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Long-term testing of composite through-thickness properties

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Long-term testing of composite through-thickness properties

Andreas T. Echtermeyer,
Truls S. Ekeberg,
Odd E. Sund
Det Norske Veritas AS
Veritasveien 1
N-1322
Høvik
Norway

The use of composite materials offshore has increased over the last years. Long term performance of a component is an important consideration for users and authorities when evaluating a composite solution. Long term data of composites are widely available for many material combinations. Data in sea water environment are more difficult to find. However, most of the available long-term data is related to fibre dominated properties. The argument for measuring these properties is that composites are designed with fibres running in the main load bearing path. Composite structures where fibres do not carry the main load should be avoided.

Practical applications have shown that it is sometimes impossible to carry all significant loads through the fibres. This is particularly the case for the design of joints. The loads are often transferred through the matrix in the joint. The lack of data in long term performance of matrix dominated properties, in particular interlaminar shear strength, has been a considerable problem when evaluating such constructions.

The measurements of long term interlaminar shear properties in this study showed that the influence of sea water was negligible for this laminate. Both static and cyclic fatigue cause a significant reduction of interlaminar shear strength with time, about 35% reduction after 20 years and 80% reduction after 106 cycles. This reduction should be considered when designing joints or other components where interlaminar shear strength is critical.

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EXECUTIVE SUMMARY

The use of composite materials offshore has increased over the last years. Long term performance of a component is an important consideration for users and authorities when evaluating a composite solution.

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Practical applications have shown that it is sometimes impossible to carry all significant loads through the fibres. This is particularly the case for the design of joints. The loads are often transferred through the matrix in the joint. The lack of data in long term performance of matrix dominated properties has been a considerable problem when evaluating such constructions.

This study investigates the matrix dominated long-term behaviour of a typical glass polyester marine laminate. Cyclic fatigue and stress rupture (static fatigue) data were measured to provide the basis for the evaluation of long term performance. Characteristic long-term performance curves were calculated with a 97.5% tolerance and 95% confidence based on the procedures given in the DNV offshore standard for composite components, DNV-OS-C501.

The influence of sea water on short and long-term properties of the laminate was negligible for this laminate. Both static and cyclic fatigue cause a significant reduction of interlaminar shear strength with time, about 35% reduction after 20 years and 80% reduction after 10^6 cycles. This reduction should be considered when designing joints or other components where interlaminar shear strength is critical.

1 INTRODUCTION

The use of composite materials offshore has increased over the last years. Long term performance of a component is an important consideration for users and authorities when evaluating a composite solution.

Long term data of composites are widely available for many material combinations /1-6/. Data in sea water environment are more difficult to find /7-9/. However, most of the available long-term data is related to fibre dominated properties. The argument for measuring these properties is that composites are designed with fibres running in the main load bearing path. Composite structures where fibres do not carry the main load should be avoided.

Practical applications have shown that it is sometimes impossible to carry all significant loads through the fibres. This is particularly the case for the design of joints. The loads are often transferred through the matrix in the joint. Two examples of typical joints are given in Figure 1. The T joint will have critical interlaminar shear stresses when the vertical part is loaded in bending, compression and tension. Peel stresses can also be critical for this joint. The lap joint is often used to connect two pipes. The axial loads on the pipe will cause interlaminar shear stresses in the joint. Note that not only the interface, but the entire laminate is exposed to interlaminar stresses.

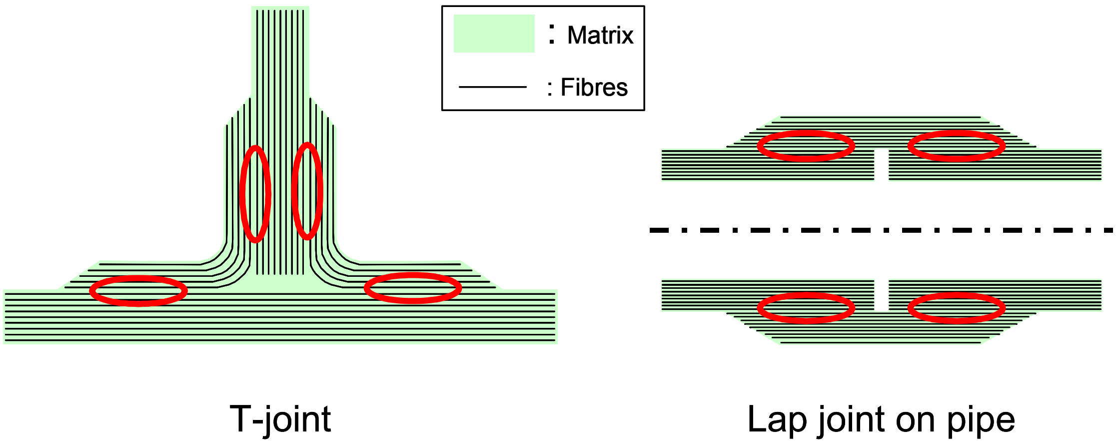

Figure 1 Two typical composite joint designs. The encircled areas can have critical interlaminar shear stresses, depending on the loading conditions.

The lack of data in long term performance of matrix dominated properties has been a considerable problem when evaluating such constructions. The objective of this study was to characterize the long term interlaminar shear properties, giving more confidence into the design of complicated composite structures. Whether more readily available in-plane shear data can be used to estimate the through thickness data was also investigated.

2 MATERIALS

The materials used for the interlaminar shear specimens were typical marine/offshore laminates. The glass reinforcement was WR 9622 R24-810 (woven roving) from Ahlstrøm AB and the polyester resin was Norpol 200-M800 from Reichold AS.

The Norpol 200-M800 polyester is a medium reactive isophthalic/neopenthylglycol polyester resin. Polyester is a thermoset with covalent bonds between all molecules that decompose on heating and cannot be reshaped. Norpol no.1 (MEKP) was used as hardener. The mixing ratio is 1% hardener. The polyester has a gel time of 35-45 minutes. The Norpol 200-M800 had the batch number 20643474 and was produced in week 24 of the year 2001.

The woven roving 9622 R24-810 was produced of continuous E-glass and had the reference number 00385D53C0201. Roving batch numbers were 0038010063 for weft and 0037010016 – 0037010022 for warp. The reinforcement was dated 09.02.2001.

A laminate with woven roving reinforcement can be described as a sequence of unidirectional plies in the form of a cross plied or 0/90 laminate. Typical unidirectional ply properties for such a laminate are given in Table 1 /10/.

Table 1 Material properties (Orthotropic unidirectional ply model)

Young's modulus in fibre direction	E_1	26.7 GPa
Young's modulus transverse to fibre direction	E_2	8.4 GPa
Young's modulus in through thickness direction	E_3	9.6 GPa
In plane shear modulus	G_{12}	3.5 GPa
Through thickness shear modulus	G_{13}	2.8 GPa
Through thickness shear modulus	G_{23}	2.8 GPa
In plane Poisson's ratio	ν_{12}	0.29
Through thickness Poisson's ratio	ν_{23}	0.29

3 EXPERIMENTAL SETUP

3.1 FABRICATION

Test specimens were manufactured from eight identical plies of glass/polyester laminate with a hand lay-up technique. A flat glass plate with Teflon coated surface was used as a mould. The woven roving sheets were cut out, and resin and hardener where thoroughly mixed together. The resin mixture was applied with a brush between the layers. Serrated rollers were used to compact the material against the mould to remove air. It was important not to roll too hard or too soft, but just to get the right balance between the resin, fibres and voids. The aim was to produce a typical marine composite with a normal fibre to resin ratio and not a “hi-tech” material that can only be produced with pressure and vacuum, more typical for the aerospace industry.

The laminate sheet was cured without pressure at room temperature for two days, thereafter post-cured at 50 ^{o}C for 24 hours. This post-curing should have cured the specimens completely. The laminate sheet was cut in specimens and left at room temperature for at least two weeks before testing.

Specimens were tested dry and wet. The dry specimens were kept in air while all specimens for testing in wet conditions were completely immersed in seawater for a month at 50 ^{o}C. The seawater was made according to ASTM standard D1141-98 /11/. Since the specimens were completely post-cured before the exposure to warm seawater, additional curing during the soak period in water should not have taken place.

3.2 WEIGHT FRACTIONS AND VOID CONTENT

The laminate had a fibre weight fraction of 60% and a void content of 3.5%. This represents a typical, good laminate used in the marine industry.

The glass weight fraction was determined in accordance to ISO standard 1172 /12/. The glass weight fraction was 59.8%, with a standard deviation of 1%.

