WHITE PAPER

Fatigue Performance

of ArmaForm PET-based foam cores
in different grades and densities
conducted by KTH Institute.

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MAKING A DIFFERENCE AROUND THE WORLD

ArmaForm® Fatigue Testing

ArmaForm is used in the most demanding structural sandwich applications, such as wind turbine rotor blades. Its long term behaviour under cyclic loading conditions is of major concern.

ABSTRACT

ArmaForm PET-based foam core has, since its introduction in 2007, been used in the most demanding structural sandwich applications, such as wind energy rotor blades. Fatigue testing of virgin PET-based ArmaForm Core, called AC grade, proved that the material had the same excellent fatigue properties, regardless of density. Since then, AC grade has been almost completely replaced with the GR grade, which is produced from 100% recycled PET, offering a much more environmentally friendly product solution.

Testing demonstrated that it could match the same performance as the AC grade. Lately, the increased interest in high density core to replace end-grain balsa wood (EGB) in rotor blade applications required further verification of fatigue properties, as the testing on AC grade has been limited to AC115 (density 115 kg/m³) and below. Again, it was shown that fatigue properties, when normalised, are independent of density. All grades and densities have a fatigue threshold level of > 60% and easily meet the DNV GL requirement for use in wind turbine applications.

INTRODUCTION

The most typical requirement for a mechanical structure is that it withstands a certain static load at a defined maximum deflection, without collapsing. Because most structures are subjected to repeated load cycles (= fatigue) in actual use, designers are also faced with the task of predicting fatigue life.

The definition of fatigue testing can be thought of as simply applying cyclic loading to a test specimen to understand how it will perform under similar conditions in actual use. The load application can either be a spectrum load or a fixed load. The load application may be repeated millions of times and even up to several hundred times per second.

A common way to visualise time to failure for a specific material is the S-N curve. For engineering purposes and material selection, both plastics and metals are tested by determining experimentally the relationship between stress and life. Specimens are subjected to cyclic loading at different levels of **stress, S**, and the number of cycles to **failure, N**, is measured at each stress level.

The results are graphed as stress as a function of cycles to failure, which is commonly called an **S-N curve** or a Wöhler curve. The basic advantage of S-N curves is that they directly yield a graphic estimate of expected life in terms of a key design parameter: stress. Thus, in a situation that is very similar to the test conditions, one can derive a design stress directly from the S-N curve at the design life of the part.

A safety factor must be applied to such a design stress in recognition of the fact that a key variable in both the test and the part is uncontrollable, namely flaws. Even where numerical application to design is impractical, the S-N curve is useful in ranking materials and in measuring the effects of the many secondary variables that affect the fatigue performance of plastics, such as frequency and thickness.

TEST SETUP

Fatigue tests on sandwich structures are normally performed with bending loads, as they are known to be the most demanding. The four-point bending test method provides an almost pure shear stress in the core, between the inner and outer supports, and is hence suitable for the purpose.

The ASTM test standard C393-00 'Standard Test Method for Flexural Properties of Sandwich Constructions' describes the test set-up and requirements but is only designated for static and not fatigue testing. However, the same basic set-up can be used for the fatigue testing. The testing was performed at +23° C (±1° C) and approximately 50% relative humidity.

The loading ratio R is the ratio between the minimum and maximum load applied during a loading cycle. The test frequency needs to be adjusted to the load level so that failure would not occur due to local heating in the core. For foam core, this will normally result in a test frequency of 2-4 Hz but can sometimes be as low as 1 Hz.

A sample is supported on two outer bearings, and the load is introduced at the two central positions, hence the four-point bending test. The test starts with the definition of the static point of break. This static test deforms the material until it breaks, and the result defines the maximum load.

