WHITE PAPER

Fatigue Testing

Fatigue tests are performed to confirm the durability and damage tolerance of mechanical structures. Testing involves the application of millions of cyclic loading to the test specimen. Test results allow designers to predict a fatigue life.

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ArmaPET™

ArmaPET™
FATIGUE TESTING

Since its introduction in 2007, ArmaPET Struct foam core has been used in the most demanding structural sandwich applications, such as wind turbine rotor blades. Its long term behaviour under cyclic loading conditions is therefore of major concern.

Fatigue testing of ArmaPET Struct based on virgin PET, in the following called AC grade, in different densities was conducted by KTH institute. Since then, AC grade has been almost completely replaced with ArmaPET Struct based on 100% recycled PET, called GR grade.

Testing demonstrated that the GR grade could match the same performance as the AC grade.

The increasing 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 the AC grade has been limited to a density of maximum 115 kg/m^3. It was shown that fatigue properties, when normalised, are independent of density. All grades and densities show 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.

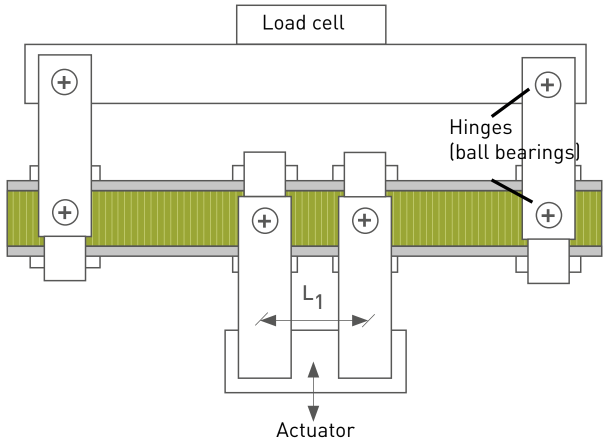


Figure 1: Four-point bending test setup

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

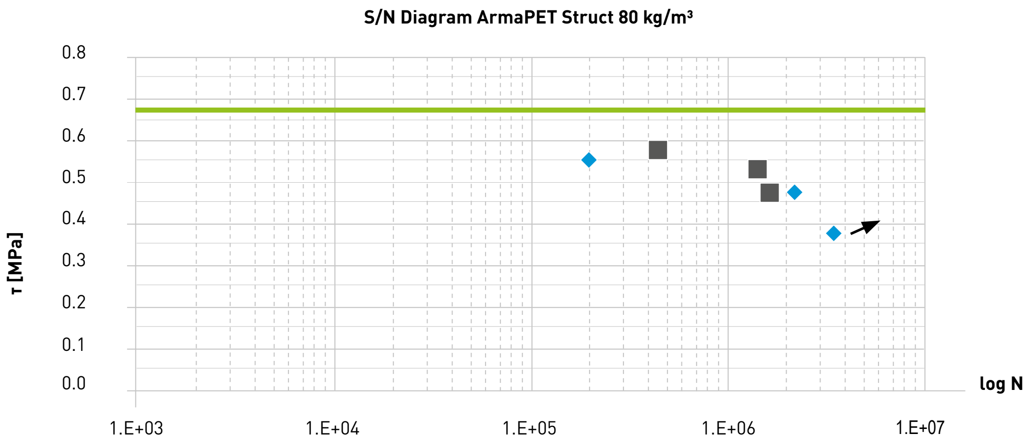
Armacell ran the fatigue testing at KTH Royal Institute of Technology (Department of Aeronautical and Vehicle Engineering) in Stockholm, Sweden. Sandwich panels used for the test were manufactured using the infusion technique with, typically, four layers of glass-reinforced resin on each side of the 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.