The void content was obtained by examining several cross-sections of the laminate at different positions with a microscope. Pictures taken with the microscope were analyzed with image processing software called Zeiss KS300 /13/ measuring the void area vs. cross-sectional area ratio. The void content was $3.5 \pm 2\%$ based on the analysis of 11 pictures. A void content of 5% is a commonly accepted upper boundary for acceptable marine composite structures.

3.3 SPECIMEN GEOMETRY

Interlaminar shear strength is often measured according to ISO 4585 standard or ASTM D2344 standard. Both tests are not pure shear tests and some bending may occur. To avoid the bending problems, especially under long term conditions, a specimen with a symmetric double-lap composite joint was made. The geometry of the tested specimens is as shown in Figure 2. The overall goal of the test specimen design is to introduce interlaminar shear stresses between layers, thus enabling a characterisation of the interlaminar shear strength of the laminate. The interlaminar stresses are the stresses acting on the interface of two adjacent laminae (or plies).

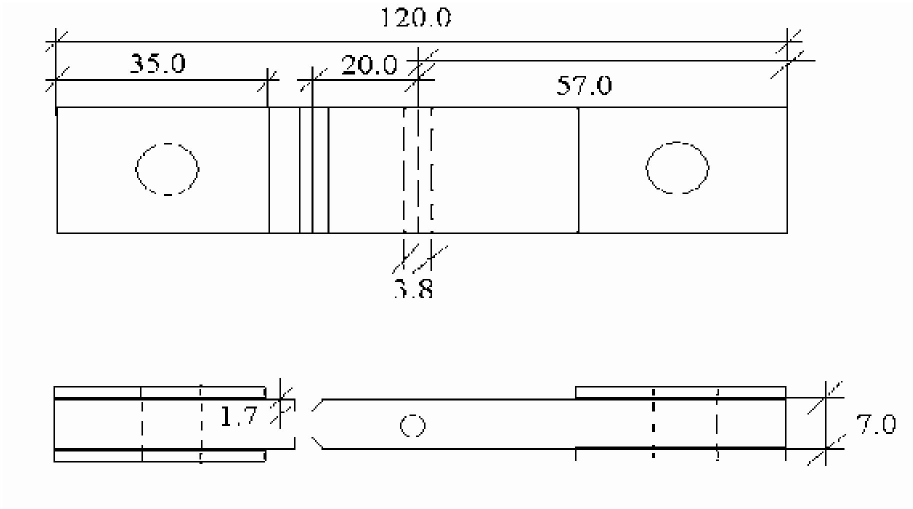

Figure 2 Geometry of specimens (all dimensions in mm)

Failure occurs if the interlaminar shear stresses are sufficiently high. A short span is used to initiate shear failure. To ensure that shear failure and not tension failure of the notched cross sections occur, the distance between the notches and the drilled hole was adjusted accordingly. To ensure that the specimens for the compressive tests would not fail prematurely due to buckling of the thin sections between the hole and the cuts, the tabs of these specimens had to be extended past the connection holes, to increase the buckling resistance of this area. This critical area and the extension of the tabs are illustrated in Figure 3.

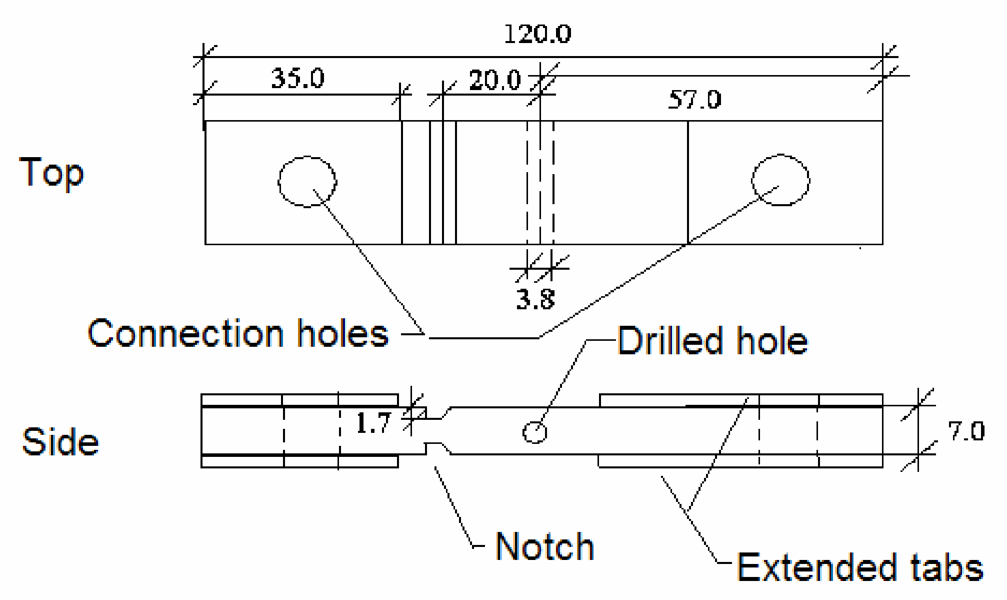

Figure 3 Specimen with extended tabs

The diameter of the drilled hole was chosen to meet two requirements: The middle layers should be cut away while the outermost layers should be left intact. Each ply is approximately 0.875 mm thick. Due to the nature of the woven roving fibre material, it is difficult to accurately define where the layers are separated, as the individual fibre strands are merged with each other, giving the interface a somewhat three dimensional character.

The cuts in the surface were approximately 1.70 mm deep, enough to effectively prevent the outer layers from carrying any load at one end of the specimen. Holes with slightly different diameters were tested to establish the appropriate diameter. A hole with a diameter of 3.9 mm was chosen to ensure that all of the 4 middle layers and the immediately surrounding matrix were cut away, while retaining strength in the outermost layers. Figures 7 and 8 demonstrate that good interlaminar shear failure was obtained. The failure surface shows clearly the pattern of the woven reinforcement.

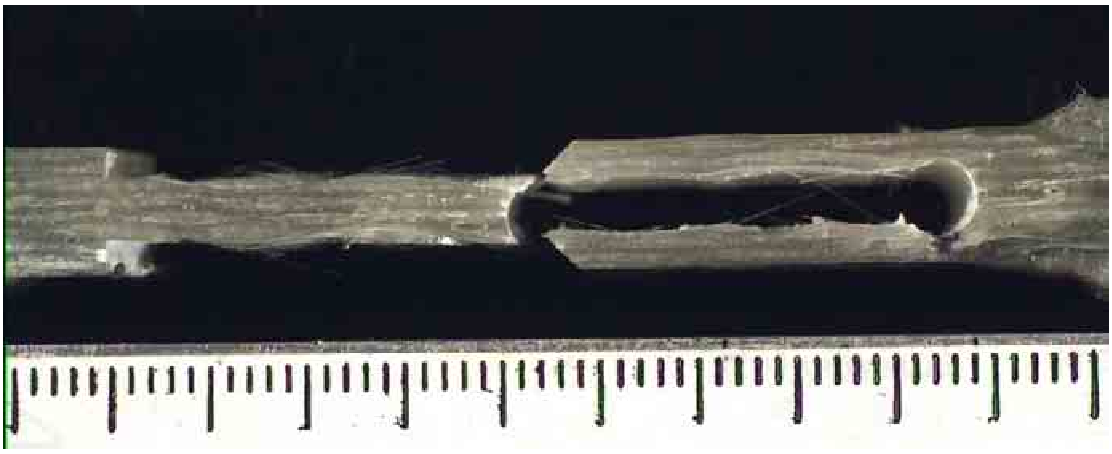

Figure 4 Shear lap specimen after failure, seen from the side

Figure 5 Shear lap specimen after shear-failure, seen from the top

The average interlaminar shear strength, τ , is calculated from the applied force F and area A as given in equation 1.

$$\tau = F / A \qquad [\text{MPa}] \tag{1}$$

The shear area A was determined by multiplying the shear length of the specimen with the width. The shear length is shown in Figure 6.

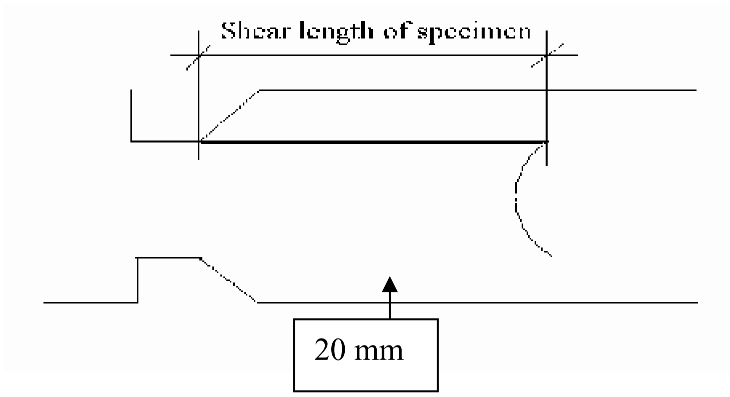

Figure 6 Shear length of tested specimen

An FE analysis of the joint was performed to investigate the shear stress distribution and peel stresses. The analysis showed the typical characteristic of stress concentrations at the notch and hole for such specimens as shown in Figures 7 and 8. The standard test specimens would show the same characteristics. The measured shear strengths may therefore be somewhat conservative. However, interlaminar shear failure will most likely be surrounded by matrix cracking. The matrix cracks will introduce similar stress concentrations as observed in this test. The same applies for the peel stresses.