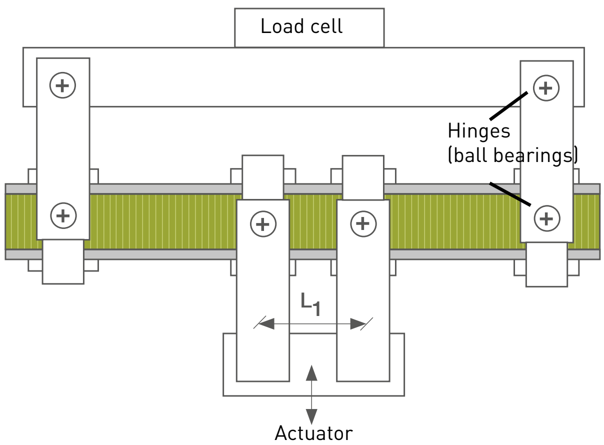


Figure 1: Four-point bending test setup

After the static test, the dynamic test starts whereby the material is loaded at a given stress level. When the sample breaks, the test is stopped, and the corresponding number of load cycles is noted. This test is repeated constantly (with different stress levels) to get a track record of failures by means of the S-N curve.

TESTING AT KTH

Armacell ran the fatigue testing at KTH Royal Institute of Technology (Department of Aeronautical and Vehicle Engineering) in Stockholm, Sweden.

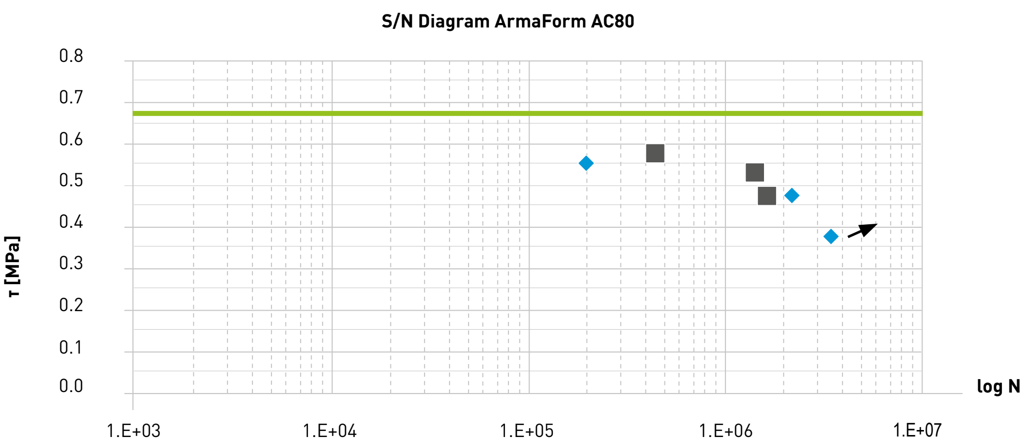
Sandwich panels used for the test were manufactured using the infusion technique with, typically, four layers of glass-reinforced resin on each side of the core. The testing was performed at +23° C (±1° C) and approximately 50% relative humidity. The loading ratio is, except where otherwise noted, R=0.1, i.e. the ratio between the minimum and maximum load applied during a loading cycle.

