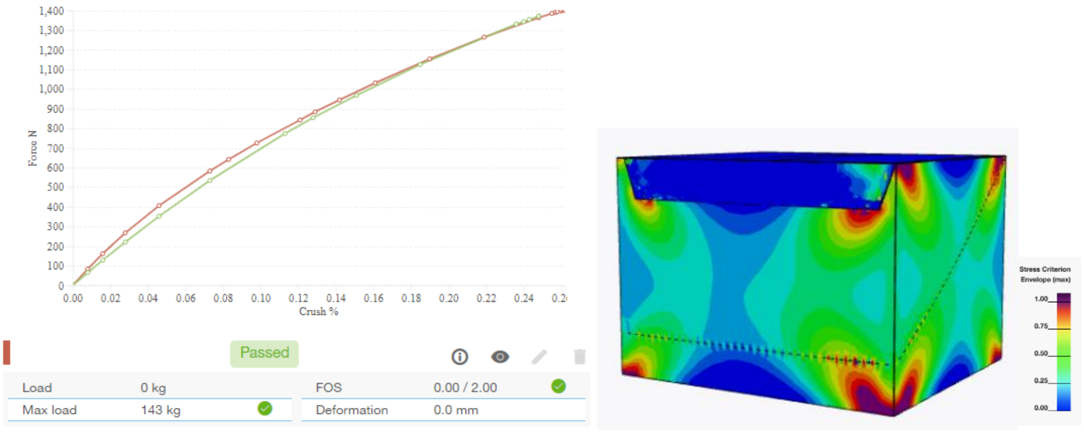
Material: B320

FEFCO / Special geometry: 0713 / Glued, perforation

Test with fixed material data, elastic



Test with fixed material data, plastic



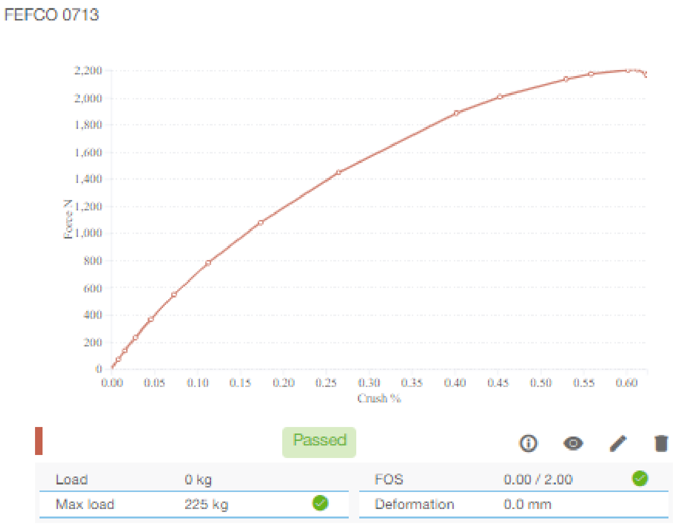
BOX 12

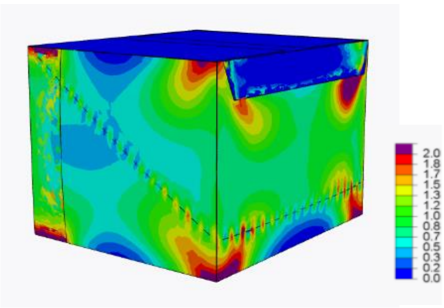
Inner dimensions: 350x300x250 mm

Material: C390

FEFCO / Special geometry: 0713 / Glued, perforation

Test 1





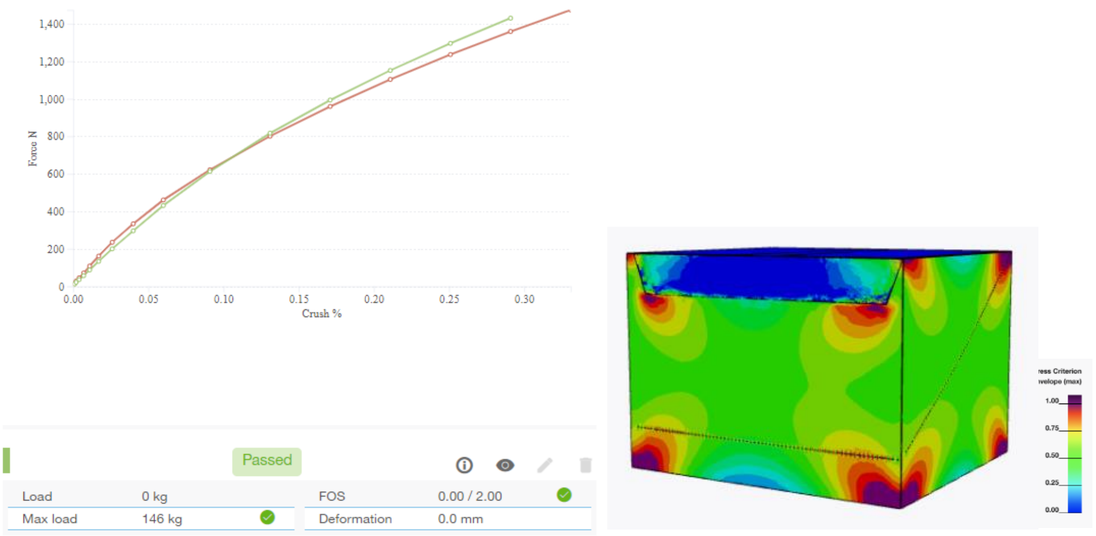
BOX 12

Inner dimensions: 350x300x250 mm

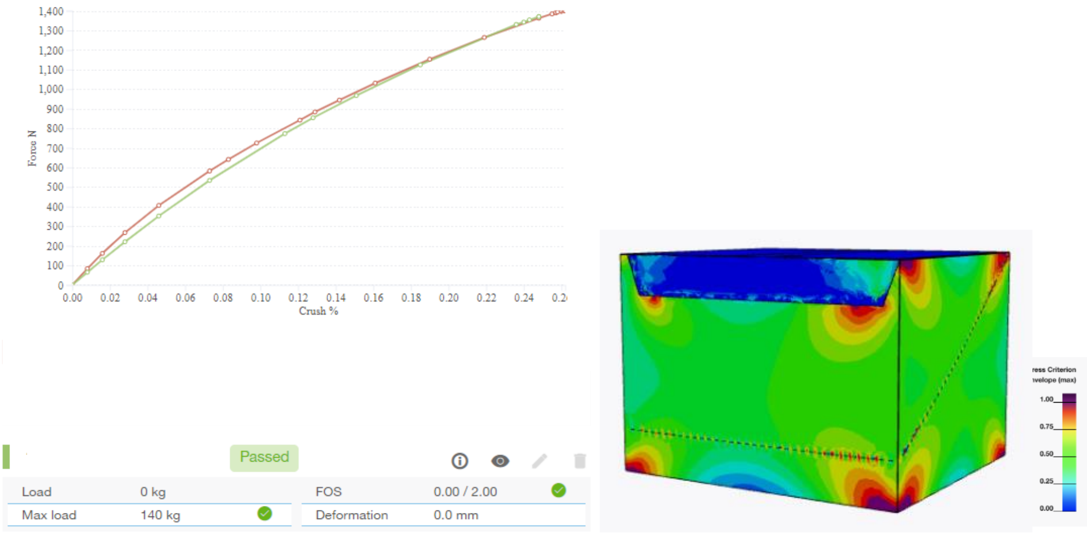
Material: C390