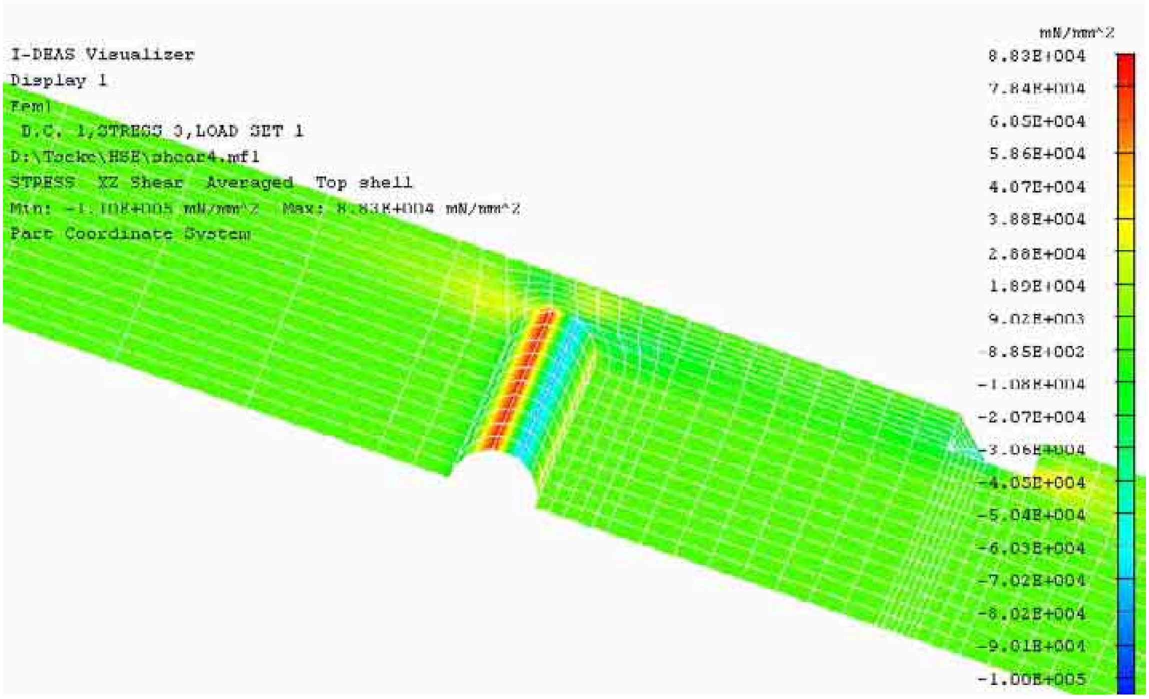

Figure 7 Plot of shear stresses in the y=0 plane, seen from underneath (No deformation)

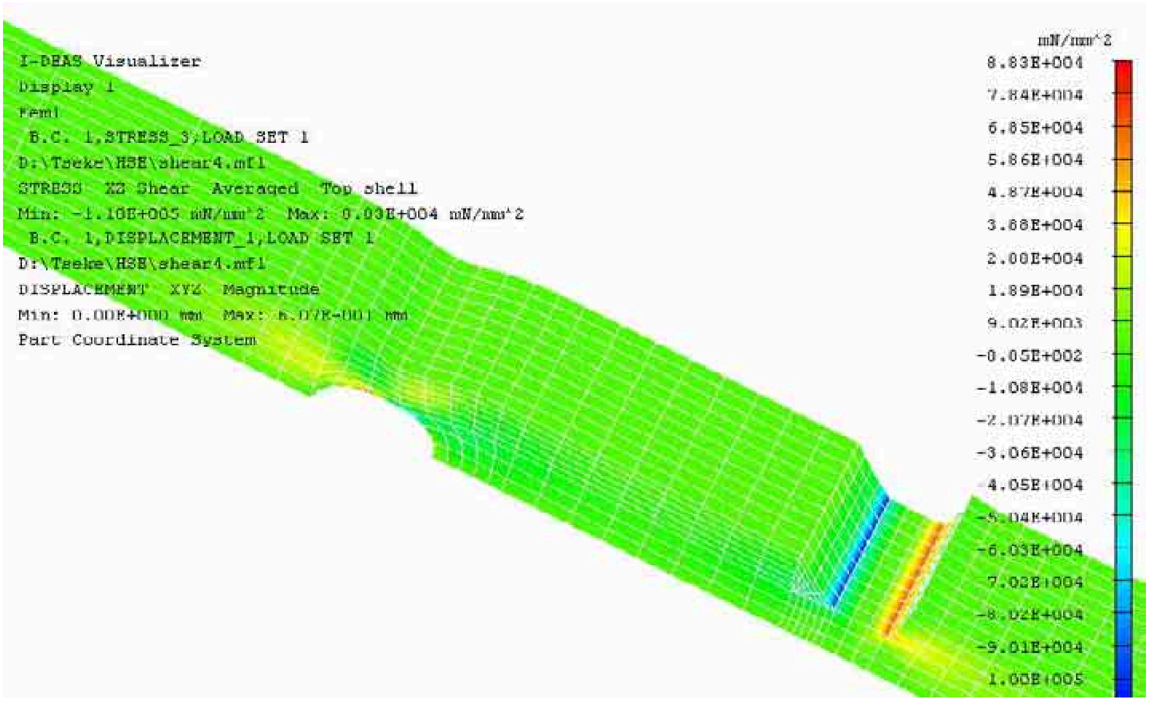

Figure 8 Plot of shear stresses in the y=0 plane, seen from above. (Scaled deformation)

3.4 TEST MACHINES

Short time tests and fatigue tests were carried out in a standard servo-hydraulic test machine. The wet specimens were immersed in sea water during testing. Specimens were placed inside a tube filled with water during the test. The lower grip was immersed in water while the upper grip was in air. The entire gauge area of the specimen was always immersed in water.

Special equipment was built for the long-term term stress rupture testing. A fixture with a lever arm was built to apply the load, as shown in Figure 9. The arm of momentum was ten times longer on the left hand side of the pole than on the right hand side giving a tension force ten times larger than the load. Loads up to 10kN could be applied to the specimen. Specimens were put in series and they were reconnected after failure of one specimen. The friction in the system was low to ensure that the weights on one side of the arm gave the proper loading to the specimens connected to the other side of the arm.

Specimens tested in wet conditions were placed inside a plastic tube. The tube was filled with seawater and a water pump was used to circulate the seawater. This is shown schematically in Figure 10. The circulation was slow, just to keep the seawater in movement.

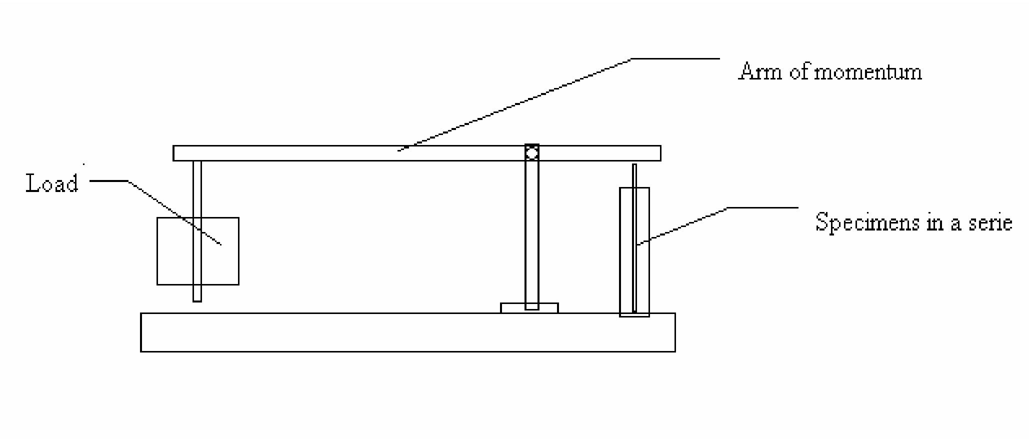

Figure 9 Test rig for long term testing

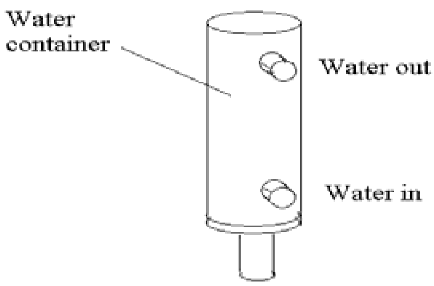

Figure 10 Water container made of plastic

4 TEST RESULTS

4.1 INTRODUCTION

Long-term tests were divided into two categories: static and cyclic fatigue tests. Each category included testing of specimens in both dry and wet conditions. To provide baseline data for comparison, a series of static tests to establish ultimate strength of the specimens was initially performed. These initial tests were also performed in both dry and wet conditions

4.2 CHARACTERISTIC STRENGTH

The most important strength data for a structural application is the characteristic strength. This is a minimum strength the material should always have taking the natural scatter of properties into account. In accordance to DNV offshore standard for composite components characteristic values were established with 97.5% tolerance and 95% confidence /10/.