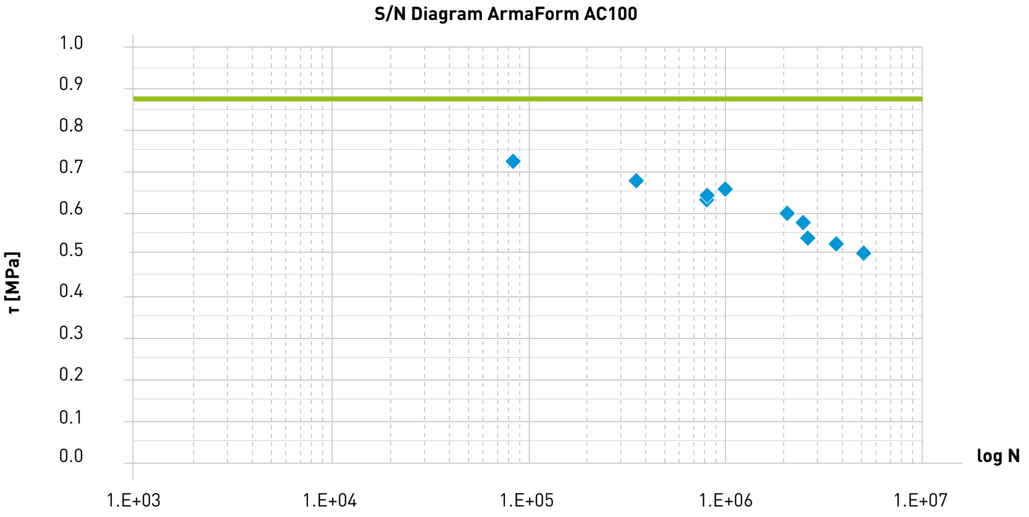
The test frequency was adjusted to the load level so that failure would not occur due to local heating in the core, i.e. 2-4 Hz. The common failure mode for cellular foams begins in the part of the beam between the inner and outer supports as this area is loaded in shear. Then, in this region, multiple cells fail individually during the fatigue loading forming a shear crack propagating at a 45° angle against the laminates. For ArmaForm Core that includes a weld line the crack can kink and follow the weld line so that the crack continues to propagate perpendicular to the face sheets.

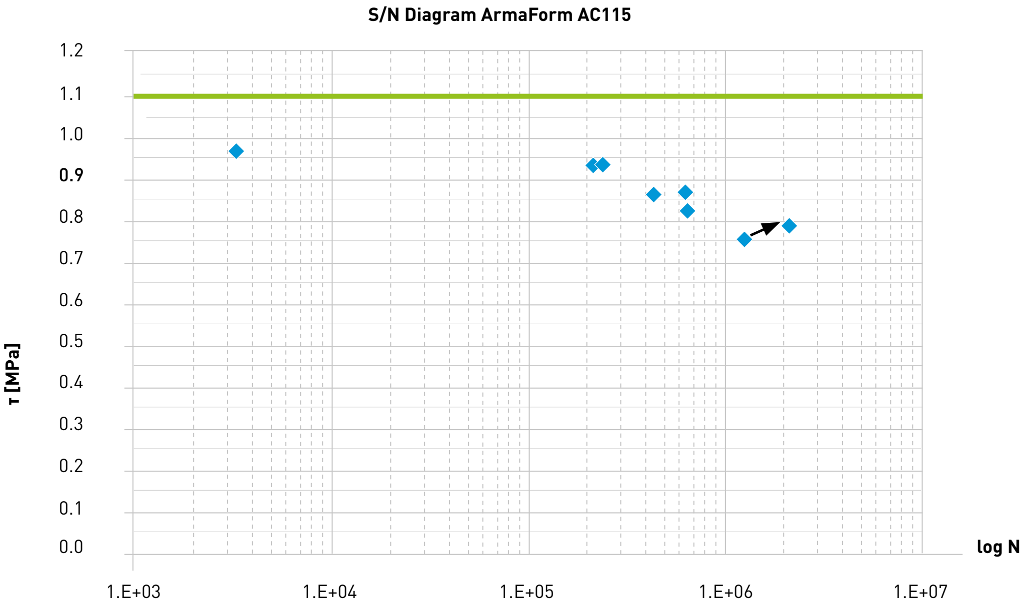
Figure 2: Test setup of the four-point bending sandwich beam for fatigue test and typical fatigue failure mode

DENSITY AND FATIGUE

To evaluate the influence of density on the fatigue performance, three different densities of the AC grade were tested. The results are given in the following three S-N curves [1].







