Ultrasonic Monitoring of a Fiber Reinforced Plastic—Steel Composite Beam During Fatigue

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ABSTRACT

The use of composite superstructures on current or newly built steel hulls is a recently emerged technology. The economic estimations predict that the extra costs for putting composite superstructures, with the present safety margins, on steel ships will be paid back in only 2-3 years. This also makes the ships having smaller ecological footprints with less fuel consumption and CO_2 emissions. In this stage of development it is needed to ensure the durability of the joints between the steel and glass fiber reinforced plastic.

The first step is that the joints must first be proven to withstand fatigue. In this test a 4-meter beam, which represents the joint, were investigated for fatigue progression by a four-point-bending fatigue test. In order to show that ultrasonic material monitoring techniques can be used to monitor the damage progression, the beam was measured during the tests until failure.

The test was successful both in showing that the joint could withstand high levels of mechanical exposure, and in that the ultrasonic techniques accompanied the damage progression which means that they may be used on vessels during operation.

INTRODUCTION

From operational perspectives, the condition of the hull structure is prone to be more vulnerable in certain areas, such as close to heavy machinery or shafts. Other places of interest are those where material parts are joined. The materials may be the same but may also be such as the joint between the hull structure of steel and a composite superstructure. These pose additional problems because the superstructure of steel has much lower Young's modulus than the composite and will follow the steel structure when the ship is subjected to global bending. The steel joint which is attached to the composite structure will therefore take the highest stresses in the upper

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steel structure if the superstructure has such corresponding length that it contribute to the hull girder strength.

Two main questions were posed in this work: I. How would the joint between the composite and steel react to fatigue; and II. Would the materially more complex structure cause problems for the acoustic damage monitoring techniques ? The answers are in short that: IA. The joint withstood fatigue very well; and IIA. The damage monitoring technique experienced no major problems. This means that the method works also for structures such as complex steel hulls.

Today, the monitoring of the condition of ship structure response and condition assessments requires experts to analyse recorded data. The aim of this work is to test a nonlinear acoustic measurement technique to get an early warning of cracks or other damages of the ship hull. The final aim is to develop an IT based monitoring condition systems that move from human analysis to fully adaptive human-machine cooperation in which the computer learns to provide the right information in the right time.

The need for health monitoring and material characterization of composite materials and composite structures is examplified by the Concorde: "*Some failures were traced to water ingress at repair joints on the composite panels, but most failures did not manifest until after several years of normal service with no apparent visual degradation of the external surfaces.*" [1]. The fatigue process and other damage on the newly developed composites are not easily predicted and require sensitive and flexible methods for Non-Destructive Testing (NDT) and structural monitoring. Reinforced composite structures in general have a need for NDT methods that preferably are non-contact see e.g. [2, 3]

As damages, in general, appears relatively seldom in ships, the technique must be validated through specially adapted circumstances. The technique was tested in 2010 for the detection of damage from explosive impacts - with positive results [4]. In the work reported here, the technique was to be validated for fatigue damage monitoring of a composite steel-fiber reinforced plastic beam.

TEST DESCRIPTION

A cross-section of the composite beam is pictured in Figure 1. It was made by a core of Divinycell (marbled) surrounded by a glass fiber material (black) and reinforced by two U-beams of steel (grey). The main cause for the test was to check how much stress the attachments (crosshatched line) between the composite material and the steel could take. Sealings (triangular) are positioned to prevent water and dust from affecting the attachment area.

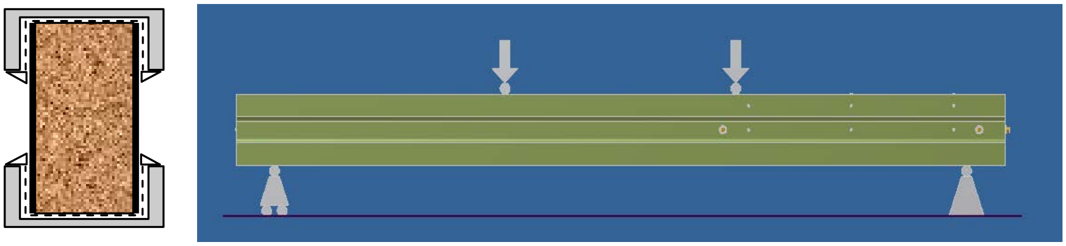

Figure 1. Left: The cross-section of the composite beams. Right: The beam with the load points shown. The supports on the floor are left and right, and the two middle points are where the dynamic load from the Instron machine forces act.

The test was performed at the SP Technical Research Institute fatigue testing lab in Borås, Sweden. The equipment used for the loading was an Instron press with the capacity of 1 MN, see Figure 2. The beam was placed on supports and exposed to four-point-bending. The load points were as shown in Figure 1, right.

Figure 2. Left: The Instron machine. Right: The test beam ready for the start of the test.

TEST APPROACH

The analysis technique is based on nonlinear acoustics. Damage in a ship hull is directly related to the nonlinearity of the material. This will show itself as a distortion of the waves.

