INFLUENCE OF GEOMETRY AND BASE MATERIAL ON THE COMPRESSIVE PROPERTIES OF FOLDCORES

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Abstract
Foldcores are an origami-like structural sandwich core, which is manufactured by folding a flat sheet of base material into a three dimensional structure. These cores offer good mechanical properties and the potential to integrate additional functions due to the flexible design. A wide range of geometries and materials are available. This study concentrates on the out-of-plane compression properties of four different Miura-ori-type foldcores, each made out of two base materials. Using new testing fixtures, a study on the dependency of the different materials and geometries on the mechanical properties under otherwise identical conditions will be presented. We show, that the normalized strength is very similar for samples out of different base materials, while the normalized stiffness variation is much more material-dependent.

1. Introduction

Foldcores have been the focus of recent research in the area of new core structures for sandwich composites. These cores offer good mechanical properties and the potential to integrate additional functions due to the open core geometry [1–4]. A wide range of possible geometries and base materials can be combined and offer great flexibility and optimization potential, but also increase the parameter space to be screened to identify suitable cores for a specific application.

Using finite element analysis (FEA) is one option to analyze the large number of possible geometry combinations. For small models or rough estimations of strength and stiffness, this approach is quickly implemented but generates imprecise results. Important influences like imperfections caused by the manufacturing process or material failures, which reduce the mechanical properties of the foldcores, are not considered there [5, 6]. This fact in combination with coarse meshes results in overestimated values for strength and stiffness. Realistic results can be produced with more detailed models, but these increase the computational effort significantly. These models take the manufacturing process into account and use special material models. For isotropic and anisotropic materials such models have been developed by different researchers [5–7] and have been validated for specific geometries. Because of the detail level, these simulations require a lot of experience and always have to be calibrated with real world tests to get material parameters for modeling. For this reason, destructive testing will be necessary for the forseeable future.

Various studies about the mechanical properties of foldcores, in particular the Miura-ori geometry, can be found in literature [8–11], but a comparison is complicated due to the large differences of study goals, test setups, varying manufacturing processes and materials used. The focus in this study is on the out-

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of-plane compression properties for four different Miura-ori-type foldcores. Each of these geometries is made out of two materials under identical and reproducible manufacturing conditions. Since the testing of cores is time consuming, a newly developed hybrid method for out-of-plane compression tests is used [12]. The new fixtures avoid bonded facesheets and are reusable. This minimizes the testing overhead and enables quick screening of a large number of geometries. The emphasis in this study will be on the relative deviation between the geometries depending on the used base material and facilitates the generation of comparable data.

2. Unit cell selection and sample preparation

For the study four different unit cell configurations were selected which are shown in Fig. 1 on a 5mm grid. All cells have the same height of 20mm and a unit density of 200m^{-1}. Geometry #1 presents the simplest possible configuration of a foldcore with only straight creases and two surfaces per unit cell. A more complex geometry is the classical Miura-ori type represented by sample #2 with a angle of 90° between the major crease line segments. As an extension of the classical Miura-ori type, geometry #3 include additional straight creases in the baseline which results in four extra surfaces per unit cell. The zigzag angle for configuration #3 is also $2 \times 45° = 90°$. For the last geometry #4 the angle between the major creases is changed to $2 \times 87°$, which results in a nearly blocked configuration. The base of geometry #4 is similar to type #3.

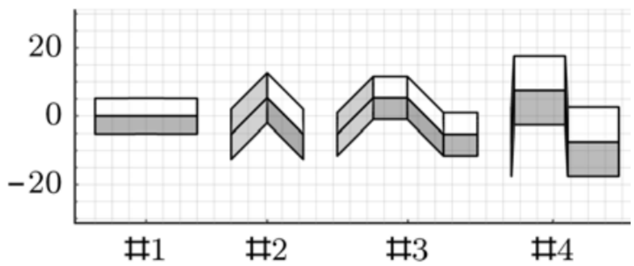

Figure 1. Top view of the chosen unit cells (grid subdivision 5mm)

To get an overview of the unit cell geometries and samples used for the compression tests, all cells are shown in Fig. 2. In addition the crease pattern as well as the geometry of the respective sample used in the test is displayed. The dimensions of the samples are determined by the maximum number of whole unit cells that fit in a box of 150mm × 150mm × 20mm. To avoid influences of different stabilization at the outer front and back edges of the core, additional folds with half core height are added as shown in Fig. 2. These extension ensure consistent boundary conditions for all geometries.