FEFCO / Special geometry: 0713 / Glued, perforation

Test with fixed material data, elastic



Test with fixed material data, plastic



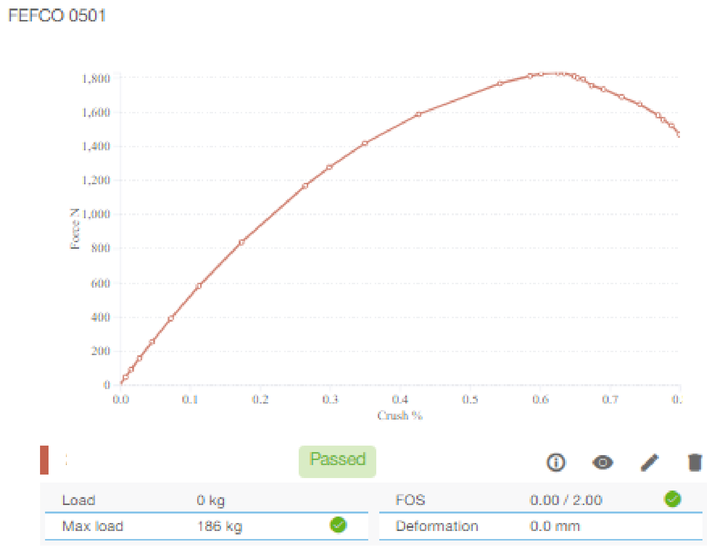
BOX 13

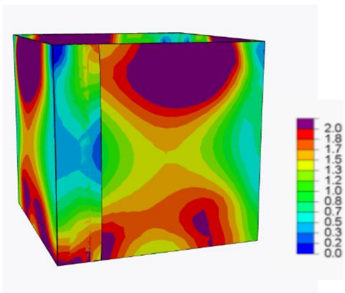
Inner dimensions: 200x200x195 mm

Material: EB485

FEFCO / Special geometry: 0501 / Glued

Test 1





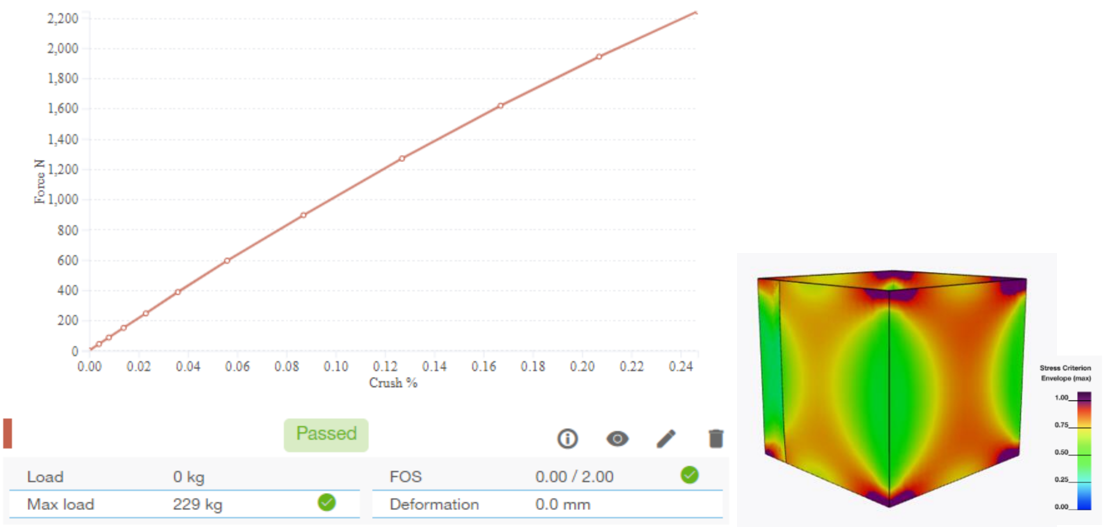
BOX 13

Inner dimensions: 200x200x195 mm

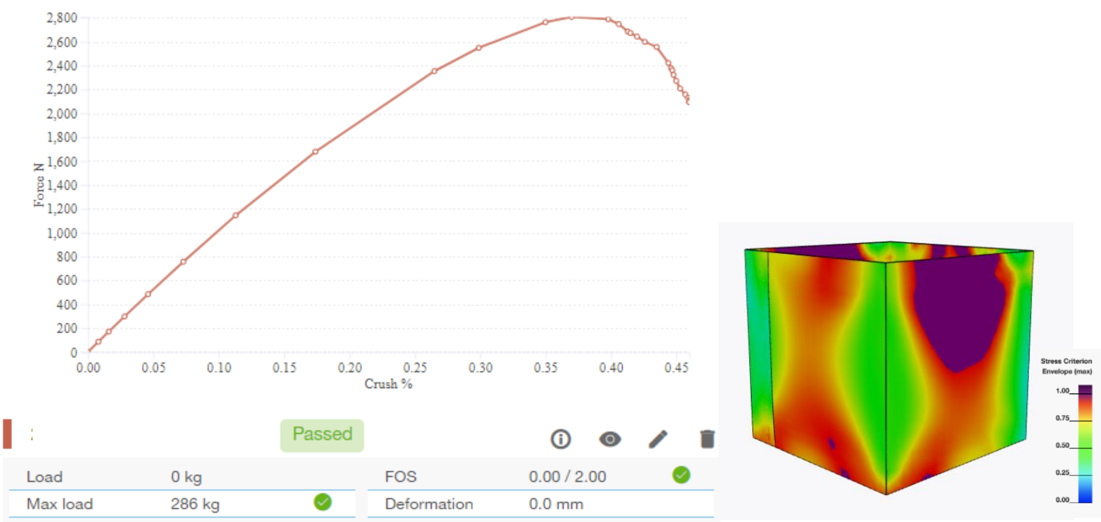
Material: EB485

FEFCO / Special geometry: 0501 / Glued

Test with fixed material data, elastic



