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Patrik Kubaska
E-mail: pkubaska969@gmail.com
Tin Matulja
E-mail: tin.matulja@riteh.hr
Marko Hadjina
E-mail: hadjina@riteh.hr
Faculty of Engineering University of Rijeka, Vukovarska 58

Carbon Mast Structural Damage Detection Using Ultrasonic NDT Method

Abstract

Glass and carbon fibers as materials have become the primary choice in the construction of smaller vessels. The advantages of these materials are good mechanical properties, they are relatively light materials that today anyone with a little knowledge can handle and also, financially speaking, they are materials that are affordable to almost everyone. One of the disadvantages is that composite materials are not homogeneous. This would mean that irregularities can be observed in the cross section of the laminate of such composite vessel or equipment. These irregularities are usually negligible because they simply belong to the property of composite materials. The problem arises when imperfections are caused by human factors or the action of some external force such as residual air in the laminate or delamination. Such imperfections during navigation can cause catastrophic damage. Although visible damage may seem small, it is very likely that there is much greater damage to the laminate that is not visible because it is located somewhere between the layers of fibers. Various methods exist for detecting such damage and imperfections, which can be invasive or non-invasive. The focus of this paper is on detecting the magnitude of damage in the laminate of the carbon mast of a racing sailboat Melges 32 using a non-invasive ultrasonic testing method. The Avenger EZ device was used for testing only.

Keywords: Carbon mast, Laminate, Damage detection, NDT method, Ultrasonic testing

1. Introduction

This paper describes the procedure of ultrasonic testing of the carbon fiber mast of a Melges 32 sailboat for the purpose of damage repair. The first part of the paper explains the basic features of composite materials, especially those containing carbon fibers, as well as methods for testing composite laminates. In the continuation of the paper, the procedure of ultrasonic testing of materials is described in more detail, as well as the equipment needed to perform the testing itself. Finally, the carbon mast of the Melges 32 sailboat was tested to determine the extent of the damage and to repair the damage itself.

2. Composite materials

Composite materials are obtained by joining materials together to form a material that has better mechanical properties than separate materials. The characteristic of composite materials is that they usually have better specific strength, better modulus of elasticity and better heat resistance. When making composite materials, basic materials are selected that have satisfactory characteristics for the required purpose. Composite materials can be divided according to the type of matrix and according to the type of reinforcement.

According to the type of matrix, composite materials are divided into:
- Ceramic matrix composites (CMC)
- Polymer matrix composites (PMC)
- Metal matrix composites (MMC)
- Carbon-Carbon Composites (CCC)

According to the type of reinforcements, composite materials are divided into:
- Fiber-reinforced composites
- Particle reinforced composites
- Structural composites

The main role of the matrix is to interconnect the reinforcement and transmit force to it, give shape to the composite and protect the material from external forces while the role of reinforcement is to improve the strength and modulus of elasticity of the composite material itself.

2.1. Carbon fiber composites

Carbon fiber composites consist of carbon fibers and a polymer matrix, with the polymer matrixes being divided into plastomers and durometers.

Plastomers:
- Polyethylene (PE)
- Polypropylene (PP)
- Polyamide (PA)
- Acrylonitrile butadiene styrene plastic (ABS)

Duromers:
- Epoxy resin
- Vinyl-ester resin
- Polyester resin

Epoxy resin is most commonly used as a matrix in carbon fiber reinforced composites. The properties of such a composite largely depend on the length and diameter of the carbon fibers, the fiber orientation, the fiber to matrix ratio in the composite, and the mechanical properties of the fibers and matrix themselves. Figure 1 shows some of the possible orientations of the carbon fibers in the matrix.