As a first example of how the system can monitor the obtained signals for damage, we will show how it affects a single frequency. In Figure 3, left, is seen the signal when a material is un-damaged. The single frequency exist, but nothing else. In Figure 3, right, is seen how the frequency spectrum includes many more frequencies when the material is damaged. Higher harmonics are created, and their amplitudes are indicative of the level of damage [5, 6, 7].

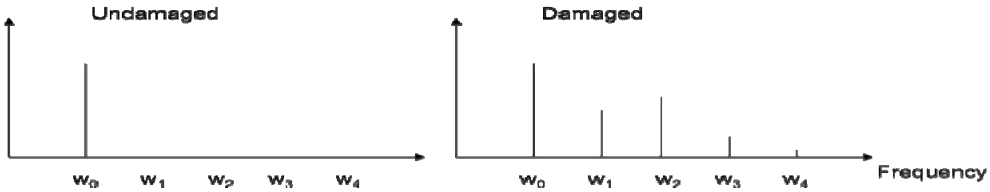

Figure 3. When a single frequency is input to the material, the same frequency is measured when the material is undamaged. When the material is damaged, higher harmonics are created and can be measured.

As a second example of how the system can monitor the obtained signals for damage, we will show how the nonlinearity affects a single high frequency combined with a number of lower frequencies. The nonlinear wave modulation technique was conceptually introduced in the 1960’s [8] and has been used for different applications during the years, see for example [9, 10, 11]. In Figure 4, left is seen the signal when a material is un-damaged. Then the single high frequency exist, and the lower frequencies, but nothing else. In Figure 4, right, is seen how the frequency spectrum includes a multitude of frequencies when the material is damaged. The higher harmonics are created, as well as combination frequencies resulting in so called side-bands around a number of higher frequencies. The amplitudes of the newly created frequencies is an indicator of the level of damage.

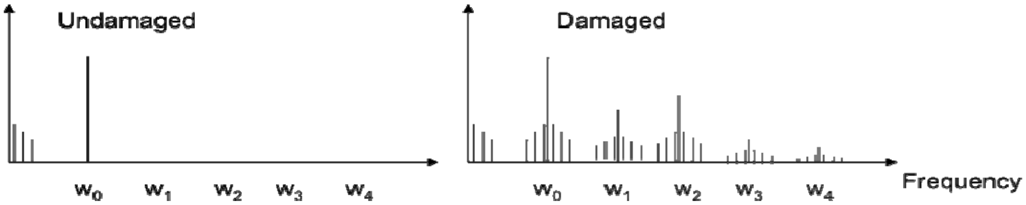

Figure 4. When a single high frequency and number of lower frequencies are input to the material, the same frequencies is measured when the material is undamaged. When the material is damaged, a large number of combination frequencies are created and can be measured.

TEST PARAMETERS

A 4-meter long glass fiber was tested by using the techniques described above. The damage level was monitored during the fatigue test.

At first a static load was gradually increased, see Figure 5, and between these loadings measurements detecting damage of the material were made.

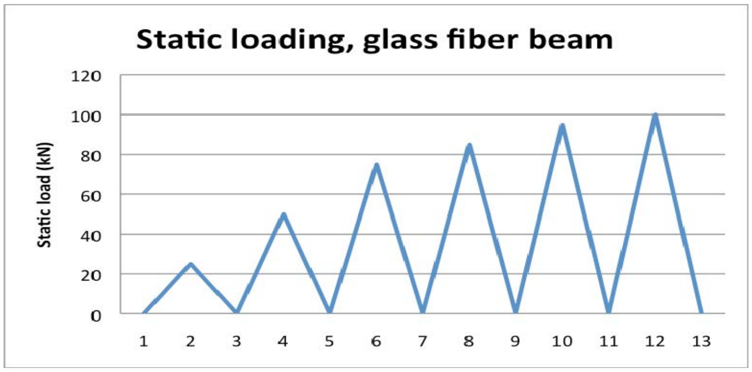

Figure 5. The initial static loading of the beam.

After these static loadings the remaining deformation were measured to 1.2 mm in the middle of the beam.

The static loads were now changed to a dynamic load pending between 10 kN and 100 kN. The frequency was set to 0.75 Hz at first and was then raised to 1 Hz after around 7 900 cycles. After about 72 000 cycles the frequency was raised again to 1.15 Hz, remaining at that speed for the rest of the test. It was difficult to estimate how long the beam would last at the current load. Therefore, after many cycles, see Table 1, the load was gradually increased to 200 kN, which resulted in a failure.

Table 1. The loading scheme of the glass fiber beam.

Cycle numbers	Load	Comments
1-13	Static, see Figure 5	March 3, 2011
13- 1 761 993	Dynamic 10 kN-100 kN	Fq 0.75 - 1.00 - 1.15 Hz.
1 761 994- 1 847 013	Dynamic loads of 130 - 150 - 160 - 175 - 200 kN.	March 22, 2011.

RESULTS

The main result of this test are shown in Figures 6 and 7 where the elastic stiffness response and the Damage level indication are presented as functions of the number of cycles.