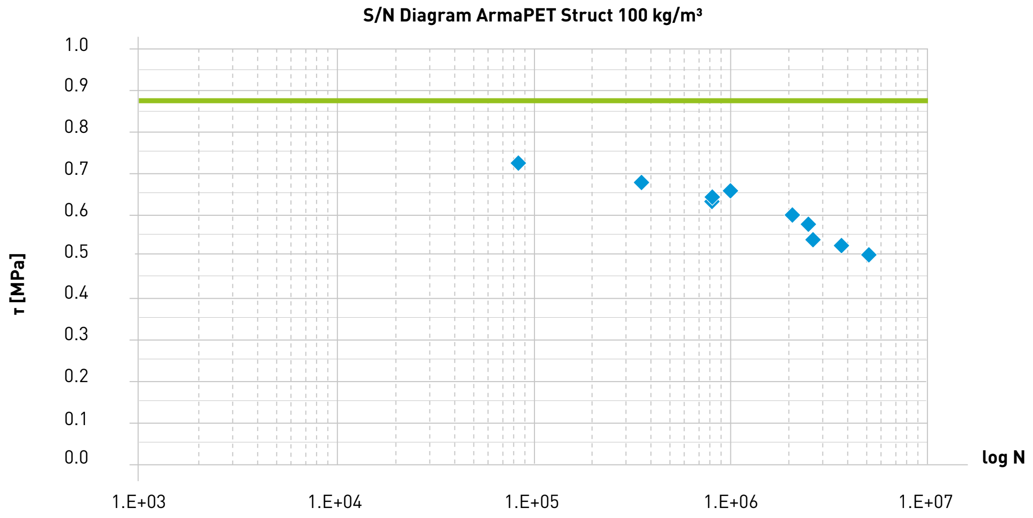
The test frequency was adjusted to the load level so that failure would not occur due to local heating in the core, i.e. 2-4 Hz. The common failure mode for cellular foams begins in the part of the beam between the inner and outer supports as this area is loaded in shear. Then, in this region, multiple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

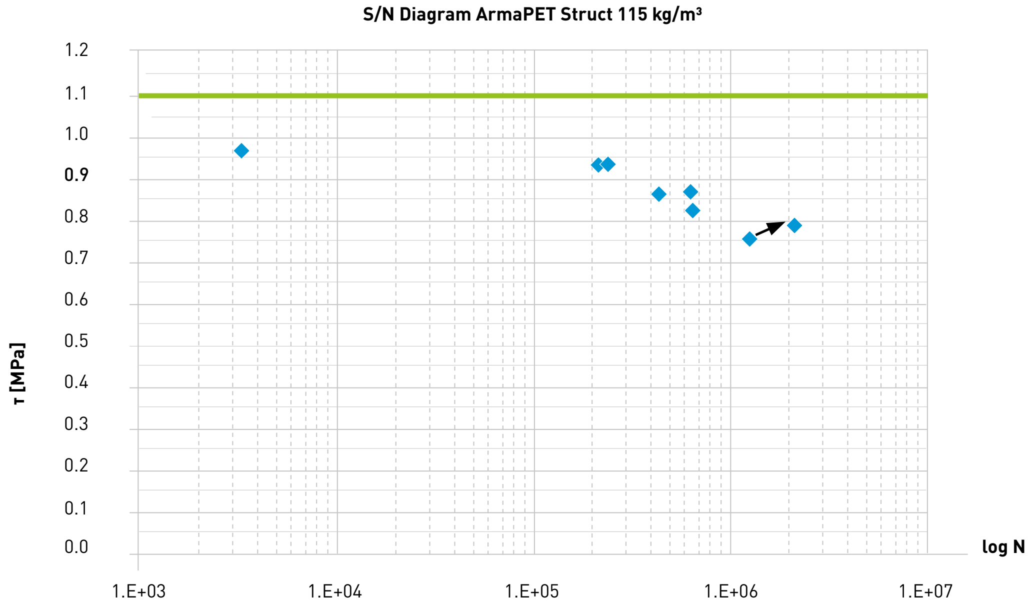
Figure 2: Test setup of the four-point bending sandwich beam for fatigue test and typical fatigue failure mode