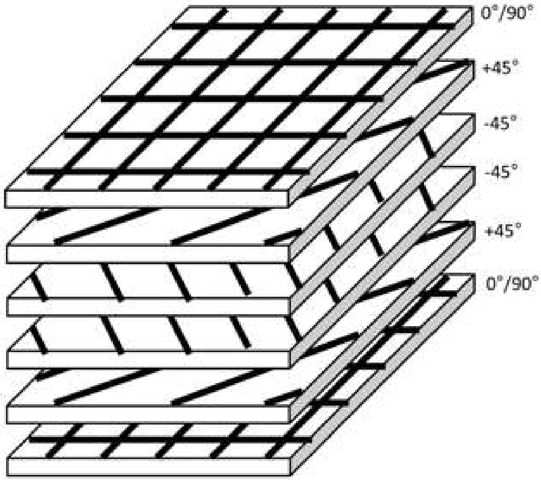

Figure 1. Fiber orientation

2.2. Testing of composite materials

Carbon fiber composite laminates often contain imperfections that can cause damage due to external loads. In order to eliminate the possibility of damage, it is necessary to examine the laminate. Test methods are divided into invasive and non-invasive. Invasive methods are also destructive methods because a sample is taken for testing the laminate, and the sampling itself creates damage in the laminate. For composite materials, non-invasive laminate testing methods are far more acceptable.

Basic division of non-invasive methods:
- Visual inspection
- Tapping method
- Ultrasound method
- Radiography
- Eddy-current method
- Thermography

The primary noninvasive method of testing laminate is visual inspection. Although composite laminates hide imperfections and damage well, it is possible to determine the location of some significant damage with the help of visual inspection. A slightly more advanced method would be the tapping method. With the tapping method, a blunt object is tapped on the surface of the laminate and, with careful listening, a change in the sound produced is sought, which would indicate an imperfection in the laminate. Although this method cannot provide a detailed picture of the condition of the laminate, it is still used because it very quickly gives an idea of the size and location of imperfections in the laminate without the use of expensive test equipment.

Radiography uses an X-ray generator that penetrates the laminate and on the other hand comes into contact with a detector or X-ray sensitive film. In some places, X-rays are more absorbed into the material, and in some less, so a detailed picture of the condition of the laminate is obtained. The disadvantage of this method is that X-rays are harmful to humans and other living things.

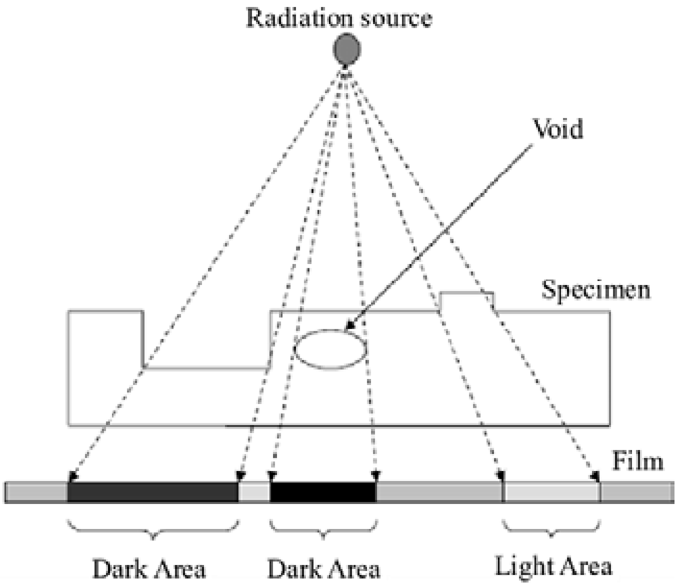

Figure 2. Radiography

Eddy current method is less commonly used in composite laminates and more commonly in metal inspection.

The reason for this is that in this method a coil that generates a magnetic field is brought close to the material. A magnetic field near an electrically conductive material induces an electric field in that material which also creates its own magnetic field that interferes with the original magnetic field in the coil. This interference changes with respect to material thickness and internal imperfections. Although carbon is an electrically conductive material and it is possible to test laminate by this procedure, this method is still more used in metal testing.