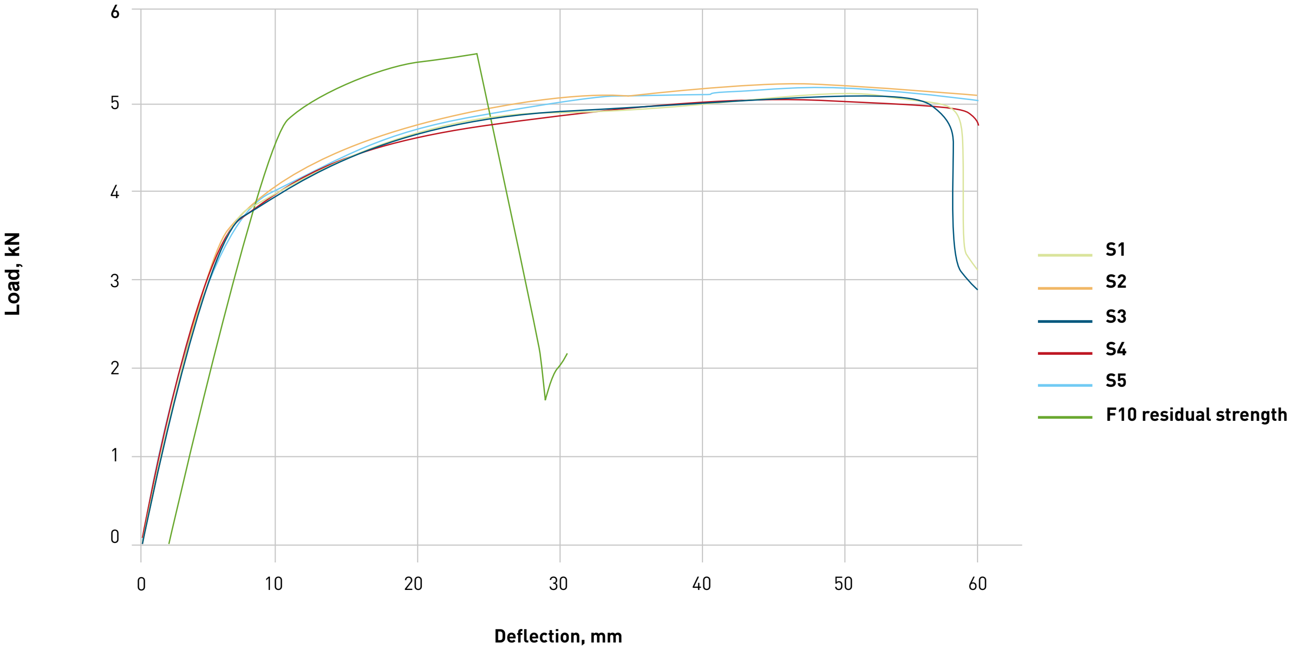
Graphic 1-3: Curve for AC80, AC100, AC115

The fatigue performance in relation to the static strength of the materials tested is excellent. One can observe that all qualities tested here can sustain well over five million cycles at load levels corresponding to 60-70% of the shear strength. For structural core materials, the stress level at which the material reaches five million load cycles can normally be defined as the fatigue threshold level.

For other structural core materials, such as those based on PVC core, this level is at 30-35% of the static failure load. However, all tested AC grade densities have a fatigue threshold level higher than 60%.

One test sample, AC100 - F10, was tested at 60% of the static shear strength for five million load cycles. The test was then stopped, and a residual strength test was performed. It is interesting to see that the stiffness is basically the same as the 'virgin' material (not tested in fatigue). This is in contrast to other polymer cores that, after a number load cycles, already start to lose strength and stiffness slowly.

Furthermore, the maximum load sustained in the residual test is higher than the static strength test (see graphic 4) at the expense of a lower elongation at break, but this still yields a higher safety factor in operation.