Test with fixed material data, plastic



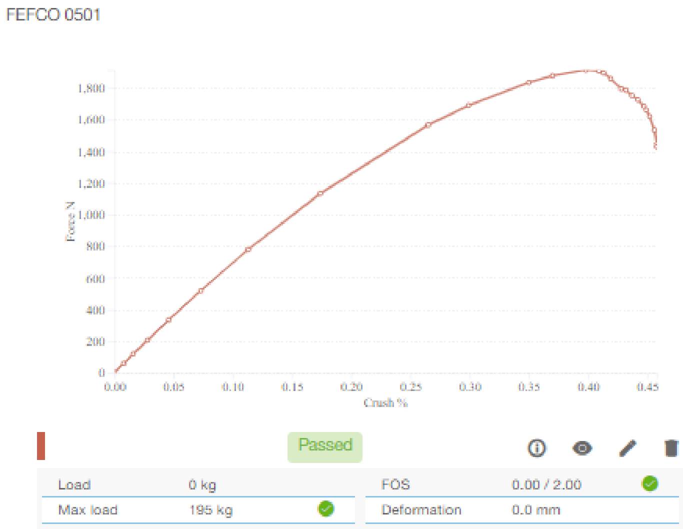
BOX 14

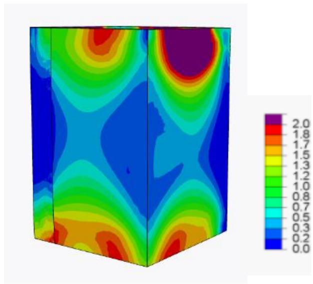
Inner dimensions: 200x200x300 mm

Material: EB485

FEFCO / Special geometry: 0501 / Glued

Test 1





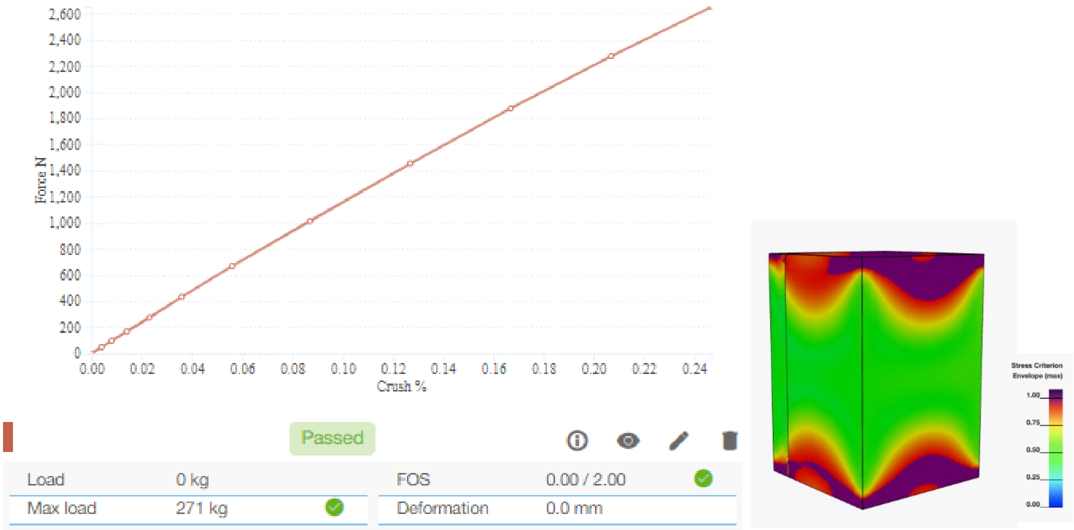
BOX 14

Inner dimensions: 200x200x300 mm

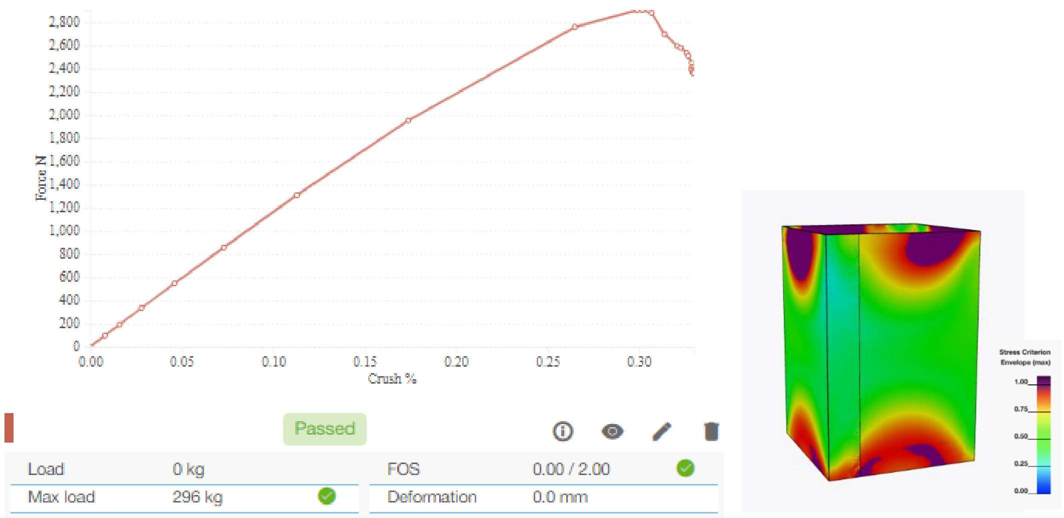
Material: EB485

FEFCO / Special geometry: 0501 / Glued

Test with fixed material data, elastic



Test with fixed material data, plastic



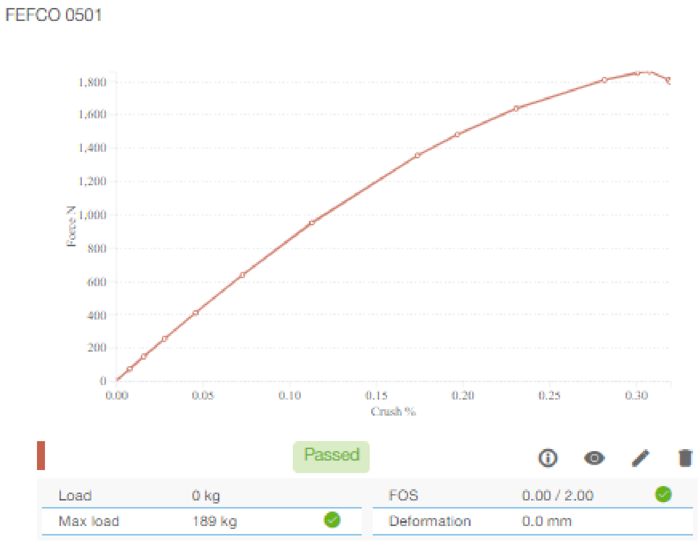