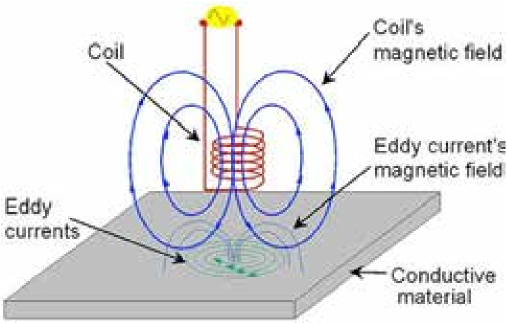

Figure 3. Eddy current method

In thermography, a special camera measures the radiation of the material in the infrared part of the electromagnetic spectrum. According to black body radiation theory, all bodies that have a temperature above absolute zero radiate in the infrared spectrum. Thermography is a quick and easy way to test a material that instantly gives a picture of the condition of the material over a large area, but if it is imperfections and damage that are deep in the material then a much better picture of the condition of the material is obtained using the ultrasonic test method described in the next section.

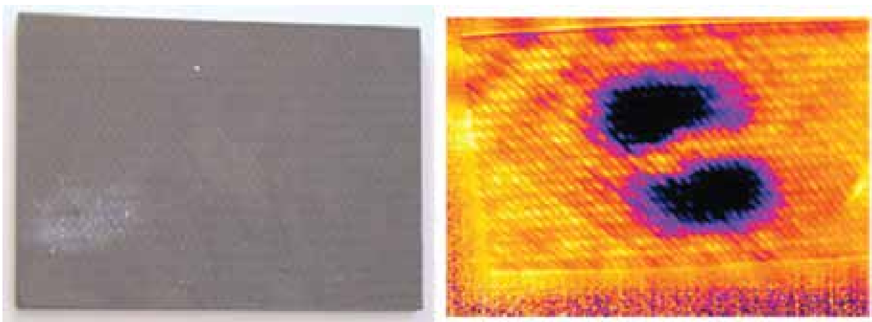

Figure 4. Termography

2.3. Ultrasonic testing of composite materials

Ultrasonic testing of solid materials is used to detect material imperfections and microcracks. It is based on the fact that solids are good conductors of sound waves. Sound waves are reflected within the material from its sides, and at the same time they are reflected from all imperfections in the material. The interaction of the material itself and the sound waves is better the smaller the wavelength of the sound. This also means that higher frequency waves are used. This material testing method is characterized by frequency waves from 0.5 MHz up to 25 MHz. The reason for this is that the interaction of waves is most pronounced if a wave of a certain wavelength comes into contact with an imperfection that is similar in magnitude to the wavelength of that sound. The observed laminates in composite vessels are usually a few millimeters thick, so it is necessary to adjust the sound wavelength so that it is in the range of a few millimeters. Equation 1 defines the sound wavelength for a given speed of sound and frequency. The speed of sound in air is approximately 343 m/s, but this value is not applicable in this case. As explained earlier, solid materials are good conductors of sound, which means that the speed of sound in solid materials is much higher than the speed of sound in air, so it is necessary to adjust the value of the speed of sound in the equation for the observed material. In case of carbon laminates that would be 3070 m/s.

$$\lambda = \frac{c}{f} \tag{1}$$

c = Speed of sound [km/s]
f = Frequency [MHz]
λ = Wave lenght [mm]

The method of ultrasonic testing of materials is mainly based on two different procedures. The first procedure would be based on the measurement of reflected sound waves (pulse-echo) while the second procedure would be based on the measurement of waves that have completely passed to the other side of the material (through-transmission). In practice, the method of measuring reflected waves is used much more for the reason that the measurement requires access to the material from only one side. The reflected wave method is also used to determine the speed of sound through the observed material. If the thickness of the material and the time required for the transmitted sound wave to return to the piezoelectric element are known, it is very easy to calculate the speed of sound through that material.

$$c = \frac{2d}{t} \tag{2}$$

c = Speed of sound [m/s]
d = Thickness of material [m]
t = Time [s]

Compared to other methods of non-invasive testing of solid materials, the ultrasonic method has its advantages and disadvantages.