The characteristic strength σ_c for a static test is given by:

$$\sigma_C \quad \overline{\sigma} - k_m \hat{\sigma} \,. \qquad \textbf{(2)}$$

where the standard deviation is denoted by $\hat{\sigma}$, and the mean shear strength is given by $\overline{\sigma}$. The coefficient k_m is dependent of number of test specimens and is given in Table 2 /10,14/:

Table 2 Coefficient k_m values

Number of test specimens	k_m
3	9.0
4	6.0
5	4.9
6	4.3
10	3.4
15	3.0
20	2.8
25	2.7
Infinite	2.0

The characteristic long term properties were also calculated with a 97.5% tolerance and 95% confidence, according to the method given in DNV offshore standard for composite components /10/. The stress rupture curve is typically written in the form:

$$\log\sigma \quad \log\sigma_0 - \beta\log t \qquad \textbf{(3)}$$

where σ is the applied stress, t is the time, β is the slope of the curve and σ_o denotes a short term strength. The short term strength is usually similar to the measured static strength, but does not need to be the same.

Similarly the fatigue SN curve is usually written as:

$$\log\sigma \quad \log\sigma_0 - \alpha\log N \qquad \textbf{(4)}$$

where N is the number of cycles, α is the slope of the curve.

To obtain the characteristic curves for the mean stress rupture curve or cyclic fatigue, curves are converted to:

$$\log t_{mean} \quad \log t_0 - \frac{1}{\beta}\log\sigma \tag{5}$$

and

$$\log N_{mean} \quad \log N_0 - \frac{1}{\alpha}\log\sigma \tag{6}$$

The stress acts as an independent variable whose values are controlled by the experiment, whereas the time and number of cycles depends on the stress and is subjected to uncontrollable sources of error.

The experimental data are fit with a straight-line least squares regression model to equations 5 and 6.

A characteristic value of the time can be found in the following manner:

$$\log t_c \quad \log t_0 - x\log\sigma - X\sigma_{\varepsilon} \tag{7}$$

The characteristic value of $\log N_c$:

$$\log N_c \quad \log N_0 - x\log\sigma - X\sigma_{\varepsilon} \tag{8}$$

where X is a constant depending on the number of specimens, given in Table 3 below /10,15/. The parameter x is 1/β or 1/α respectively.

Table 3 Values of coefficient *X*

Number of tests	*X* for case 1	*X* for case 2
10	3.9	4.7
15	3.4	4.0
20	3.1	3.7
50	2.6	3.0
100	2.4	2.6
Infinite	2	2

The coefficient values for case 1 are valid within the range of stresses from testing. Case 2 coefficient values are to be used for extrapolation outside the testing-range. Case 2 is valid within a concentric range of $\log\sigma$ twice the length of the range covered by tests.

Transforming the curves back into the standard formulation gives the following expressions for the characteristic stress-rupture curve and the characteristic SN curve:

Stress rupture: $$\log\sigma_c \quad \log\sigma_{0c} - \beta\log t \tag{9}$$

Cyclic fatigue: $$\log\sigma_c \quad \log\sigma_{0c} - \alpha\log N \tag{10}$$

where the subscript *c* indicates the characteristic values.

4.3 STATIC STRENGTH

Specimens were loaded in tension or compression until interlaminar shear failure between the layers occurred, providing baseline data for normalisation of fatigue loads. The results for testing in dry conditions are given in Table 4.

The same shear strength in compression as in tension would be expected under theoretically perfect conditions, but this is not the case as can be seen from the results in Table 4. The somewhat higher shear strength level in compression can be explained by lower peeling effects. If it is not known whether a component is loaded in tension or compression the lower tensile values should be used. The tensile/compressive fatigue testing also showed that the specimens failed mostly in tension.

Test results for specimens immersed in seawater are shown in Table 5. The short-term strength of the wet specimens did not change relative to the strength of the dry specimens.

4.4 STRESS-RUPTURE TESTS

Stress-rupture testing was done from about 1 hour up to 12000 hours in air and in seawater. Testing was done with tensile loads. The results from the static strength tests are used as reference, and by applying various fractions of the ultimate load, interrelated data for static loads and resulting times to failure are obtained. These data are expected to show a linear relation in a log stress – log time representation.

The data for the stress rupture tests in dry conditions are summarised in Table 6. Figure 11 shows the mean and characteristic stress rupture curve. The equations for the stress rupture are:

Mean regression curve dry: **(11)**

$$\log\sigma \quad -0.0283\log t + 1.1493$$

Characteristic regression curve dry: Case 1-interpolation **(12)**

$$\log\sigma \quad -0.0283\log t + 1.0733$$

Characteristic regression curve dry: Case 2- extrapolation **(13)**

$$\log\sigma \quad -0.0283\log t + 1.0586$$

The data for the stress rupture tests in seawater are summarised in Table 7. Figure 12 shows the mean and characteristic stress rupture curve. The equations are:

Mean regression curve in seawater: **(14)**

$$\log\sigma \quad -0.0300\log t + 1.1317$$

Characteristic regression curve in seawater: Case 1-interpolation **(15)**

$$\log\sigma \quad -0.0300\log t + 1.0817$$

Characteristic regression curve in seawater: Case 2- extrapolation **(16)**

$$\log\sigma \quad -0.0300\log t + 1.0729$$

Results of the wet and dry conditions of the stress-rupture shear testing are compared in Figure 13. The mean long term strength at wet conditions is clearly lower then the strength at dry conditions. However, the dry specimens showed a mush higher scatter in the test results, therefore the difference in the characteristic curves is small.

Table 4 Static strength data, dry conditions

Specimen Designation	Type of loading	Specimen width [mm]	Maximum load [kN]	Shear strength [MPa]
Dry1	Tension	20.1	12.7	16.3
Dry2	Tension	20.0	14.7	19.0
Dry3	Tension	20.0	12.8	16.0
Dry4	Tension	20.0	12.0	15.4
Dry5	Tension	20.0	14.3	18.4
Dry6	Tension	20.0	10.9	14.0
Average	**-**	**-**	**12.8**	**16.5**
Standard Deviation				**1.88**
Characteristic shear strength value				**8.42**
Dry1	Compression	20.0	18.1	23.3
Dry2	Compression	20.0	15.6	20.1
Average	**-**	**-**	**16.8**	**21.7**
Standard Deviation				**2.25**

Table 5 Static strength data at wet conditions

Specimen Designation	Type of loading	Specimen width [mm]	Maximum load [kN]	Shear strength [MPa]
Wet1	Tension	20.0	11.5	14.8
Wet2	Tension	20.0	13.8	17.75
Wet3	Tension	20.0	14.4	18.45
Wet4	Tension	20.0	12.1	15.65
Wet5	Tension	20.0	15.7	20.2
Wet6	Tension	20.0	11.9	15.35
Average	**-**	**-**	**13.2**	**17.05**
Standard Deviation			**1.64**	**2.1**
Characteristic shear strength value				**8.02**
Wet2	Compression	20.0	17.85	23.0
Average	-	-	-	-
Standard Deviation	-	-	-	-

Table 6 Stress rupture data at dry conditions

Specimen Designation	**Specimen Width [mm]**	**Load [% of reference]**	**Load [kN]**	**Shear strength [MPa]**	**Time to failure [h]**	**Comments**
Static, reference	-	100	12.8	16.5	0.1	
Dry1	20	87.6	11.20	14.45	1.1	
Dry2	20	88.2	11.30	14.55	1.3	
Dry3	20	82.7	10.60	13.65	0.2	
Dry4	20	82.7	10.60	13.65	1.7	
Dry5	20	77.3	9.90	12.75	22.6	
Dry6	20	74.5	9.55	12.3	993	
Dry7	20	74.5	9.55	12.3	1008	
Dry8	20	75.7	9.70	12.5	704	
Dry9	20	75.7	9.70	12.5	108	
Dry10	20	75.7	9.70	12.5	218	
Dry11	20	77.3	9.90	12.5	60	
Dry12	20	72.1	9.24	11.9	20	
Dry13	20	72.1	9.24	11.9	70	
Dry14	20	72.1	9.24	11.9	118	No failure
Dry15	20	72.1	9.24	11.9	1294	
Dry16	20	72.1	9.24	11.9	1176	
Dry17	20	68.3	8.75	11.3	720	
Dry18	20	68.3	8.75	11.3	4870	
Dry19	20	68.3	8.75	11.3	12250	
Dry20	20	68.3	8.75	11.3	12250	No failure.

