CHANGE OF GLASS FIBER COMPOSITE CHARACTERISTIC DYNAMIC FATIGUE CURVE DUE TO ACCUMULATED STATIC FATIGUE DAMAGE

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Keywords: Glass fiber, fatigue, stress rupture, accumulated damage

Abstract

For glass fiber composites the long-term static and dynamic behavior are important properties to know to obtain a safe composite design. In the design process for offshore structures for North Sea applications, the DNV OS-C501 offshore standard is for many applications the preferred standard for composite components. This standard gives a set of design rules for establishing long-term material data for use in composite verification and validation design process. The DNV–OS-C501material models or the use of the models in the design of glass fiber based composites does not address that the characteristic dynamic fatigue curve slope may change due to accumulated static fatigue damage. A change in the slope of the characteristic fatigue curve during the lifetime of a composite structure subjected to fatigue cycles may reduce the expected lifetime for the structure. A test program was initiated to investigate the change of the dynamic fatigue characteristic curve compared to test specimen with accumulated stress rupture damage. The results show that there is a change in the slope of the characteristic curve after the material has been subjected to stress rupture damage. A model for the characteristic fatigue curve, where the slope B (M (t)) is a function of the time dependent stress rupture damage accumulation, is proposed.

1. Introduction

University of Agder participates in BIA project Marine Platform[1], where the goal is to establish an easier and more flexible method for production of light craft vessel based on modularization. These are vessels for high speed service, fully or partly dynamically supported [2] this includes also a better understanding of the design rules of composite materials for these applications. One of the most used and modern set of design rules for composite materials is DNVGL-OS-C501 [3]. This is a probabilistic approach requiring substantial amount of testing is required. For glass fibre composites the long term static and dynamic fatigue behaviour is important to understand to be able to design light weight composite structures. In the DNVGL-OS-C501 design approach the characteristic curves on static and dynamic fatigue for the composite must be established by performing several tests corresponding to the confidence level needed for the specific application. However, the design rules for glass fiber based composites does not address that the characteristic dynamic fatigue curve slope may change due to accumulated static fatigue damage. A change in the slope of the characteristic fatigue curve during the lifetime of a composite structure subjected to fatigue cycles may reduce the expected lifetime for the structure. An example may be the type IV high pressure composite air pressure vessel (CAPV) for standby purposes at high pressure (300 bars) for long period of time.Then the same CAPV may be used for heave compensating purposes for large pressure cycles. (50-150 bar). If the standard method is used the CAPV may not be able to withstand the calculated cycles with the expected level of safety, due to a possible change in the slope of the characteristic dynamic fatigue curve of the materials used. The safety factors are dependent on the acceptable probability of failure

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and are very dependent on the coefficient of variation (COV) of the burst strength of the pressure vessel[4]. The characteristic curves for dynamic fatigue and stress rupture are given by:

Static fatigue:

$$\log\varepsilon(t) = \log(\varepsilon(t=0) - B_{static}\log(t) \tag{1}$$

Dynamic fatigue:

$$\log\varepsilon(N) = \log(\varepsilon(N=1) - B_{dynamic}\log(N) \tag{2}$$

The dynamic fatigue life is calculated by the use of the S-N (or SN-Probabilistic) curve with the assumption that the material has a linear accumulated damage [5, 6,7]. The Miner Palmgren linear damage hypothesis also called Miner sum. The slope $B_{dynamic}$ is not dependent of the Miner sum due to accumulated static fatigue damage. By introducing $B_{dynamic}(M(t))$ in equation (1), a more correct slope can be found for the characteristic curve and improve the prediction of expected lifetime of composite structures subjected to dynamic cycle loads.