Advantages:
- High sensitivity to imperfections inside the material
- No preparation of the observed material is required
- The depth to which the wave penetrates is much greater than with other methods
- High precision in determining the size and position of imperfections
- Minimum equipment required for testing (usually portable equipment)
- The test procedure is not harmful to the material or the people conducting the test

Disadvantages:
- High sensitivity to surface imperfection and surface curvature of the material
- The surface of the material must be accessible for testing
- A medium is required between the surface of the material and the piezoelectric probe
- Materials that are not homogeneous are difficult to examine
- Imperfections in the material that are oriented in the direction of sound are almost impossible to detect
- Materials that are very thin (<1mm) are almost impossible to test with this method

2.4. Testing equipment

The ultrasonic material testing device is composed of several parts. The basic parts would be a central unit and a piezoelectric element. The central unit consists of an ultrasonic generator that transmits electrical pulses and a screen that displays the results obtained. The operation of a piezoelectric element is based on the piezoelectric effect of crystals such as quartz. Crystals like quartz have the ability to convert electricity into vibrations and vice versa.

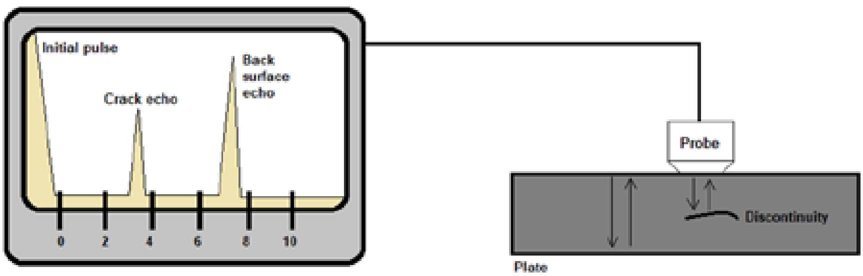

Figure 5. Ultrasonic testing equipment

The piezoelectric element is often referred to as the active element. The operation of the element itself is based on the Lippmann effect. Gabriel Lippmann was a French physicist who found that in some materials, such as certain crystals and some ceramics, polarization occurs at the ends of the material due to the execution of elastic deformation by some force. This phenomenon is especially pronounced if the ends of this material are cut straight. Lipmann also found that there is a reverse phenomenon. If the crystal is placed in an alternating electric field, an elastic deformation of the material occurs, which is called electrostriction.

In the event that the frequency of the alternating electric field coincides with the natural frequency of the material, vibration and resonance of the crystal occur. In some crystals this is quite pronounced, such as tourmaline whose frequency reaches a few hundred MHz.

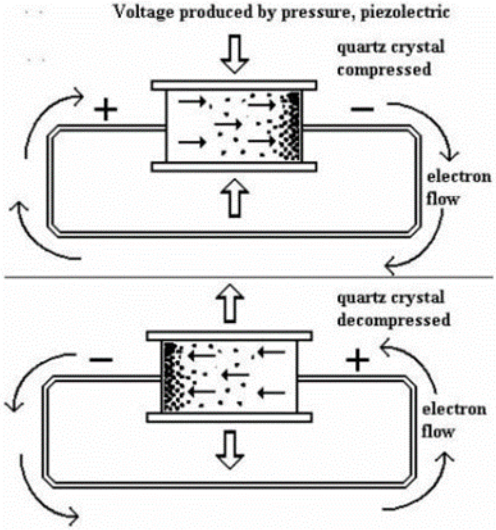

Figure 6. Lippmann effect

3. Pulse-echo method

The pulse-echo method is the method most commonly used in material testing. During the testing of the material, the ultrasonic generator emits short-term pulses of electricity that come through a conductor to a piezoelectric element that is in contact with the surface of the material. The moment an impulse of electricity reaches a piezoelectric element, it converts that impulse of electricity into mechanical energy of vibrations. The vibration is transmitted through the observed sample until it is reflected from some imperfection or from the back surface of that sample. The reflected vibrations are returned back to the piezoelectric element which converts the received vibrations into a pulse of electricity. This pulse travels back to the central unit where it is displayed on the screen.