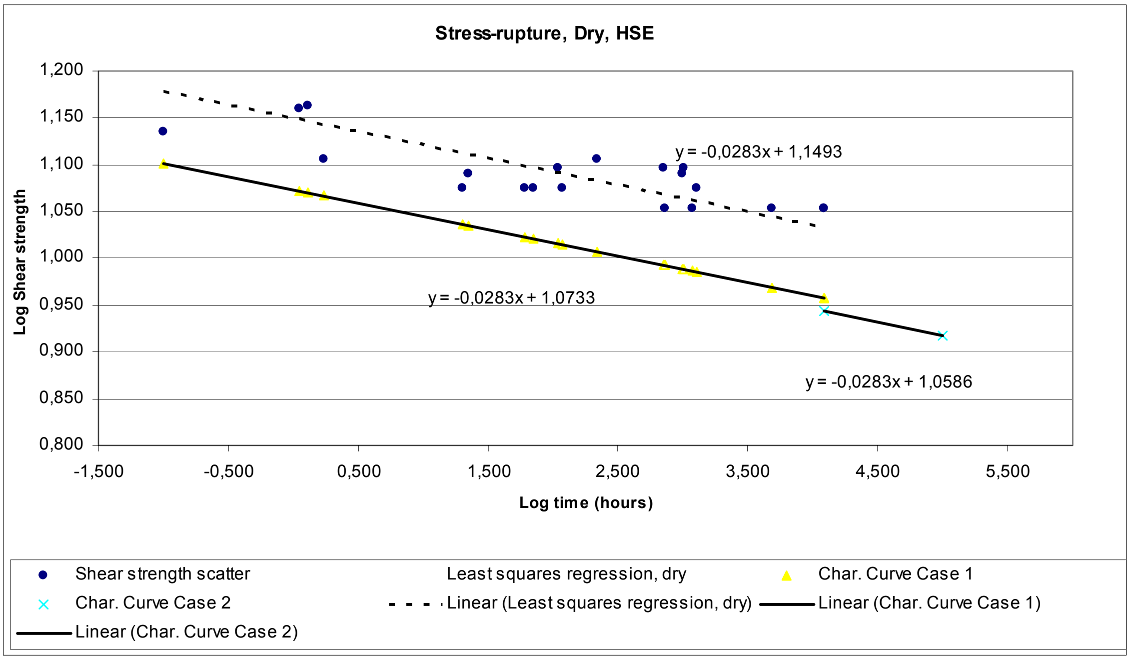

Figure 11 Interlaminar shear stress rupture curve for dry specimens. Test data, mean curve and characteristic curves.

Table 7 Static Stress rupture data for specimens in seawater

Specimen Designation	Specimen Width [mm]	Load [% reference]	Load [kN]	Shear strength [MPa]	Time to failure [h]	Comments
Static, reference	-	100	13,2		0,1	
Wet1	20	73.5	9.70	12.5	4	
Wet2	20	73.5	9.70	12.5	6.0	
Wet3	20	73.5	9.70	12.5	12.0	
Wet4	20	72.0	9.50	12.25	20.1	
Wet5	20	73.9	9.75	12.55	7.4	
Wet6	20	70.1	9.25	11.9	712.0	
Wet7	20	69.3	9.15	11.8	247.0	
Wet8	20	69.3	9.15	11.8	282.0	
Wet9	20	69.3	9.15	11.8	738.0	No failure.
Wet10	20	66.4	8.76	11.3	336	
Wet11	20	66.4	8.76	11.3	450	
Wet12	20	66.4	8.76	11.3	550	
Wet13	20	61.0	8.05	10.35	8040	
Wet14	20	61.0	8.05	10.35	11900	
Wet15	20	61.0	8.05	10.35	11900	No failure.
Wet16	20	61.0	8.05	10.35	11900	No failure.

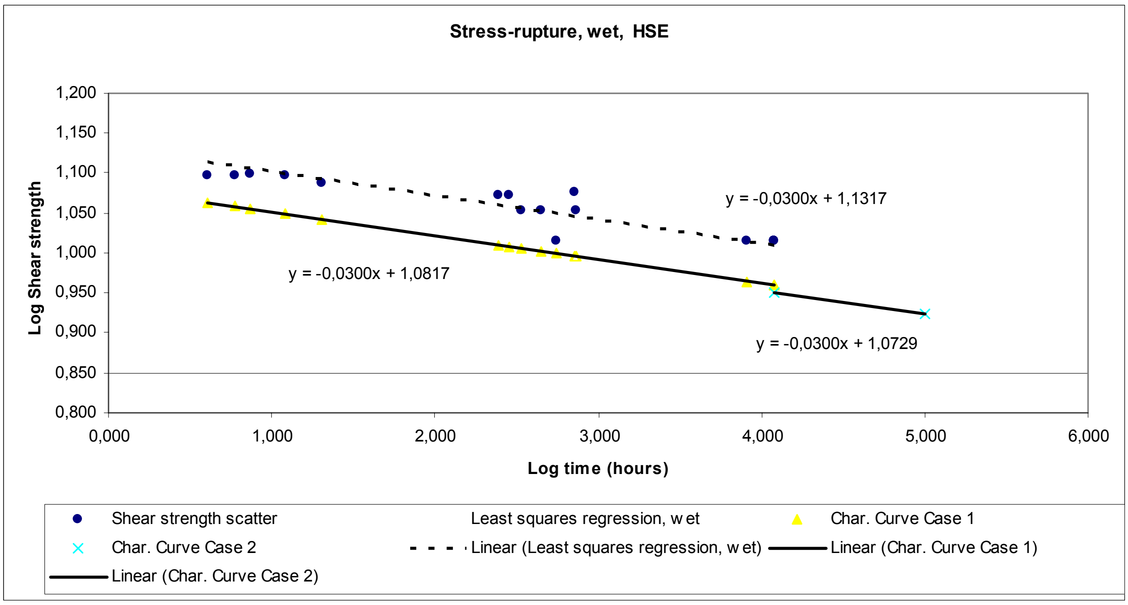

Figure 12 Interlaminar shear stress rupture curve for wet specimens. Test data, mean curve and characteristic curves.

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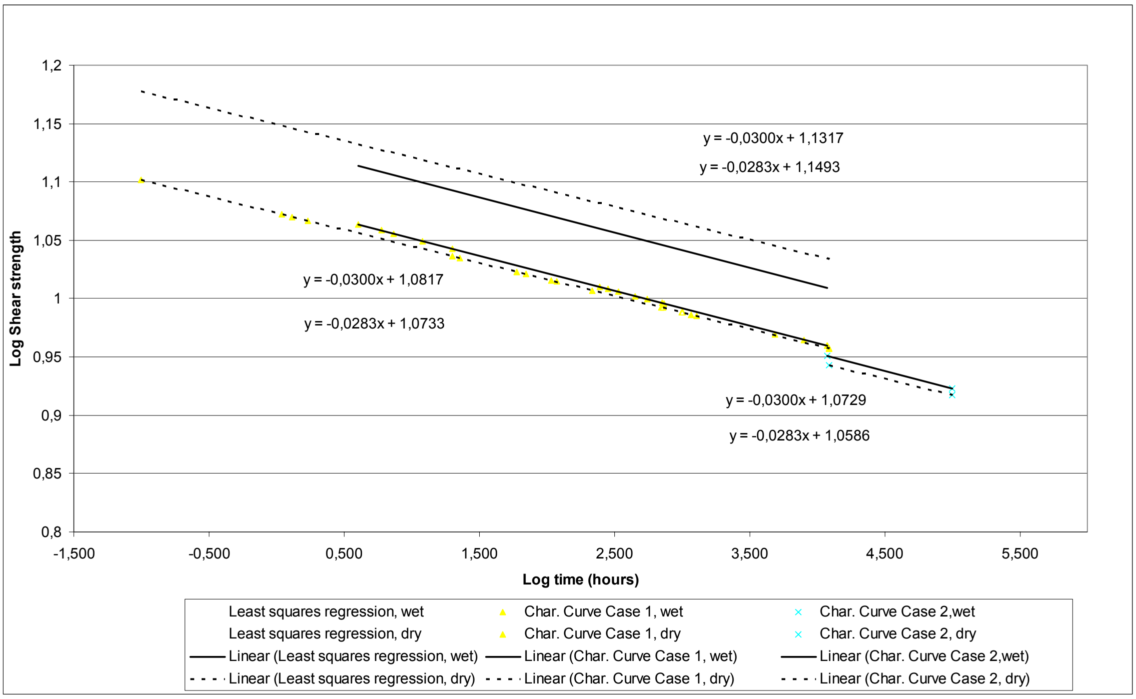

Figure 13 Comparison of stress rupture mean curve and characteristic curves for both wet and dry conditions.