DENSITY AND FATIGUE

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







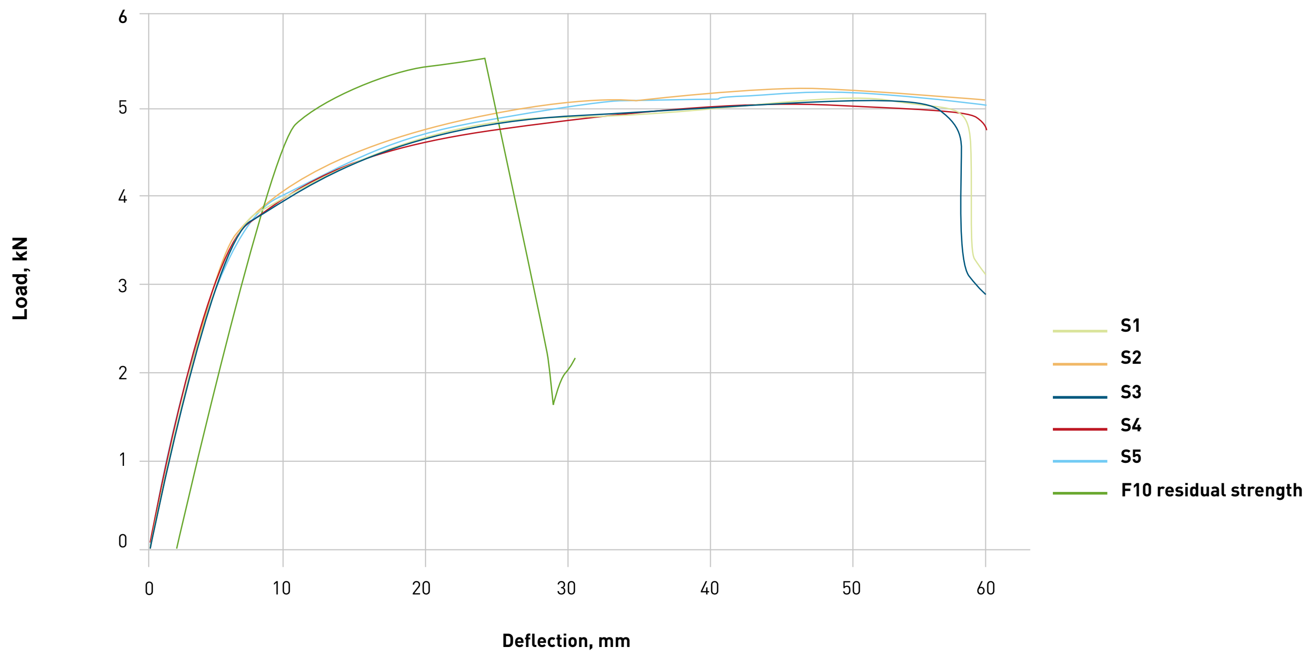
Graphic 1-3: Curve for ArmaPET Struct AC80, AC100, AC115

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 densities have a fatigue threshold level higher than 60%.

ArmaPET Struct 100 kg/m³ 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 for the materials not subjected to any test. 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 at the expense of a lower elongation at break, but this still yields a higher safety factor in operation. See graphic 4.



Graphic 4: Static load deflection curves for ArmaPET Struct 100 kg/m³

GRADE AND FATIGUE

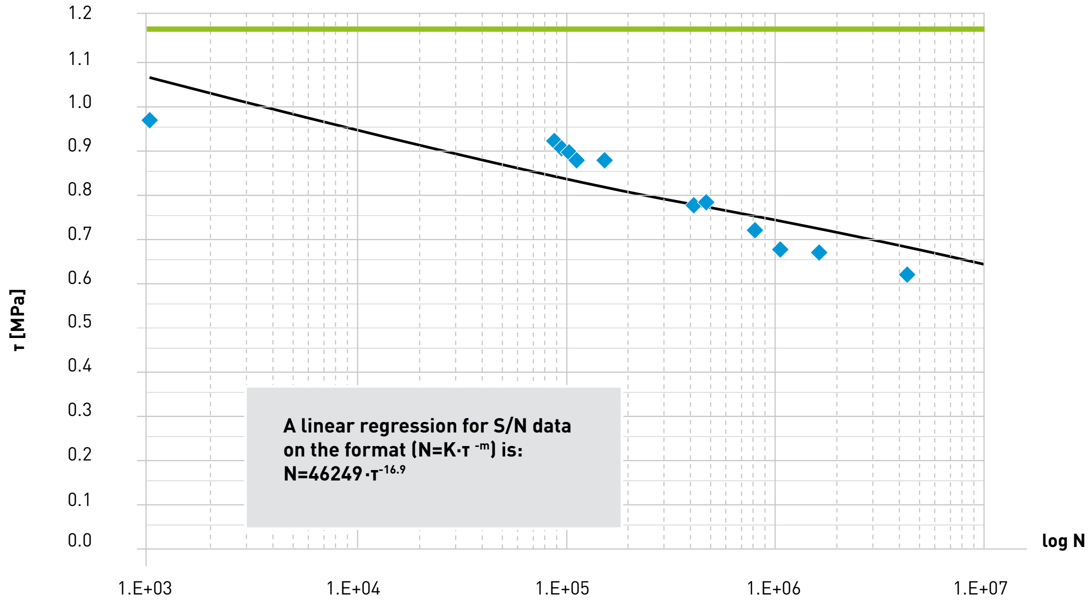
ArmaPET Struct based on 100% recycled PET was launched in 2010 and is the further development of the AC grade. It is made by Armacell´s unique and patented process technology enabling the production of PET foam products based on post-consumer PET bottles.