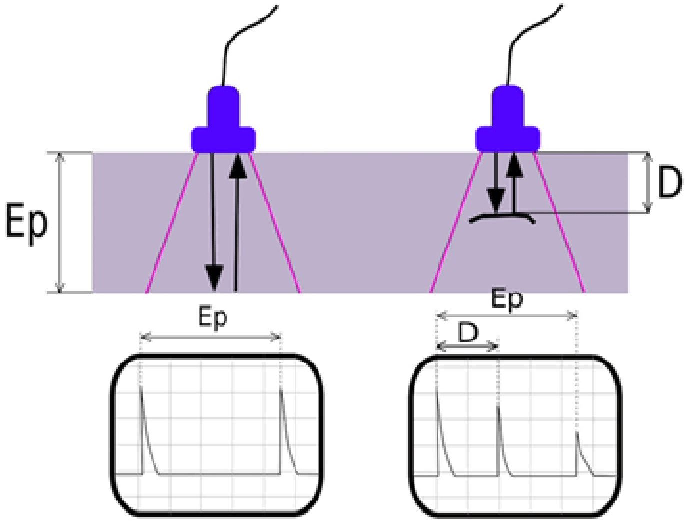

Figure 7. Pulse-echo method

In the pulse-echo method, there are two types of probes with a piezoelectric element that are most commonly used. They are divided into probes with one element and probes with two elements. Single-element probes use the same piezoelectric element to transmit and receive vibrations while two-element probes have one piezoelectric element to transmit vibrations and another element to receive vibrations.

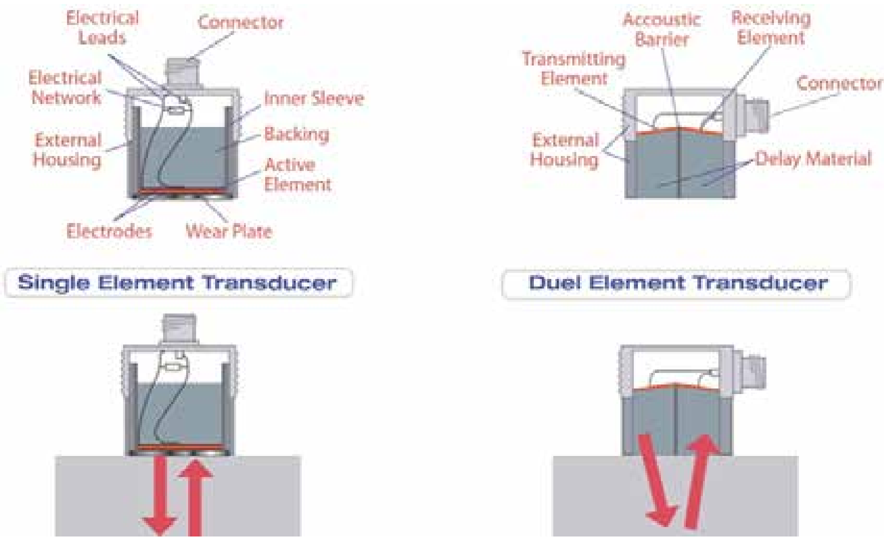

Figure 8. Transducer types

Single-element probes are most commonly used to test for imperfections in metals and delamination in composite materials while two-element probes are most commonly used to detect damage caused by corrosion on metal or to test very thin materials such as sheets because they have much less interferences.

4. Testing and results

The acquired theoretical knowledge about the method of ultrasonic testing of solid materials was applied in the detection of structural damage in a mast made out of carbon fiber. The mast, as one of the basic parts of a sailboat, is constantly loaded with forces during sailing. It is loaded with lateral forces of variable intensity due to various and sudden wind gusts and is also under constant pressure load due to the steel rigging.