Each geometry was manufactured out of two different base materials. The first material is EnDURO ICE 130 paper by Sihl [13], which consists of a paper-film-paper layer structure. Due to this design, the material offers a high tear- and water-resistance and is well-suited for folding. The average grammage of the paper is 126±2 g/m^2 with an average thickness of 160μm. This results in a physical density for all unit cells made out of EnDURO ICE 130 of $200\text{m}^{-1} \times 0.126\ \text{kg/m}^2 = 25.2\ \text{kg/m}^3$. The EnDURO ICE 130 was not chosen for mechanical performance, but offers a low cost, easy to handle material, which does not require any additional manufacturing steps (e.g. curing) after folding. In contrast the second material, aluminum EN AW-1050A, is suitable for foldcores with high mechanical performance [14]. The average grammage of the used aluminum foil is 257.3 g/m^2 with an average thickness of 100 μm. The unit density for the aluminum foldcores is also 200m^{-1} so the physical density is $200\text{m}^{-1} \times 0.2648\ \text{kg/m}^2 = 52.96\ \text{kg/m}^3$. For both materials, sheets were precreased with a Trotec Speedy 400 laser system. All samples were folded using a semiautomatic process.

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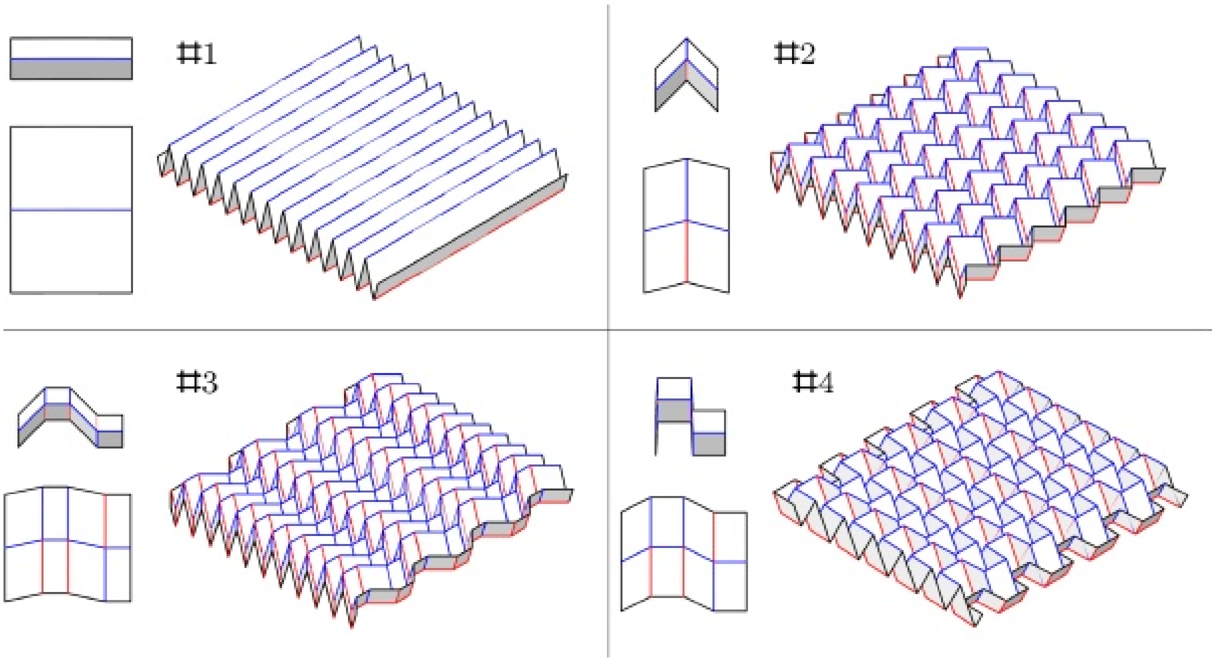

Figure 2. Geometries #1 to #4. Left: unit cell top view and crease pattern. Right perspective view of the tested sample geometry.