To ensure that the GR grade did perform in the same excellent way as the AC grade, we repeated the fatigue testing at KTH in accordance with the directives from GL, needed for the certification of core materials used in wind blade structures [2].

ArmaPET Struct GR115 was tested up to five million cycles and did show again a fatigue threshold > 60% for R=0,1 [3], see graphic 5.

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

>60%
FATIGUE
THRESHOLD

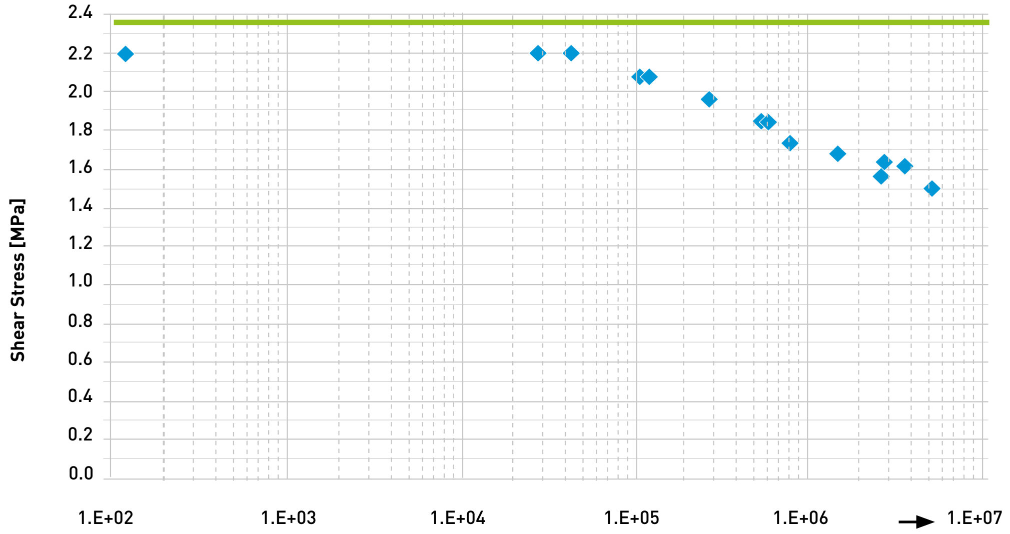


Graphic 5: Fatigue performance of ArmaPET Struct 115 kg/m³

HIGH DENSITY AND FATIGUE

The increased interest and use of high density ArmaPET Struct in blade application to replace end-grain balsa wood required the testing of densities higher than 115 kg/m³ . Testing was done again at KTH to have a set-up as equal as possible.

The results again showed that fatigue properties, when normalised, are independent of density and grade. The test results for 200 kg/m³ density showed even a little better performance than lower densities with a fatigue threshold of >65%, see graphic 6 [4].



Graphic 6: Fatigue performance of ArmaPET Struct GR200

SUMMARY

The fatigue testing on ArmaPET Struct 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 ArmaPET Struct 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 ArmaPET Struct 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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[1] Burman M., 'Fatigue testing of sandwich Core Material, AC80, AC100 and AC115', Department of Aeronautics, Kungliga Tekniska Högskolan, Report 2009-15 rev. 2012, 2012.

[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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