2. Theoretical work

A model for the characteristic fatigue cure, where the slope B(M(t)) is a function of the time dependent stress rupture damage accumulation, is proposed. The static damage accumulation start at the first cycle. At M=0 the $B_{dynamic}=B_{dynamic}(M_{static}=0)$ and there is no residual strength at $M_{static}=1$(static fatigue failure), i.e. value of $B_{dynamic}$ should change accordingly. The dynamic curve is then given by:

$$\log\varepsilon(N,t) = \log(\varepsilon(N=1,t=0) - B(M_{static}(t))\log(N) \tag{3}$$

Where $B(M_{static}(t))$ is given by

$$B(M_{static}(t)) = B(M_{static}=0)\cdot(a+\frac{1}{b-e^{(M_{static}(t))}})^{n} \tag{4}$$

The constants a,b,n must be established for each material system. The Miner_{static} sum will increase constantly during the product life cycle and the slope of the fatigue curve can be updated during the fatigue lifetime. However, for conservative estimates the static fatigue Miner_{static} sum at the average strain level based on the estimated lifetime ,can then be used for calculating the updated slope for the dynamic fatigue curve.

3. Experimental work

A test program was initiated to investigate if there is any change in the characteristic curve between $M_{static}=0$ (no stress rupture damage), compared to test specimen with accumulated stress rupture damage $M_{static}=0.75$. Test specimen were tested according to DNV C501 to establish the characteristic curves for both dynamic fatigue (R=0.1) and static fatigue.

The material chosen were [0,90,CSM,0,90,CSM] build up with 90% at ±0°, a commercial grade used in the manufacturing of light craft vessels. The test specimen was specially made by vacuum infusion at the Norsafe AS test lab. Testing was a part of a Master thesis work at University of Agder [8].

The following test series was performed:

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Test series 0: Stress strain curves for the laminate
Test series 1: Establish the fatigue curve for test specimen with no stress rupture damage (M_{static}=0)
Test series 2: Establish stress rupture curve for test specimen
Test series 3: Stress rupture test to accumulate damage of M_{static}=0.75.
Test serie4: Establish fatigue curve for specimen with accumulated static damage (M_{static} =0.75)

Figure 1. Stress strain curves

The characteristic stress rupture curve was used for establishing static fatigue damage level, M_{static} =0.75. The characteristic fatigue curve (M_{static}=0) was then used to compare the two fatigue curves based on two different level of stress rupture damage.

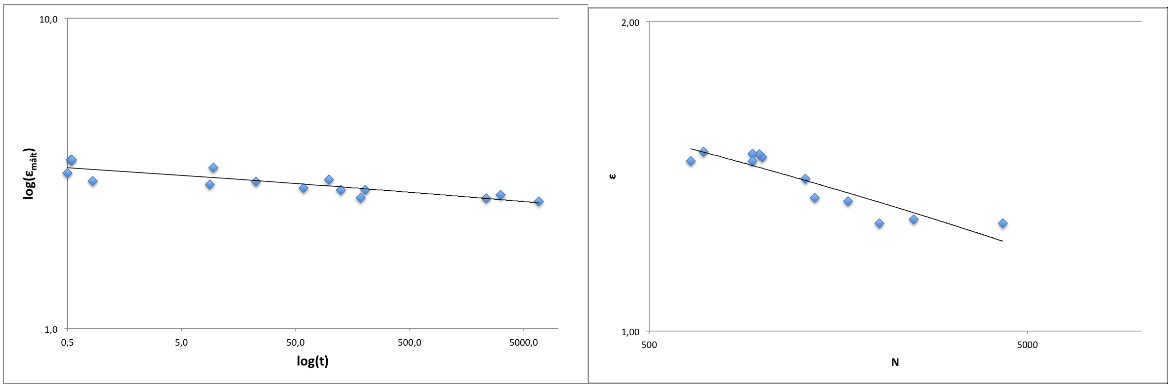

Figure 2. Stress rupture and dynamic fatigue curves

All data used is based on strain level and it was therefore important to correlate all results to strain level and the fibre volume was measured for each test specimen. The stress rupture tests were performed using a table top 50KN test machine form Zwick, and for the dynamic testing UIA 25KN Si-Plan test machine.

4. Results

The results show that there is a change in the slope of the characteristic curve after the material has been subjected accumulated stress rupture damage. The results indicate a vertical shift of the characteristic dynamic fatigue curve, but also a clear change of the slope for specimen subjected by static fatigue or stress rupture testing, (M_{static}=0.75). The proposed model can be used to estimate the behaviour of the characteristic dynamic fatigue curve for other level of stress rupture accumulated damage. Tests are ongoing to obtain curves for other levels of damage accumulation.