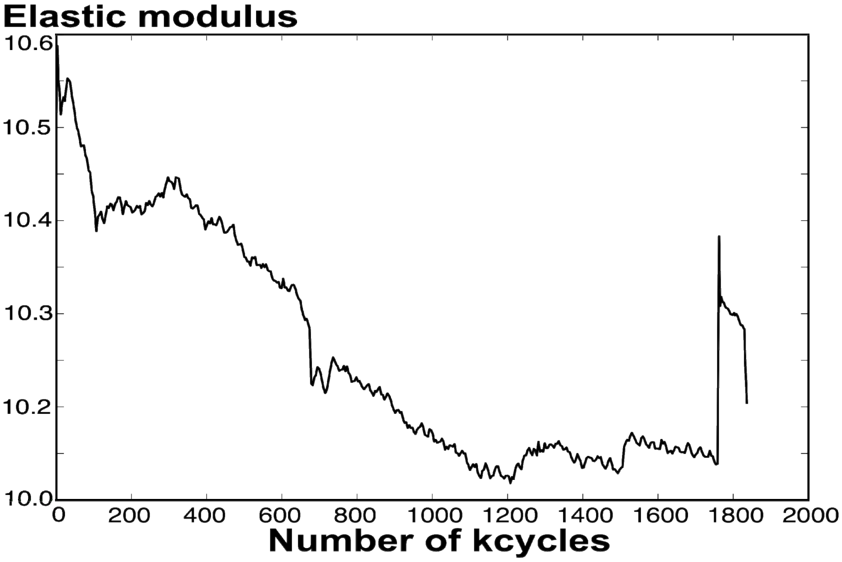

Figure 6. The Elastic modulus during the fatigue test.

The Damage detection curve shows several aspects distinctive for this applied technique: A. Even during the very first static loading cycle, an increase is measured. The method is sensitive to very early damage. B. The Damage level is an increasing function, which reflects the actual damage progression. This is a defining characteristic thing for this technique.

When comparing the Elastic response (Figure 6) and the Damage level (Figure 7) there are a couple of important differences. The Elastic response have sudden jumps which happen when the external conditions change. At the same time the actual damage does not change instantaneously. Therefore, this elastic parameter is not a completely suitable property for the damage. On the other hand, the Damage level curve slope increases, but it is continuous and it does not exhibit any sudden jumps when the external parameters change.

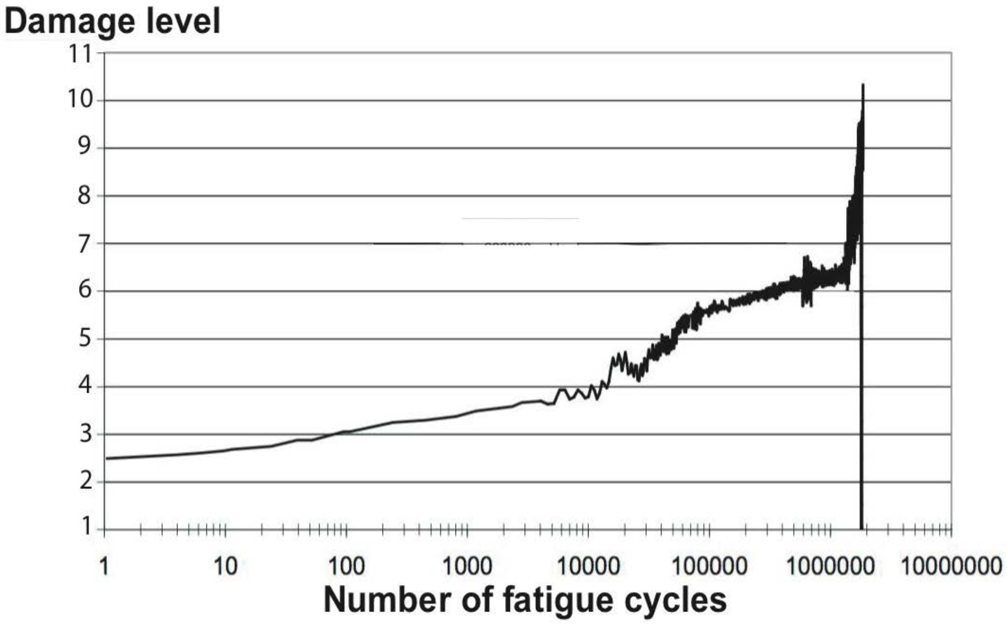

Figure 7. The Damage level shows how the progressive damage can be monitored during the fatigue test.

CONCLUSIONS OF TEST

The general conclusions that can be drawn from this test are that the damage measuring technique is applicable to materially complex structures and that the technique is well suited for fatigue monitoring. This means that early warning of damages are possible which has an impact on Life Cycle Performance Assessment.
Through these results savings may be assessed in the following ways:
A. Thanks to monitoring we could go to weaker structures
B. Thanks to pre-fatigue detection ability time between inspections may be increased.
C. Specific to the parameters in this fatigue test, it was proven that the steel - fiber composite joint was strong and held out a long time for fatigue loading. Therefore large savings through the use of composite superstructures are possible.
There would also be a safety contribution in that suddenly appearing damages would be detected and notified so that catastrophic events might be avoided.

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