BOX 15

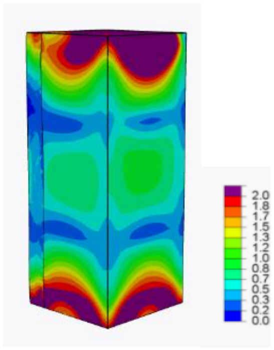
Inner dimensions: 200x200x500 mm

Material: EB485

FEFCO / Special geometry: 0501 / Glued

Test 1





BOX 15

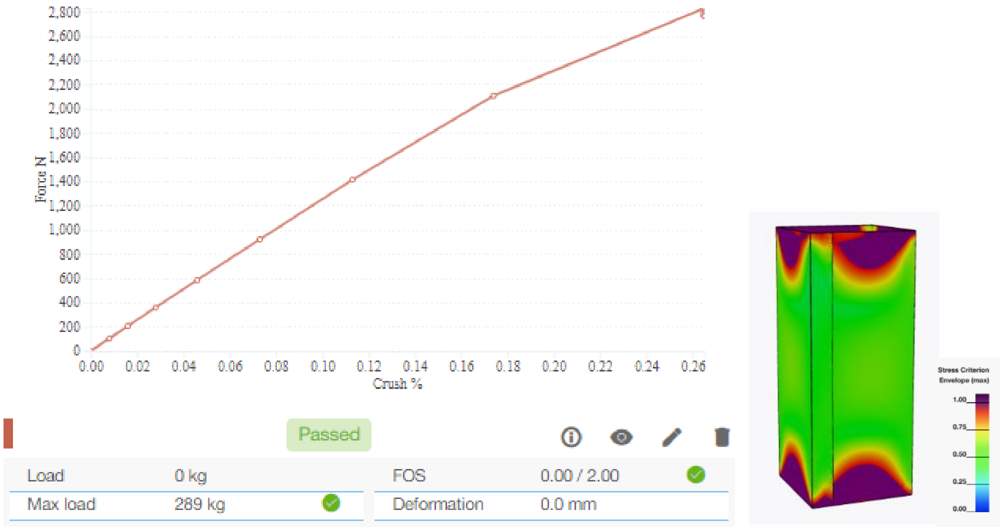
Inner dimensions: 200x200x500 mm

Material: EB485

FEFCO / Special geometry: 0501 / Glued

Test with fixed material data, elastic

Test with fixed material data, plastic



BOX 16

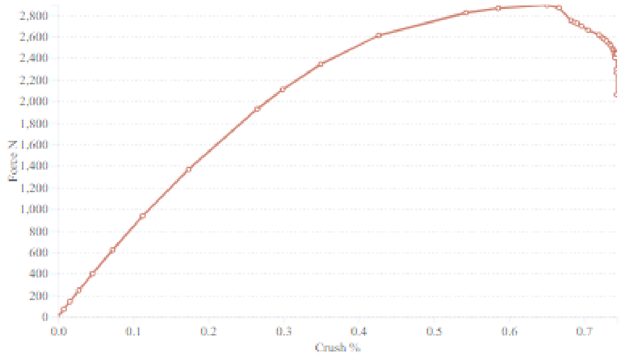
Inner dimensions: 200x200x195 mm

Material: BC545

FEFCO / Special geometry: 0501 / Glued

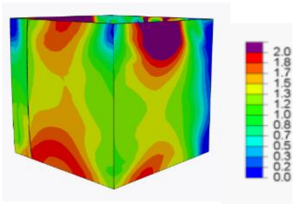