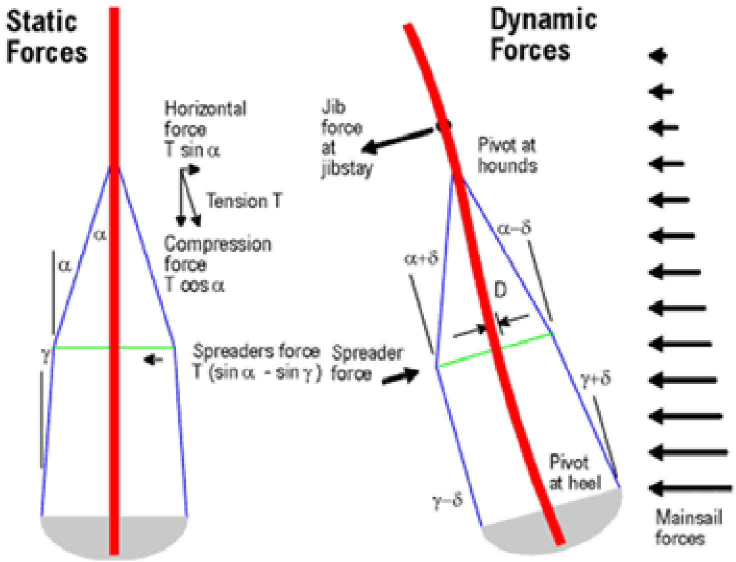

Figure 9. Forces on sailboat mast

The analyzed mast is the mast of a Melges 32 class sailboat. It is a two-part mast made of carbon fiber. The reason why the mast is designed in two parts is primarily to make it easier to transport. Damage was caused to the upper part of the mast during sailing in strong winds. At the time of sailing downwind there was damage in the rigging which caused a short-term torsional load of the mast and shortly after the rupture of the upper section of the mast into two parts.

Masts are generally not designed to withstand torsional loading because it almost never occurs under normal conditions.

Figure 10. Mast damage

At first glance, the damage to the mast is only near the site of the section rupture. However, as mentioned earlier, the problem with composite materials is that most often internal damage is many times greater than it is apparent.

An Avenger EZ ultrasound scanner was used to determine the size and type of damage. It is a hand-held portable device that uses the pulse-echo method to find damage. A piezoelectric probe operating at a frequency of 5 MHz was used for the measurement. Calibration of the device itself is relatively simple when it comes to testing homogeneous materials such as steel and aluminum. When working with composite materials, the process is somewhat more complicated. It is necessary to have pre-made pieces of a similar laminate as the mast for calibration. The wall thickness of the mast was measured with a movable scale in several places and an average thickness of 6.5 mm was obtained. Since the mast is mostly pressure loaded, most of the layers in the laminate have fibers oriented in one direction that go from the top of the mast all the way to the lower end of that mast section.

Pieces of approximately the same 6.5 mm thick laminate were made by hand laminating using a vacuum bag. It is important that the calibration pieces have similar thickness and structure as the mast. The device was roughly calibrated on the made piece of laminate and was subsequently calibrated on the part of the mast that was not damaged. Since the mast wall thickness is known to average 6.5 mm, this size was taken as a reference. Any larger deviation from the ideal 6.5 mm requires more attention when testing. The ultrasound examination was started approximately 75 cm from the rupture site of the mast and gradually moved closer to that rupture site with the probe. Before the measurement, the probe is coated with gel so that there is no air between the surface of the material and the probe and in order to create the best possible contact of the probe with the surface, which also results in better transmission of sound waves into the material itself. In contact with the material surface, the device displays graphically the sent and received wave as well as the value in millimeters to the first obstacle. In this case, the obstacle was the inner side of the mast wall, so a value of 6.28 mm was obtained.