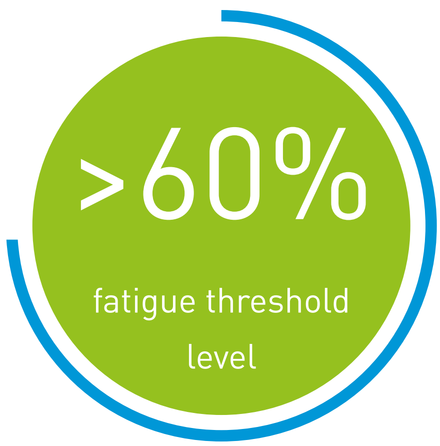
Graphic 4: Static load deflection curves for AC100

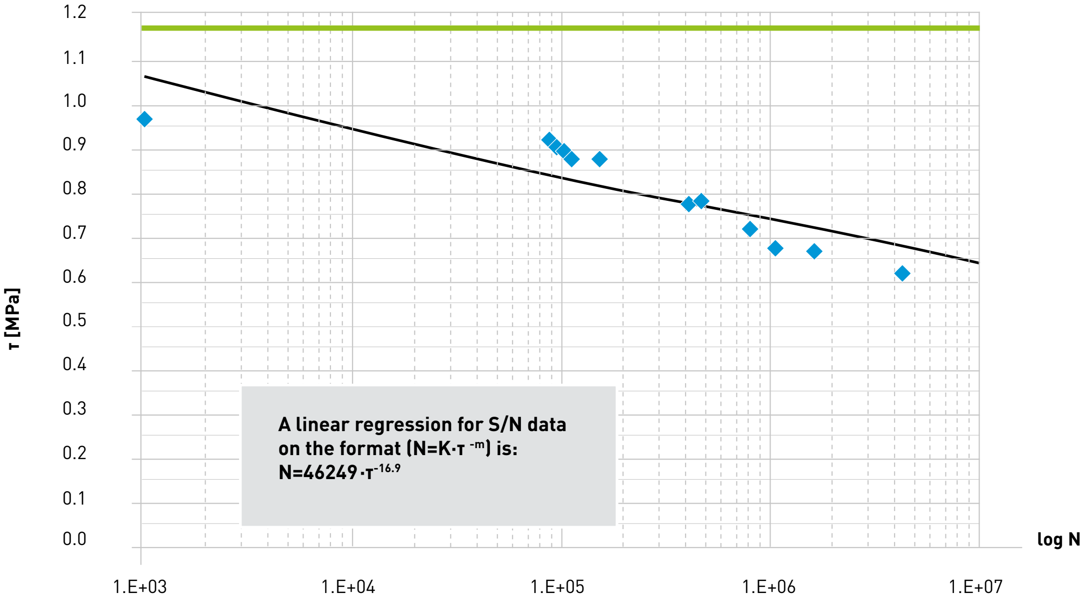
GRADE AND FATIGUE

ArmaForm GR grade is the further development of the AC grade, and is made by Armacell's patented technology to produce PET foams from 100% recycled PET raw material base.

To ensure that the GR grade did perform in the same excellent way as the AC grade in fatigue, the material was put through testing at KTH in accordance with the directives from GL for the certification of core materials to be used in wind blade structures [2]. Test data for GR115 tested up to five million cycles did show again a fatigue threshold > 60% for R=0,1 [3], see next page graphic 5.

The m-value calculated from the slope of the curve for GR115 m=16,9 is well above the m>10 required by GL. All results were equal or even a little better for GR115 than the ones for AC115 and with a very good correlation, showing that the GR grade was a great substitute for the former grade.