3. Mechanical testing

The most important mechanical properties for sandwich core materials are the flatwise compression and shear strength and stiffnesses. The flatwise compression properties are usually used for a first assessment of the core, because compressive testing require less effort than shear testing. There are two different methods of testing a sandwich core under compression: unstabilized or stabilized. Unstabilized testing is suitable for cores which are stable in shape, so it is not necessary to bond face sheets to the top and bottom of the core. For foams and honeycombs this method is common because the cores do not show a tendency for lateral movement. Foldcores need to be stabilized in comparison to these cores. The stabilized testing method increases the effort due to the face sheets, which are bonded to the core.

In this study a new testing fixture is used, which combines the advantages of stabilized and unstabilized testing. For the fixtures, a set of acrylic plates was produced for each sample, with 90° V-grooves according to the major crease lines (Fig. 3). The samples are fitted into the grooves without any additional bonding and ensure a shape as close as possible to the designed geometry. In contrast to stabilized testing, the fixed crease lines still have rotational degrees of freedom in the grooves. This may result in earlier buckling failure compared to stabilized tests and therefore may give a conservative estimate of the core strength and stiffness. After testing, the acrylic fixtures are reusable and preparing a new sample only takes a few seconds. The transparency of the acrylic plates allows for easy checking of correct positioning of the sample between the test plates.

A Hegewald & Peschke 250kN universal testing machine was used for compressive testing. Forces were measured with a Class 1 250kN load cell. To ensure a even force introduction over the acrylic testing fixture, the samples were placed between two parallel plates and the plates were closed with a constant speed of 0.5 mm/min, in accordance with DIN 53291 [15]. For the parallel pressure plates a special testing device was used, which is linear guided by ball bearings and is shown in Fig. 3. For each

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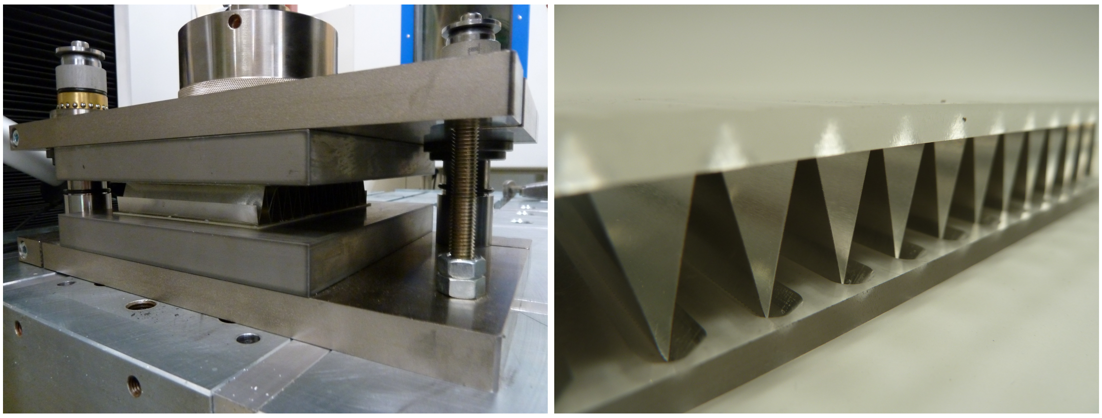

Figure 3. Left: Parallel testing fixture. Right: Aluminum sample positioned between the acrylic upper and lower fixtures

geometry out of EnDURO ICE 130 the test data were taken from [12] and for the aluminum cores seven samples were manufactured to ensure a reasonable degree of statistical assurance.

Table 1. Results of flatwise compression tests for all geometries and materials. Shown are mean values of strength (σ_{max}), compressive modulus (E_S) and their respective standard deviations (σ) and variational coefficients (c_v).