Test 1

FEFCO 0501



Passed

Load	0 kg		FOS	0.00 / 2.00	✓
Max load	295 kg	✓	Deformation	0.0 mm	



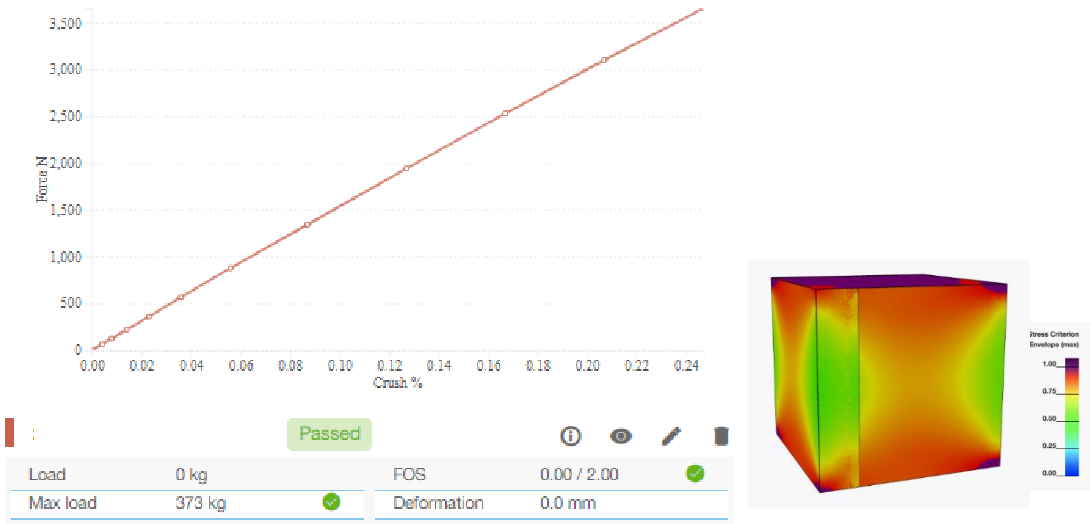
BOX 16

Inner dimensions: 200x200x195 mm

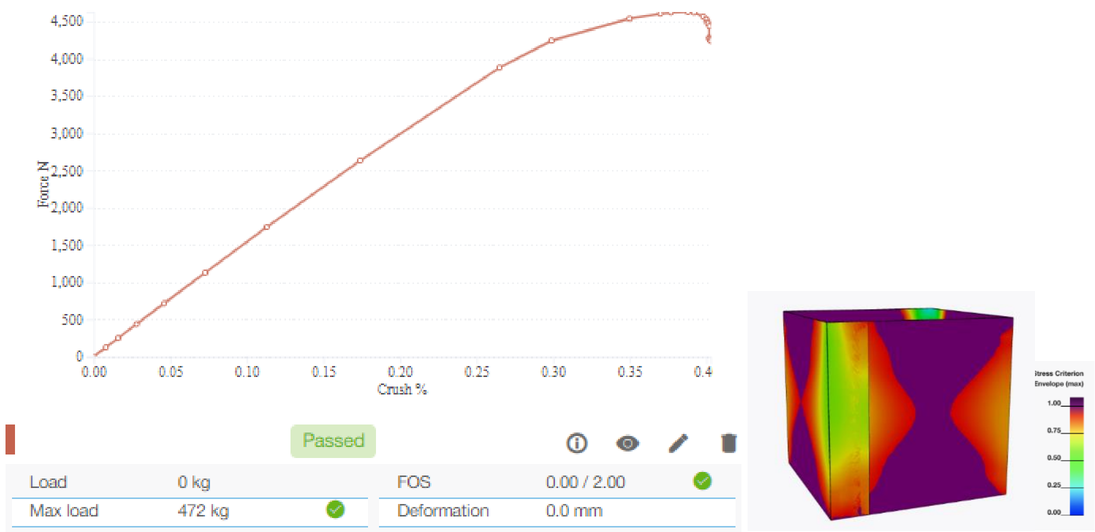
Material: BC545

FEFCO / Special geometry: 0501 / Glued

Test with fixed material data, elastic



Test with fixed material data, plastic



BOX 17

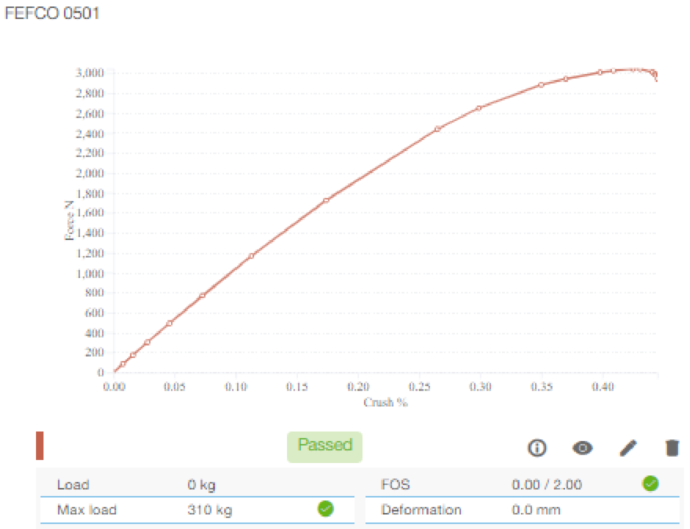
Inner dimensions: 200x200x300 mm

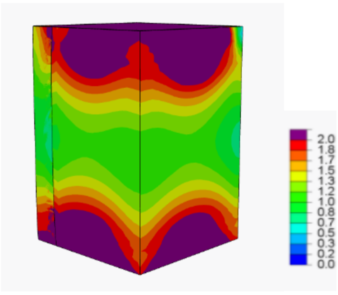
Material: BC545

FEFCO / Special geometry: 0501 / Glued