Figure 11. Result 1

Figure 11 shows the three signals received. The first and most pronounced signal is a transmitted wave that bounced off the surface of the mast wall without entering the material itself. This wave needs to be filtered out of the measurement for the reason that otherwise the device will show the wrong wall thickness and later the wrong place and size of the imperfection in the material. The second signal shows a wave bounced off the inner surface of the mast wall to a depth of 6.28 mm. This is the signal that needs to be recorded on the mast to know the exact position where the damage does not exist. The third and smallest signal is not common, but occurs if the laminate is well made and it shows a wave that has already bounced off the inner surface of the mast wall and once again made its way all the way through the mast wall again and once again bounced off the inner surface of the mast and back into the ultrasonic probe. The obtained value is approximately twice the mast wall thickness.

Figure 12. Position 1

Figure 11 and figure 12 show ideal conditions where damage does not exist and only the thickness of the mast wall is measured. Figure 13 shows a situation where the damage in the wall of the mast is close to the surface from which we are measuring. Ultrasound no longer shows at what depth the inner surface of the wall is but only shows the location of the damage. It can be concluded that it is a case of delamination. The layers of laminate are separated from each other and between them there is a layer of air that does not allow sound to travel freely through the material.

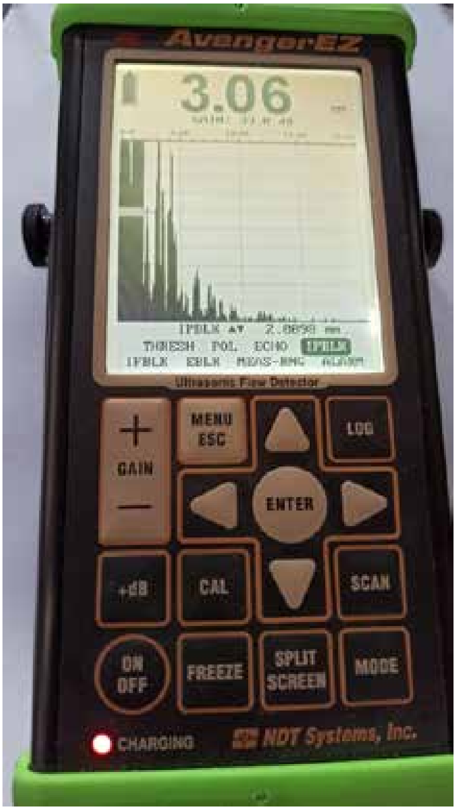

Figure 13. Result 2

The measuring position as well as the obtained value are marked on the surface of the mast in order to finally get a detailed picture of the magnitude of the damage to the mast.

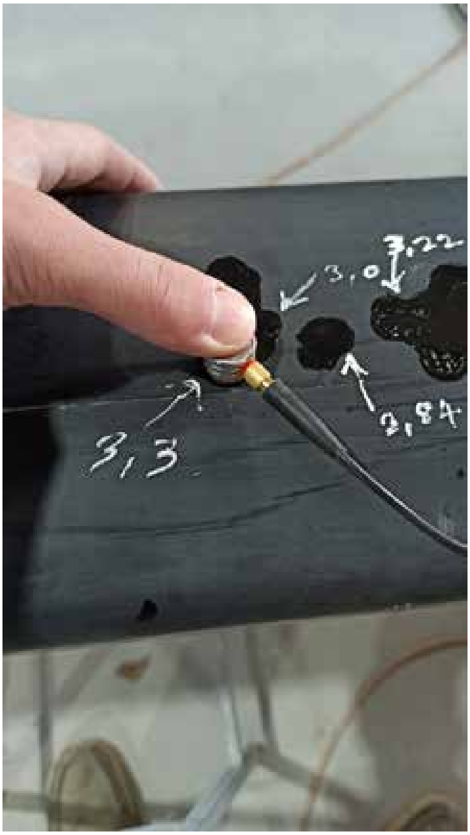

Figure 14. Position 2

In certain situations, the measurement result was not completely clear at first. As shown in figure 15 , the feedback signal from the inner surface of the mast wall is clearly visible at 7.16 mm but there are two signals also visible near the outer surface of the mast wall.