Material	Aluminum				EnDURO ICE 130			
Geometry	#1	#2	#3	#4	#1	#2	#3	#4
σ_{max} / kPa	33.39	501.59	518.43	525.96	9.30	80.19	83.48	86.41
σ_σ / kPa	4.43	9.18	19.17	6.62	0.57	2.52	5.47	3.84
c_{V_σ} / %	13.28	1.83	3.70	1.26	6.17	3.15	6.56	4.45
E_s / MPa	1.40	14.28	22.43	18.74	1.11	6.58	7.41	4.19
σ_E / MPa	0.44	0.79	2.34	0.55	0.19	0.91	0.92	0.24
c_{V_E} / %	31.36	5.51	10.45	2.94	17.02	19.83	12.48	5.77

4. Results

The strength and stiffness for all samples were computed by evaluating the maximum stress σ_{max} and a secant modulus E_S. To evaluate the modulus, the secant between the points for 0.45% and 0.65% of σ_{max} were used, except for geometry #1 out of aluminum, because there is a deviation within the chosen range (Fig. 4). The gradient before and after this deviation is similar, so for this sample a range from 0.65% to 0.85% of σ_{max} was used to calculate the compressive modulus. All other samples show a linear behavior between 0.45% and 0.65% of σ_{max}. Due to the material and influences of the manufacturing process, the measured densities showed minimal deviations from the analytical design values. Therefore the strength and stiffness are scaled with the ratio between analytical density and measured density of the sample. The density for the EnDURO ICE 130 samples ranges from 25.0 kg/m^3 to 26.5 kg/m^3 with a median of 25.3 kg/m^3 and from 52.0 kg/m^3 to 55.0 kg/m^3 with a median of 52.8 kg/m^3 for the aluminum cores [12]. The non-load-bearing flaps were compensated for in the determination of the weights and effective areas.

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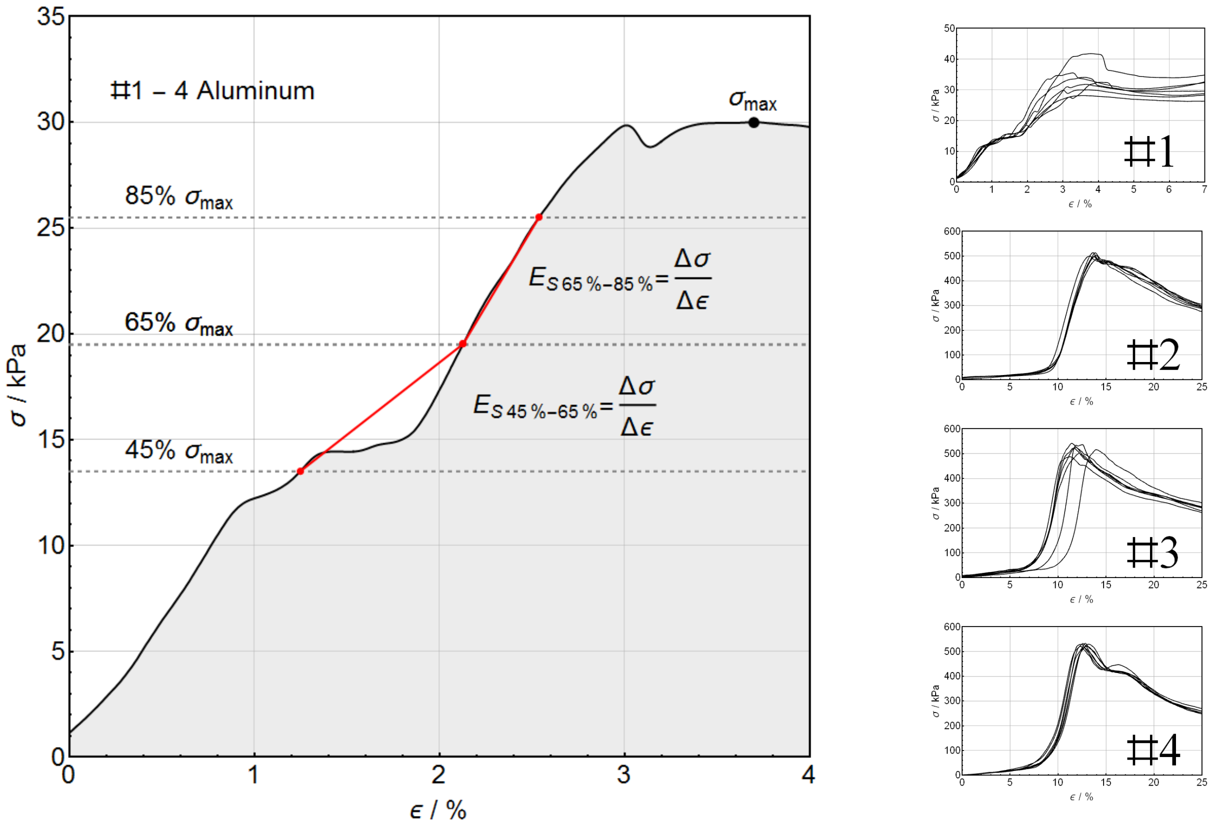