Virtual BCT results

Test 1





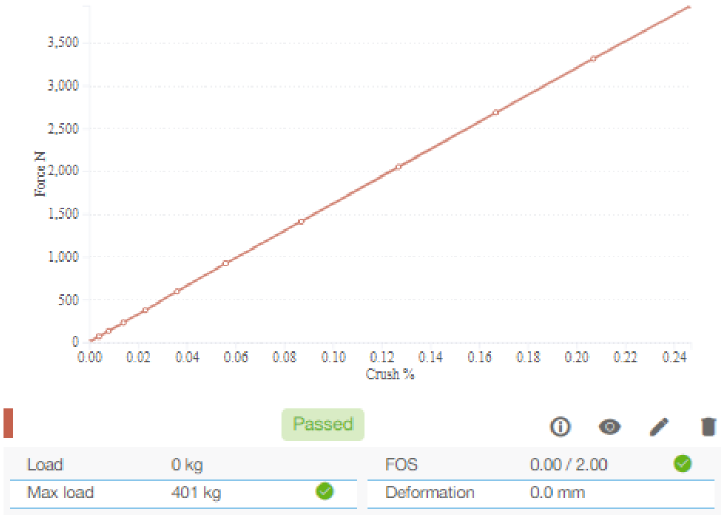
BOX 17

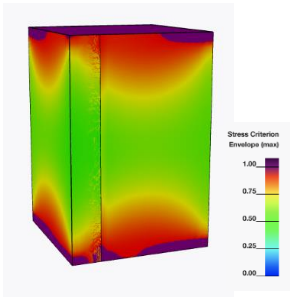
Inner dimensions: 200x200x300 mm

Material: BC545

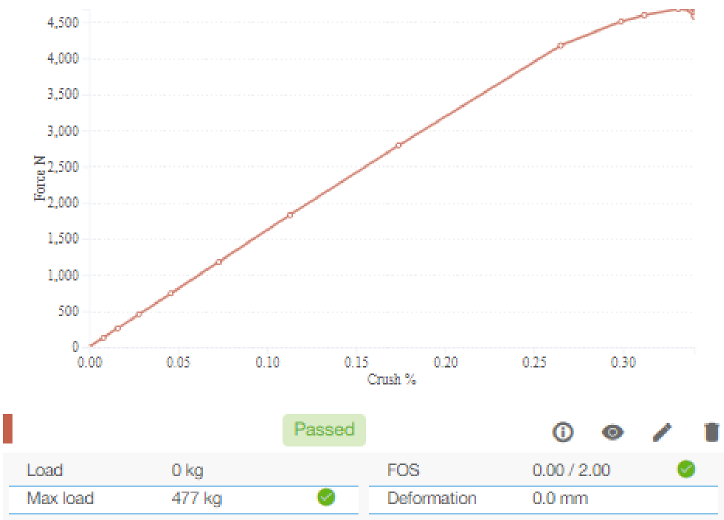
FEFCO / Special geometry: 0501 / Glued

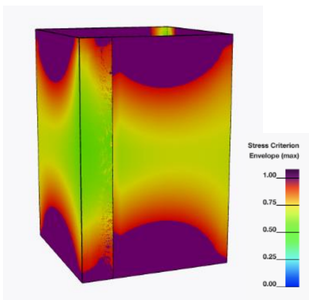
Test with fixed material data, elastic





Test with fixed material data, plastic





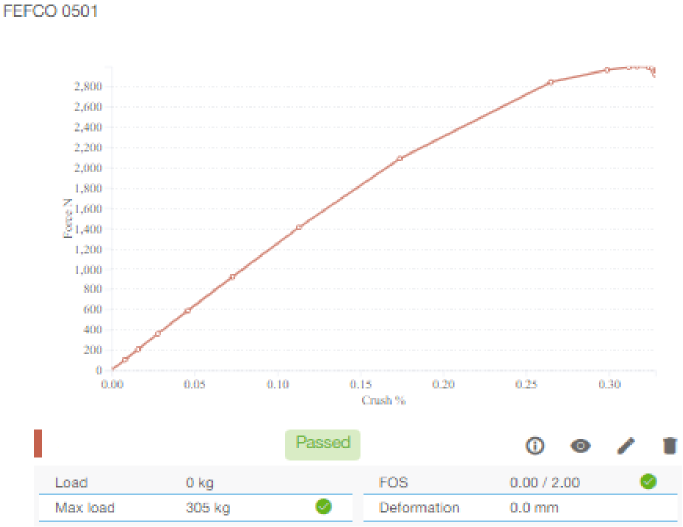
BOX 18

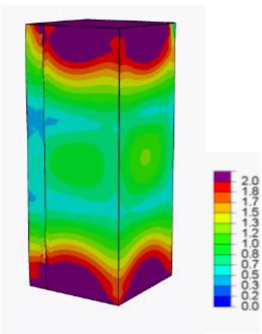
Inner dimensions: 200x200x500 mm

Material: BC545