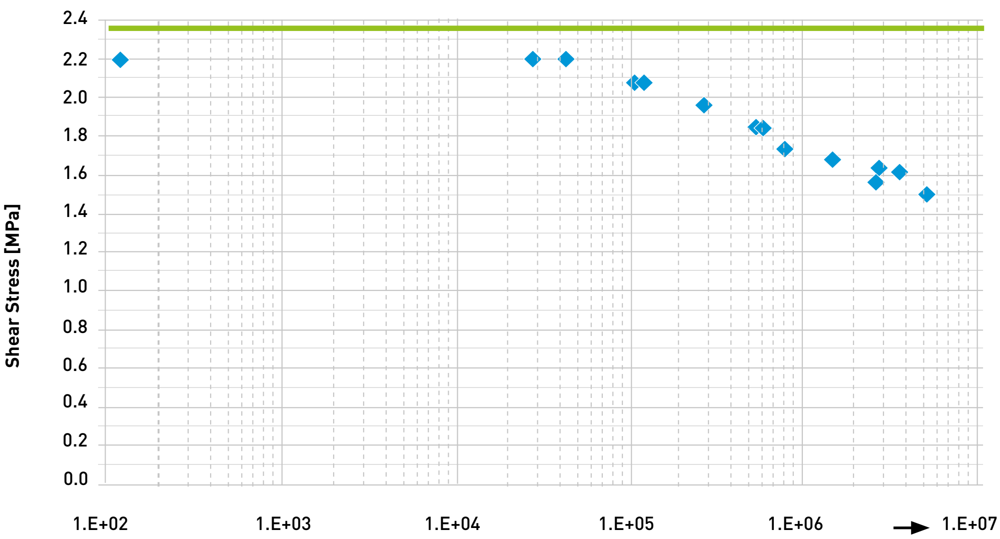


Graphic 5: Fatigue performance of ArmaForm GR115

HIGH DENSITY AND FATIGUE

The increased interest and use of high density GR grade in blade application to also replace EGB initiated a need for further testing as the highest density tested at an external laboratory was 115 kg/m^3 density. Testing was again run at KTH to have as equal a set-up as possible.

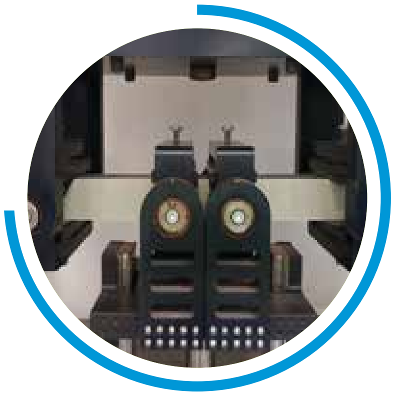
The results again showed that fatigue properties when normalised are independent of density and grade. If anything, the results for the GR200 test showed even a little better performance than lower densities with a fatigue threshold of >65%, see graphic 6 [4].



Graphic 6: Fatigue performance of ArmaForm GR200

SUMMARY

The fatigue testing on ArmaForm Core in different densities and different grades has been performed using the four-point bending test set-up. The failure mode was anticipated, and the test results show that ArmaForm Core performs very well under fatigue shear loading. The test data when normalised for density and static strength is very similar for all tested core materials.
Testing indicates that all ArmaForm grades and densities have a fatigue threshold level higher than 60% and easily meet the DNV GL requirements for use in wind energy applications.



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[2] GL, Core Materials - Requirements for the determination of the Gradient of the S/N Curve, Germanischer Lloyd SE, Materials Certification, Hamburg, Germany, Date of issue: 15.07.2012.

[3] Norrby M., 'FATIGUE TESTING OF SANDWICH CORE MATERIAL, ArmaForm GR 115', Department of Aeronautics, Kungliga Tekniska Högskolan, Report 2015-01 rev. 3, 2015.

[4] Norrby M., 'FATIGUE TESTING OF SANDWICH CORE MATERIAL, ArmaForm GR 200', Department of Aeronautics, Kungliga Tekniska Högskolan, Report 2018-01, 2018.

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As the inventors of flexible foam for equipment insulation and a leading provider of engineered foams, Armacell develops innovative and safe thermal, acoustic and mechanical solutions that create sustainable value for its customers. Armacell's products significantly contribute to global energy efficiency making a difference around the world every day. With 3,000 employees and 27 production plants in 17 countries, the company operates two main businesses, Advanced Insulation and Engineered Foams. Armacell focuses on insulation materials for technical equipment, high-performance foams for high-tech and lightweight applications and next generation aerogel blanket technology.
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