Figure 4. Left: Stress-strain diagram of aluminum sample #1-4 with marked stress levels for 45%, 65% and 85% of σ_{max} and secant modulus $E_{S45\%-65\%}$ and $E_{S65\%-85\%}$. Right: Stress-strain diagrams for geometries #1-#4 out of aluminum for all sample series. For the EnDURO ICE 130 results, see [12] detailed.

Because the samples of the two materials show large differences in strength and stiffness, the results in Table 1 were scaled. The scaling was done by dividing the strength respectively the stiffness by the maximum of all geometries out of the same material. For the strength, the maximal value is given by geometry #4 and for stiffness by geometry #3 for both materials. The scaled results can be seen in Fig. 5 and Fig. 6 for the strength and stiffness respectively. During the tests, the samples of all cores stayed firmly within the grooves of the fixtures. The results show pretty large standard deviations, which are mainly due to the semiautomatic manufacturing process. Comparing to literature and similar tests in the past, the results appear to be within acceptable range.

4.1. Overall results

Geometry #1 performs rather poorly for both materials regarding strength and stiffness. That is to be expected, because the large straight faces have a very low buckling strength compared to the other geometries. Buckling failure occurs immediately after starting the test. The samples of the Miura-ori series perform on a much higher level (Fig. 5 and Fig. 6). For all geometries the scaled strengths of #1-#4 are nearly identical for both materials. In comparison, for stiffness there is no strong correlation between samples made from different materials. Higher strength and stiffness performance for geometries #2-#4 result from smaller unit cell surfaces, which increase the buckling strength compared to geometry #1. The deformations of the EnDURO ICE 130 are reversible up to high strain levels due to the spring-like behavior of the material. In case of the aluminum, the deformations are plastic and not reversible even for comparably low strain levels.

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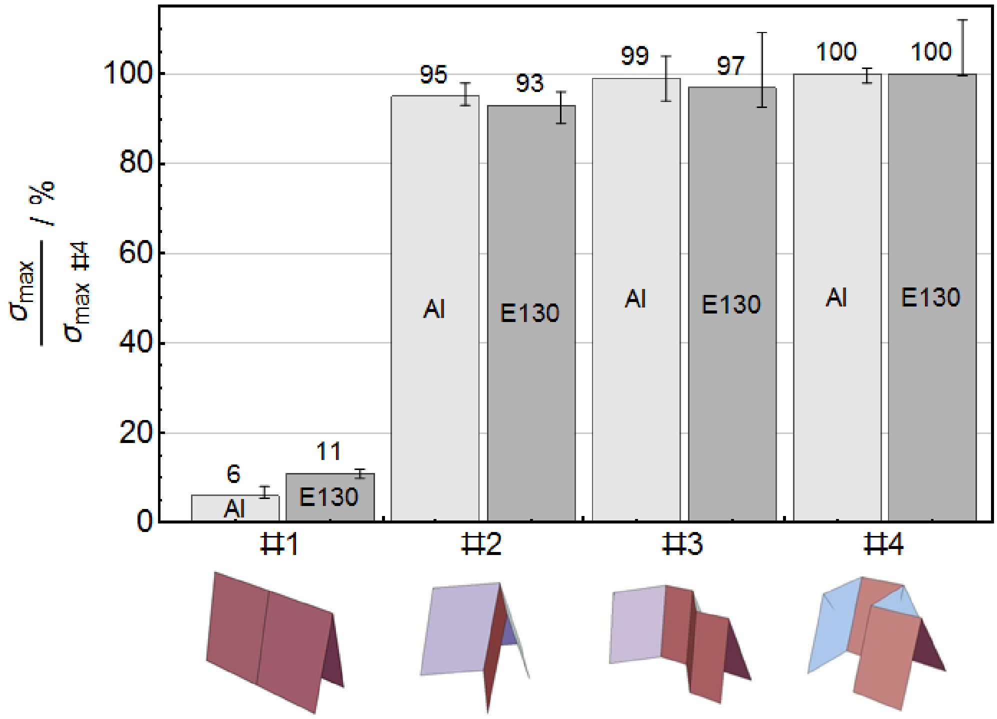

Figure 5. Scaled mean compressive strength for all samples. The brackets indicated the maximal and minimal values of the test series.