FEFCO / Special geometry: 0501 / Glued

Test 1





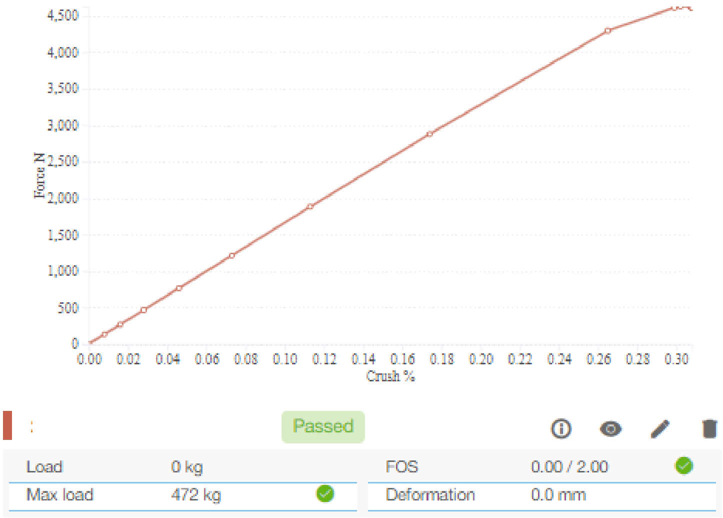
BOX 18

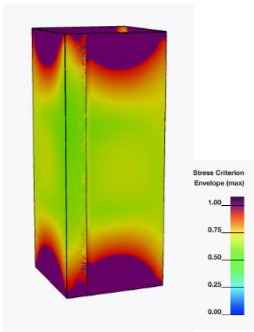
Inner dimensions: 200x200x500 mm

Material: BC545

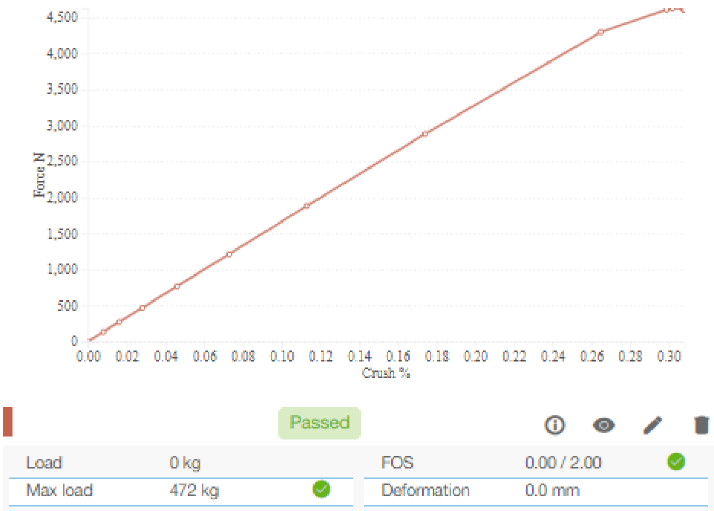
FEFCO / Special geometry: 0501 / Glued

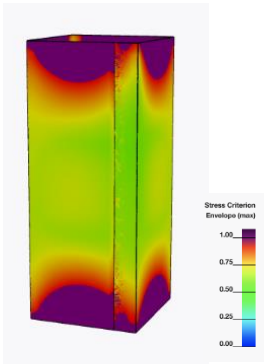
Test with fixed material data, elastic





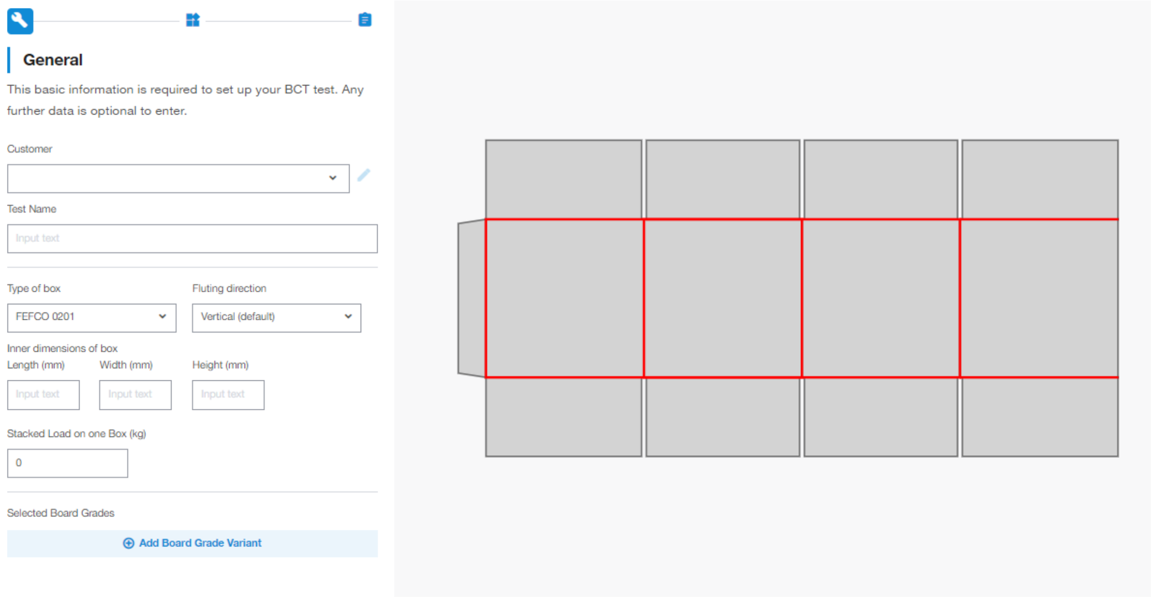
Test with fixed material data, plastic



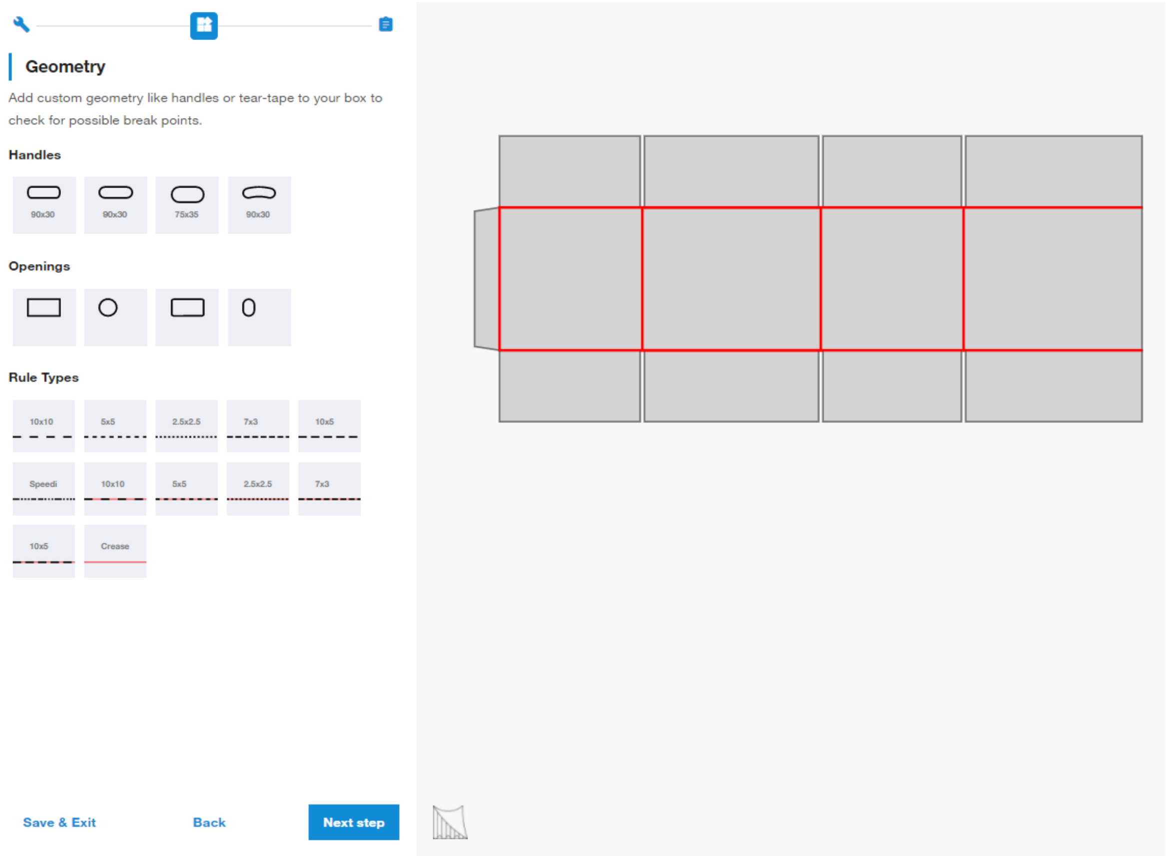


Appendix 4: The Virtual Compression Tool user interface.