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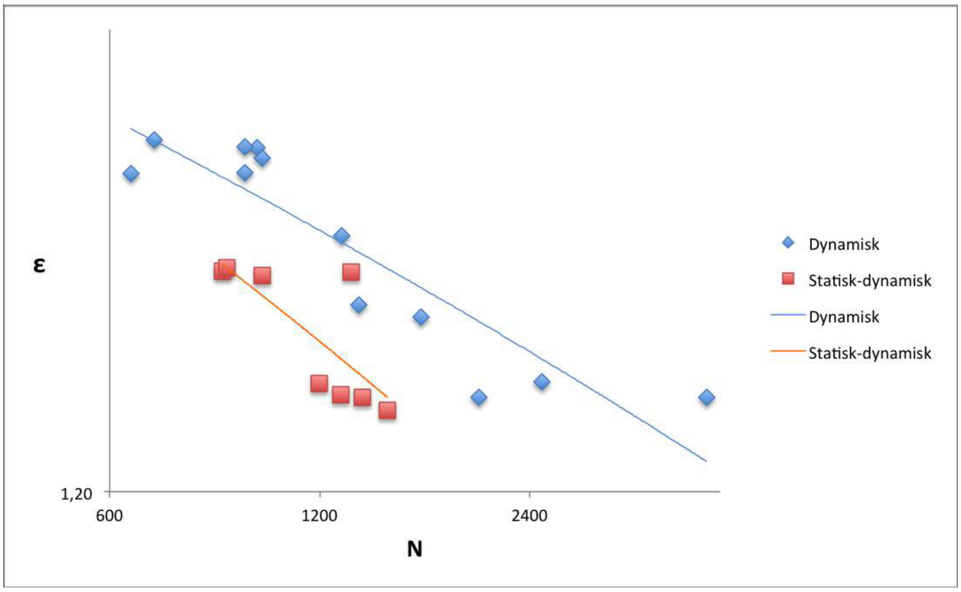

Figure 3. Characteristic dynamic fatigue curves

5. Discussion

The characteristic fatigue curves shown in figure 3 show also a typical scatter of the data points and more testing must be performed to validate the indicated change of the slope in dynamic fatigue. There were no pre-stress applied to the main fiber direction. Alignments of the fibers were carefully controlled, but some misalignments were present, however well distributed for all test specimens. The static rupture test and stress strain curves was adjusted for fiber volume and small deviation for the E-modulus and ultimate stress was obtained, indicating that the test specimen were produced correctly.

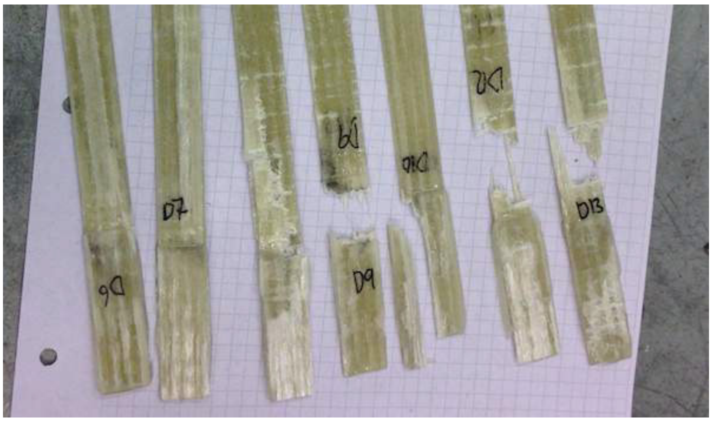

Figure 4. Test specimen failure mode

One might discuss the typical failure mode for this combination of material and test method but test specimen were carefully chosen by failure type. Some of the failures where clearly in the tabs area, and only similar failure modes where used for generating the curves. All failures close to tabs were dicarded.

6. Conclusions

The results indicate that the slope of the characteristic dynamic fatigue curve change when subjected to static fatigue loads and that the proposed modified model for the dynamic fatigue curve given in DNVGL OS-C501 can be used to improve the prediction of expected lifetime of composite structures subjected to both dynamic and static loads. A full series of dynamic testing on different level of accumulated static fatigue damage must be tested to validate if the model can be used for all dynamic and static accumulated damage levels.

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