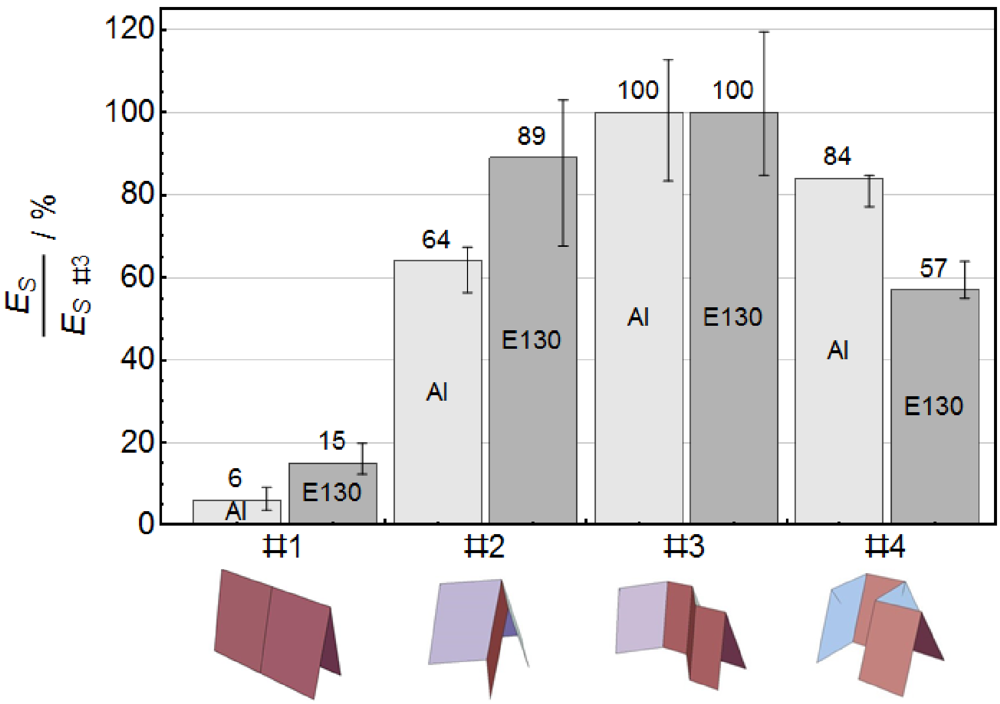

Figure 6. Scaled mean compressive stiffness for all samples. The brackets indicated the maximal and minimal values of the test series.

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4.2. Material comparison

Comparing the two materials in strength and stiffness, geometries #1-#4 show good correlation for the normalized strength of the EnDURO ICE 130 and aluminum samples. Both materials show a low performance of geometry #1 and higher mechanical performance of the Miura-ori samples. With regard to the scaling, the percentage difference between the two materials for each geometry is shown in the bar chart. For the strength the maximum deviation is 45.5% in case of geometry #1, while the maximum of the Miura-ori series is only 2.1%. The stiffness show larger deviations, up to 60% for geometry #1. Standard deviation for stiffness is also much higher than for strength. Comparing the samples #3 and #4, the performance in stiffness is reversed for EnDURO ICE 130 and aluminum with a percentage deviation of about 30% between the two materials.

5. Conclusion

Stiffness and strength for four different geometries, each out of two materials, have been evaluated using a new testing fixture consisting of acrylic, reusable plates. In combination with the laser scoring manufacturing process of the samples, this approach enables a quick and easy method to screen a large number of foldcore geometries and materials in a short time. A comparison between the two materials show good correlations in strength for the different geometries with small standard deviations. Results for the stiffness have poor accordance and even the progression throughout the geometries does not show a consistent behavior for aluminum and EnDURO ICE 130.

One of the most important results of this study is that the relative strength of high performance aluminum foldcores can be estimated with samples made out of low cost and easy to handle EnDURO ICE 130 paper. This offers the opportunity to reduce testing effort and testing time significantly. To investigate the transferability of the observed correlation, further test series using different base materials are planned.

6. Acknowledgment

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