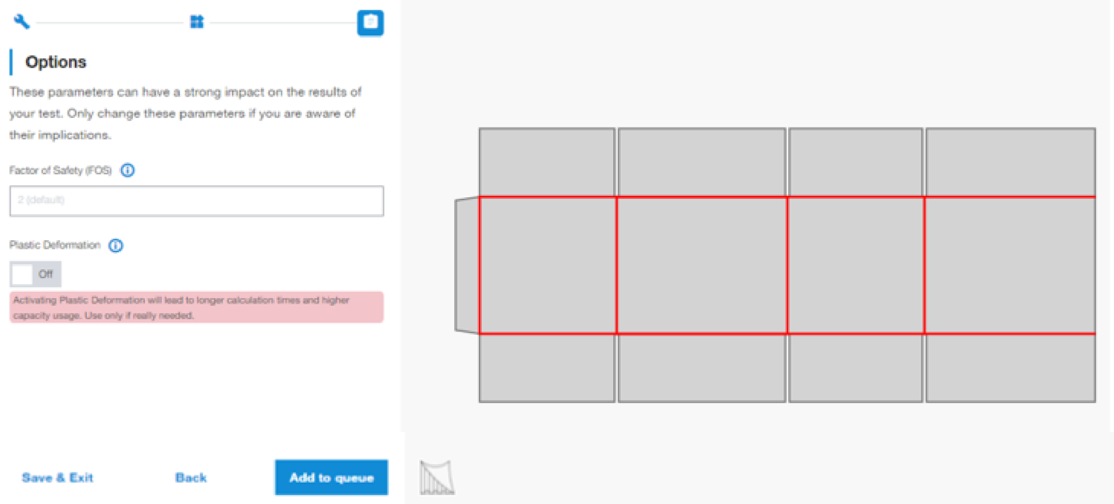
On the design step 1/3, the general information of the design is defined.



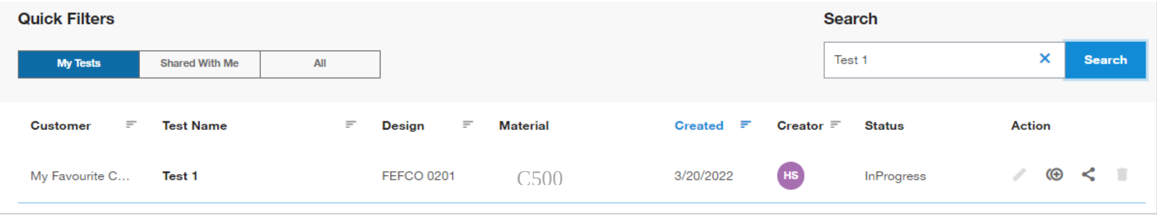
In design step 2/3, the special geometry is added to the box layout.



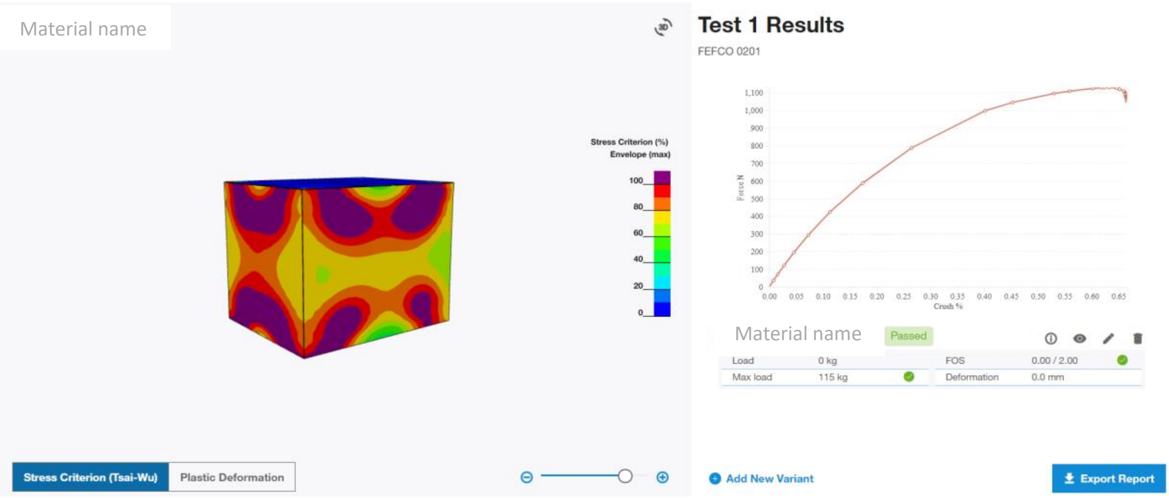
In design step 3/3, the parameters for calculation are defined.



The created box design is added to the test queue.



The calculation is complete, and the results of the virtual compression test are presented.



Exporting a separate report file provides a document for internal and external product development purposes.

LOGO Virtual Test | Test Report

TEST NAME

Page 1 of 1

Name

Title

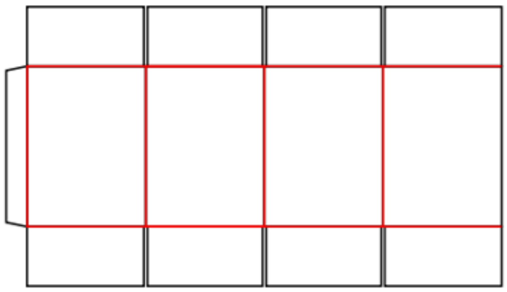
Contact Information

Issued For

User X

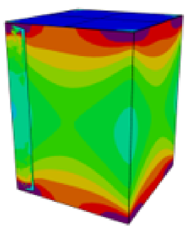
Test Setup

Box Type: FEFCO 0201
Dimensions: 200 x 200 x 270
Load on Box: 0 kg

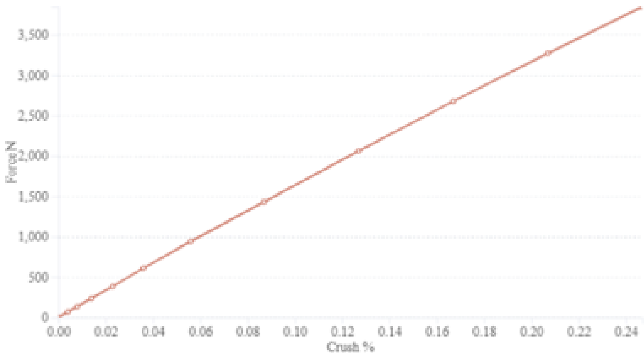


Test Result

Material	Max Load	Deformation	FOS	Passed
Recipe name	392 kg	0.0 mm	0.00	✓



Recipe name



Legal Disclaimer