4.5 CYCLIC FATIGUE TESTS

Cyclic fatigue testing was done from about 1000 to 2 10^6 cycles in air and in seawater. The cyclic fatigue tests were performed using the same test specimens as the static fatigue tests. However, during cyclic fatigue testing the specimens were loaded in both tension and compression, at a load ratio of R = -1, i.e. $\sigma_{compr.} = - \sigma_{tensile}$ and $\sigma_{mean.} = 0$.

The most readily obtainable information on fatigue behaviour is the relationship between the applied cyclic stress amplitude S and the number of cycles to failure N. When plotted in graphical form this results in an S-N curve. Test frequencies were chosen to be low enough to avoid overheating which may result in short-term thermal-softening failures. In addition, test frequencies were chosen to obtain a roughly constant strain rate in the specimens to avoid influences on the data from viscoelastic effects.

Characteristic data were calculated the same way as in the stress-rupture section, with time to failure being replaced by the number of cycles to failure.

Data for the cyclic fatigue tests in dry conditions are summarised in Table 8. The mean and characteristic SN curves for interlaminar shear strength in air are given in Figure 14. The equations for the SN curves are:

Mean regression curve dry: **(19)**

$$\log\sigma \quad 1.2399 - 0.1237\log N$$

Characteristic regression curve dry: Case 1-interpolation **(20)**

$$\log\sigma \quad 1.0190 - 0.1237\log N$$

Characteristic regression curve dry: Case 2- extrapolation **(21)**

$$\log\sigma \quad 0.9737 - 0.1237\log N$$

The data for the cyclic fatigue tests in seawater are summarised in Table 9. The mean and characteristic SN curves for interlaminar shear strength in sea water are given in Figure 15. The equations for the SN curves are:

Mean regression curve in seawater: **(22)**

$$\log\sigma \quad 1.2247 - 0.1263\log N$$

Characteristic regression curve in seawater: Case 1-interpolation **(23)**

$$\log\sigma \quad 1.0258 - 0.1263\log N$$

Characteristic regression curve in seawater: Case 2- extrapolation **(24)**

$$\log\sigma \quad 0.9850 - 0.1263\log N$$

The SN curves for dry and wet specimens are compared in Figure 16. The mean regression curve of the specimens in seawater is slightly lower than the curve for dry specimens. Characteristic curves are basically identical. Seawater does not seem to influence the fatigue behaviour of interlaminar shear failure.

Table 8 Cyclic fatigue data at dry conditions

Specimen Designation	Specimen Width [mm]	Load [% reference]	Load [kN]	Shear strength [MPa]	Cycles to Failure	Test frequency [Hz]
Static. reference	20	100.0	12.8	16.5	1	
Dry1	20	42.9	5.5	7.1	2034	7
Dry2	20	35.1	4.5	5.8	15639	9
Dry3	20	23.4	3.0	3.85	19550	11
Dry4	20	15.6	2.0	2.6	1591872	12
Dry5	20	19.5	2.5	3.2	1140319	10
Dry6	20	19.5	2.5	3.2	2680000	10
Dry7	20	23.4	3.0	3.85	802398	8
Dry8	20	23.4	3.0	3.85	204100	8
Dry9	20	39.1	5.0	6.45	4595	5
Dry10	20	39.1	5.0	6.45	2137	5
Dry11	20	39.1	5.0	6.45	2330	5

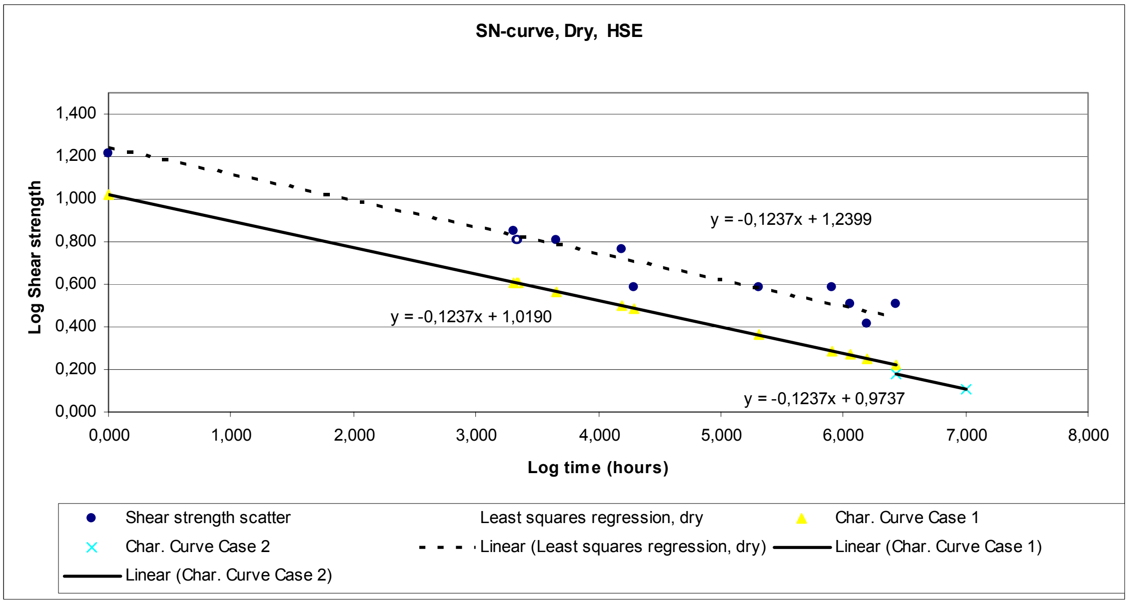

Figure 14 Interlaminar shear SN curve for dry specimens. Test data, mean curve and characteristic curves.

Table 9 Cyclic fatigue data at wet conditions

Specimen Designation	Specimen Width [mm]	Load [% reference]	Load [kN]	Shear strength [MPa]	Cycles to Failure	Test frequency [Hz]
Static, reference	20	100.0	13.2	16.50	1	
Wet1	20	18.9	2.5	5.75	2460	
Wet2	20	41.7	5.5	5.75	5098	
Wet3	20	34.1	4.5	5.75	8689	
Wet4	20	22.7	3.0	3.85	68788	
Wet5	20	15.2	2.0	3.85	265685	
Wet6	20	18.9	2.5	3.85	281478	
Wet7	20	18.9	2.5	3.20	193452	
Wet8	20	22.7	3.0	3.20	126424	
Wet9	20	22.7	3.0	3.20	1733223	

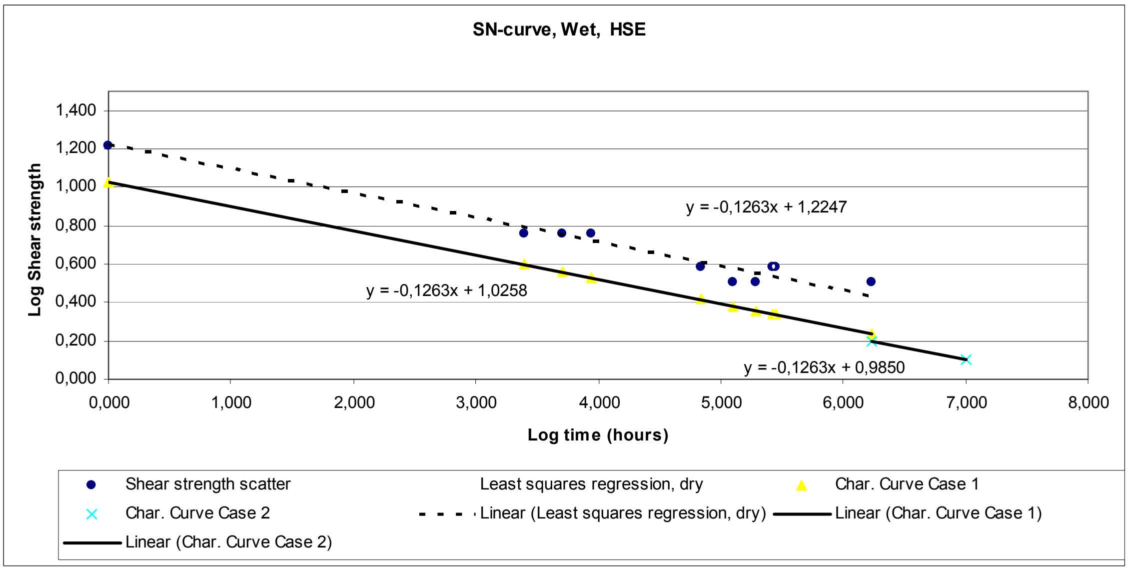

Figure 15 Interlaminar shear SN curve for specimens in seawater. Test data, mean curve and characteristic curves.