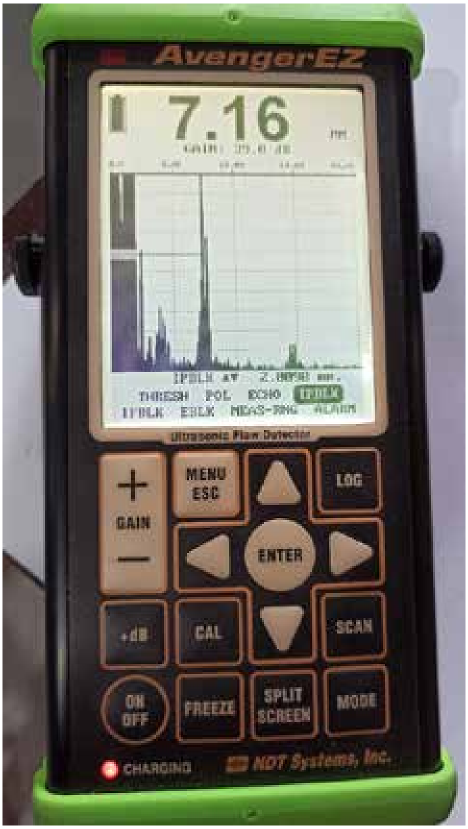

Figure 15. Result 3

The measuring point was marked on the mast in order to get a detailed picture of the condition of the mast and to determine later during the repair what kind of irregularity it is, considering that the ultrasonic examination did not give a concrete result. During the repair, that place on the mast was sanded and it was determined that it was an imperfection that occurred during the production of the mast in the factory, and that imperfection was filled with some kind of epoxy filler.

Figure 16. Position 3

After the mast was examined in a number of positions, an insight was gained into the magnitude of the damage itself. The damage, which at first glance seemed to be localized only around the rupture site, actually extends approximately 60 cm above the rupture site. The test was also performed on the lower part of the broken section and the obtained results indicated that the internal damage on the lower part is much less than on the upper part of that mast section. Figure 17 shows the amount of damage at the top of that mast section. All to the left of the red line is a wall that has layer delamination.

Figure 17 Magnitude of damage 1

The lower part of this section of the mast shows slightly less damage, but it is interesting to note that the place where the internal damage ends is not a straight line but in both parts of the mast is a curved line, which could indicate that it is indeed damage caused by torsional load. on the mast. Figure 18 shows the lower part of that mast section. Anything to the left of the red line is damage.

Figure 18 Magnitude of damage 2

5. Conclusion

When working with nonhomogeneous materials, such as composite materials, there can always be unpredictable imperfections in the material which can cause major damage. Today, composite materials are used in the manufacture of airplanes, boats, cars, sports equipment ... It is not uncommon for material fatigue or damage to occur due to the action of some external force on the material. Damages are difficult to notice in composite materials because they are most often hidden under the surface. Regular material control is very important, primarily visual inspection, and certainly material control with the help of some of the non-invasive methods. The ultrasonic testing method has proven to be one of the better methods because it is not dangerous for the operator and the material being tested, the equipment is usually small enough to be carried in the hand and also gives a very detailed insight into the condition of the material. Delaying regular material inspections can lead to catastrophic consequences such as the sinking of a vessel or the crash of a plane where in both cases there could be human casualties. Through the practical part of this paper, it was found that visual inspection of the material alone is not sufficient. The ultrasonic method determined that the damage to the laminate of the mast was many times greater than it was at first sight. By using the ultrasonic method, it is possible to precisely locate the position of the damage in the structure of the composite material. The results should be checked multiple times as it is possible to get wrong readings due to surface imperfections or curvature. The results may indicate that the mast broke during torsional load which could be possible to avoid with different composite laminates such as laminates which use more biaxial carbon fibers where the torsional load on the mast would be oriented along the fibers. It can be concluded that the damage happened because the mast was not designed to withstand a torsional load. Results of these kind of non-destructive testing's should be used to improve the design and structure of future sailboat masts.

6. Acknowledgments

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