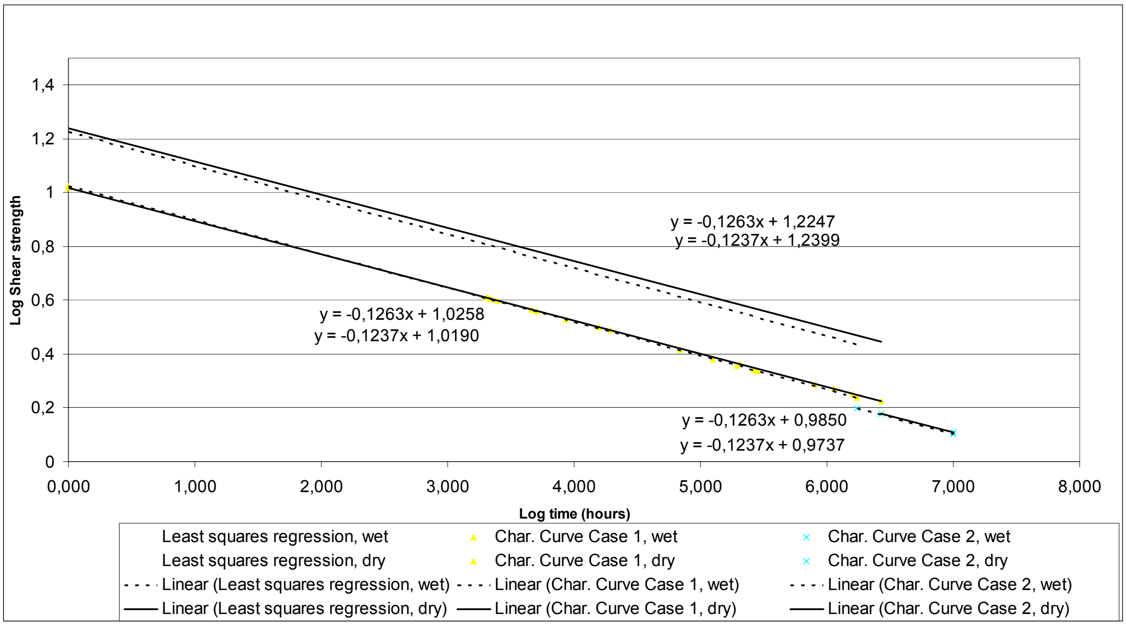

Figure 16 Comparison of interlaminar shear SN mean curve and characteristic curves for both wet and dry conditions.

5 DISCUSSION

5.1 STATIC INPLANE AND INTERLAMINAR SHEAR STRENGTH

Ply shear strength data are not often available. Inplane shear strength data can sometimes be found, interlaminar (through thickness) shear strength is very seldom reported. Designers choose often typical data and argue that inplane and interlaminar strength should be similar, since both are matrix dominated. This approach may not always be right.

One reason why shear data are not easily available is that measuring the shear strength of composite laminates is not straightforward. The matrix dominated inplane shear stress strain curve of composite plies is typically nonlinear. Shear strength can be measured by the 2-rail shear test (ASTM D4255) or it can be calculated from a tensile or compression test on a ± 45 laminate (ASTM D3518). Quite different shear strengths are reported in the literature due to the nonlinear behaviour of the shear stress strain curve. Typical values for the type of laminate used in this study are given in Table 10; they are separated in a maximum value and a shear strength at the linear limit. The most relevant strength value depends on the application.

Table 10 Comparison of inplane and interlaminar shear strengths.

	Mean value [MPa]	Characteristic value [MPa]	Reference
Inplane Shear Strength			
Typical maximum nonlinear shear strength	40	29	DNV-OS-C501 /1/
Typical shear strength at linear limit.	23	17	DNV-OS-C501 /1/
Maximum shear strength measured on a ± 45 laminate. (same system as measured in this study)	30	-	Tested according to ASTM D 3518-76 /16/
Onset of shear cracks in a ± 45 laminate. (same system as measured in this study)	14	-	Tested according to ASTM D 3518-76 /16/
Interlaminar Shear Strength			
Typical value	14	9	DNV-OS-C501 /1/
Result of this study (tensile loading)	16.5	8.4	
Result of this study (compressive loading)	22	-	

Measurements on a similar laminate as measured in this study are also shown /16/ (resin and fibres were the same, but batches were different, since the tests were made a few years earlier). Test values were slightly lower than given in the typical data.

Interlaminar shear strength is usually lower than inplane shear strength according to the typical data in DNV-OS-C501. The data measured in this study are quite consistent with the typical data. The mean strength is slightly higher and the characteristic strength is slightly lower than the typical values. Characteristic values are influenced by the number of tests made. Testing more laminates may improve the characteristic value for the system measured here.

It is interesting to note, that the onset of shear damage or nonlinearity in the inplane tests roughly coincides with the interlaminar shear strength.

5.2 LONG TERM INPLANE AND INTERLAMINAR SHEAR STRENGTH

The strength reduction under permanent load with time is described by the stress rupture curve. The reduction of interlaminar shear strength in the stress rupture curve was measured in this study to be about 35% over a typical lifetime of 20 years. The reduction is calculated relative to the strength at one minute which is assumed to be the static strength. The same reduction for fibre dominated tensile strength of glass fibre laminates is typically 50% over 20 years /10/. The comparison is shown in Figure 17. The strength reduction of the matrix dominated stress rupture curve was less than the values for the fibre dominated properties. However, the absolute values of the fibre dominated properties are much higher.

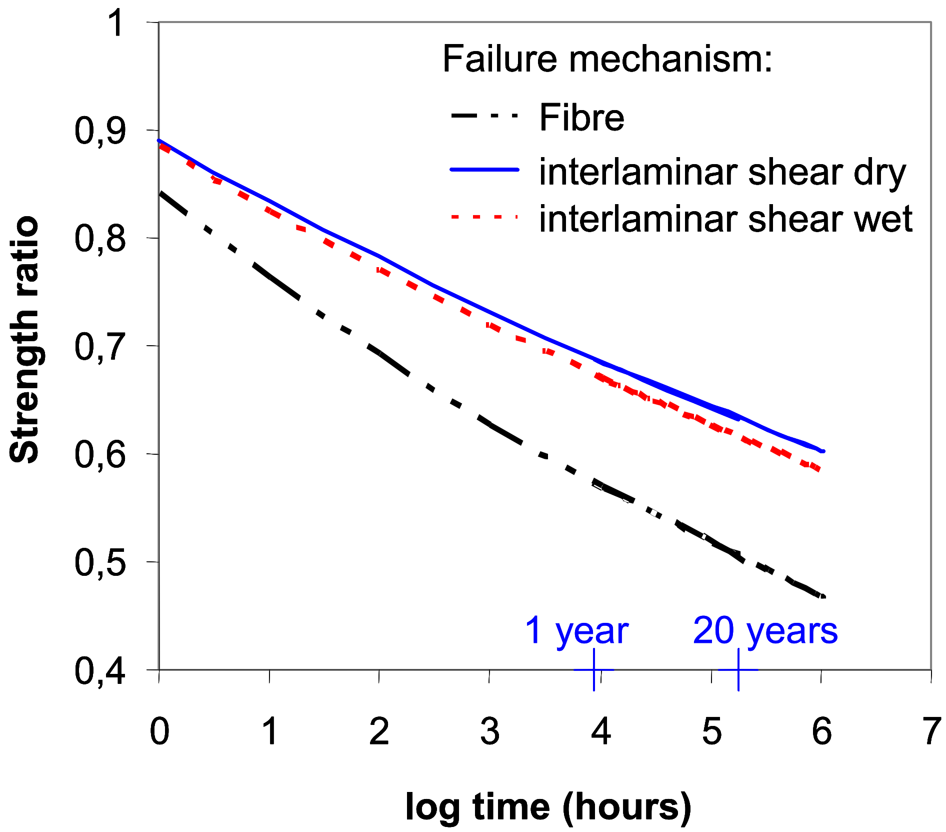

Figure 17 Stress rupture curve for fibre dominated tensile failure and interlaminar shear failure. The strength reduction is shown as the ratio of strength relative to the static strength.

The resistance to cyclic fatigue is typically described by an SN curve. A typical SN curve for glass fibre dominated ply properties describes the maximum strain ε for a given number of cycles N. It is given by $\log(\varepsilon) = \log(\varepsilon_0) - \alpha \log(N)$ where α is between 0.1 for R= 0.1 and 0.13 for R = -1. After 10^6 cycles the strain amplitude is reduced by roughly 80% /10,17/. The reduction in strength relative to the initial strength is roughly the same.

The slope of the SN curve for interlaminar shear strength was measured to be 0.124 for dry laminates and 0.126 for wet laminates. This value is very similar to the results measured for inplane properties of glass reinforced laminates with an R ratio of R= -1. Since the failure mechanisms are completely different (fibre failure vs. interlaminar matrix cracking), this must be a coincidence. For a glass epoxy system a different result was found, the interlaminar shear showed better SN behaviour than for longitudinal tension of the glass fibres /18/.

An SN curve has also been measured for tensile/compressive fatigue (R=-1) on a $\pm$45 laminate with the same properties as the laminate tested here /19/. As described above for static shear strength this test setup tests the inplane shear properties of the ply. The results show a slope of 0.15 for the SN curve of the inplane shear properties. This shows that for this laminate system fatigue degradation of inplane shear strength happens faster than of interlaminar shear strength. The reduction of inplane shear fatigue strength after 10^6 cycles is about 87%. The static shear strength data showed that inplane and interlaminar shear strength are not directly related. Therefore it is unlikely that inplane fatigue data can be used to estimate through thickness properties accurately.

A comparison of the SN curves for tensile fibre dominated failure, interlaminar shear and inplane shear is shown in Figure 18.

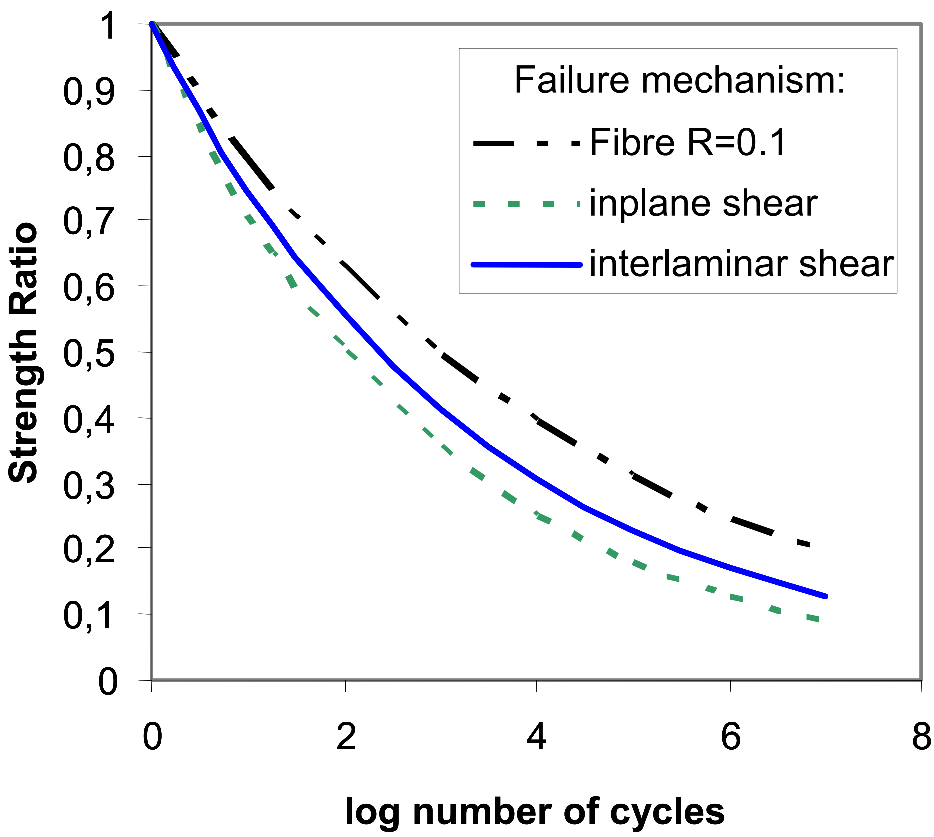

Figure 18 SN curve for fibre dominated tensile failure, inplane shear and interlaminar shear failure. The strength reduction is shown as the ratio of strength relative to the static strength.

The significant reduction of interlaminar shear strength with increasing number of fatigue cycles should be carefully considered in design. Since interlaminar shear properties are relatively low to start with a further reduction with number of cycles can have severe consequences in the neighbourhood of joints or other regions where interlaminar shear is critical.

5.3 COMPARISON OF DRY AND WET CONDITIONS

The difference in strength of laminates between dry and wet conditions is often estimated to be about 10% for glass reinforced laminates (E-glass). Most of these measurements were done in distilled water, since it has been shown that this gives the biggest degradation effect.

The test results of this study have basically shown no effect of seawater on the characteristic short and long term properties compared to dry laminates. The mean stress rupture data were lower in sea water than in air, but since the scatter of the data in air was high, the characteristic values were about the same. All other tests showed no effect of seawater on the mean properties.

For this laminate the typical reduction of 10% for service in seawater does not need to be applied to long-term data. Whether seawater always has very little effect on laminate properties should be worth investigating.

5.4 SUMMARY OF RESULTS

The discussion above showed a simple presentation of the degradation of properties with time. For actual design the characteristic strength curves should be used. The long term interlaminar shear strength data of this study are summarized in Table 11.

Table 11 Long term interlaminar shear data.

Stress rupture, Dry	Mean curve	$\log\sigma \quad -0.0283\log t + 1.1493$
	Characteristic curve, up to 1 year	$\log\sigma \quad -0.0283\log t + 1.0733$
	Characteristic curve, beyond 1 year	$\log\sigma \quad -0.0283\log t + 1.0586$
Stress rupture, Wet	Mean curve	$\log\sigma \quad -0.0300\log t + 1.1317$
	Characteristic curve, up to 1 year	$\log\sigma \quad -0.0300\log t + 1.0817$
	Characteristic curve, beyond 1 year	$\log\sigma \quad -0.0300\log t + 1.0729$
Cyclic fatigue, Dry	Mean curve	$\log\sigma \quad 1.2399 - 0.1237\log N$
	Characteristic curve, up to 10^6 cycles	$\log\sigma \quad 1.0190 - 0.1237\log N$
	Characteristic curve, beyond 10^6 cycles	$\log\sigma \quad 0.9737 - 0.1237\log N$
Cyclic fatigue, Wet	Mean curve	$\log\sigma \quad 1.2247 - 0.1263\log N$
	Characteristic curve, up to 10^6 cycles	$\log\sigma \quad 1.0258 - 0.1263\log N$
	Characteristic curve, beyond 10^6 cycles	$\log\sigma \quad 0.9850 - 0.1263\log N$
Stresses σ are in MPa, times *t* are in hours		

6 CONCLUSIONS

Long term interlaminar shear properties for a typical glass fibre polyester offshore laminate have been measured. The new test specimens gave good results and valid failures under short term static testing, stress rupture testing and fatigue testing.

The mean short term static interlaminar shear strength of this system was 16.5 MPa and the characteristic strength was 8.4 MPa. This compares well with typical values measured on other systems. All characteristic values were calculated with a 97.5% tolerance and 95% confidence.

The stress rupture curve (static fatigue) of the interlaminar shear strength showed a reduction of about 35% when extrapolated to a typical lifetime of 20 years. The reduction of interlaminar strength with time was less than the reduction of the fibre dominated inplane properties.

The cyclic fatigue SN curve showed a reduction of interlaminar shear strength of about 80% at 10^6 cycles. The reduction of interlaminar strength with increasing number of fatigue cycles was similar to reduction of the fibre dominated inplane properties, but less than the reduction for inplane shear fatigue. However, since the failure mechanisms are different, each of these properties should be measured separately for any laminate system.

The influence of sea water on short and long-term properties of the laminate was negligible for this laminate. The mean stress rupture curve showed lower values for the laminate exposed to seawater, but the characteristic values of the dry and wet laminate were basically identical. This result may indicate that seawater is much less critical than often believed.

Both static and cyclic fatigue causes a significant reduction of interlaminar shear strength with time. This reduction should be considered when designing joints or other components where interlaminar shear strength is critical.

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