THE EFFECTIVENESS OF NON-CONTACT ULTRASONICS FOR DAMAGE DETECTION ON WET GFRP COMPOSITES

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Abstract: A study of the effectiveness of traditional water coupled and non-contact ultrasonic C-Scan systems for wet damaged Glass Fiber Reinforced Polymer (GFRP) composites has been performed. Long term immersion for up to 24 months, of impact damaged GFRP plates in hot water at 65º C and 93º C causes serious matrix degradation. Water diffusion is followed by water uptake measurements. The use of water coupled pulse-echo ultrasonics proved ineffective after long-term water immersion as damaged areas become ultrasound-invisible. The use of air-coupled through thickness ultrasonics is examined for damage detection and evaluation. The contrast between impact damaged areas and water diffused areas is restored. Calibrating the system to a dry condition specimen, a good qualitative and quantitative indication of the degraded state of specimens can be obtained. This monitoring system for the degradation process proves to be very promising.

Introduction: For nearly 50 years now, Glass Fiber Reinforced Polyester (GFRP) composites have found wide acceptance and use by the Marine and process industry. The specific strength, the resistance to corrosion and fouling by the marine environment, which relates to very low maintenance costs, and the low cost compared to other composite systems, make this material system extensively used. The lack of long term design data and the absence of a validated residual strength predictive method tend to negate to some extent their merits because heavy safety margins are imposed at the design stage.
Long-term natural ageing in order to obtain design data is highly impractical, with a high cost associated [1]. Accelerated degradation testing is utilized instead with carefully chosen acceleration factors. Common accelerating factors are increasing the temperature of the exposure medium, using a more aggressive medium, using some mechanical loading during exposure or combining factors. The effects of impact damage upon the mechanical properties of composites have also been widely investigated [2]. Experimental work focused on the combined effects of environment and impact damage mainly involves short-term testing.
The current project is seeking ways to assess the long term stability and the residual compressive strength of GFRP subject to immersion in hot water and the effects of low velocity impact events prior and after immersion.

Results :

Water absorption

Water absorption tests were performed to follow the degradation state of the material. Results were taken from the average of three specimens per temperature. Similar behaviour was observed for both temperatures at a different scale in terms of time and maximum water uptake level. From Figure 1 can be observed that a multi-stage diffusion takes place. After an initial slow increase, a steeper slope increase in water gain is seen. There are two mechanisms operating past the first change point. One mechanism is increase of water absorption and the other dissolution of the polymer matrix. For both temperatures, the typical Fickian diffusion behaviour is not observed. The results observed here have also been previously observed by others [3] and could be considered as typical for polymer composites immersed in water at high temperatures for extended time.

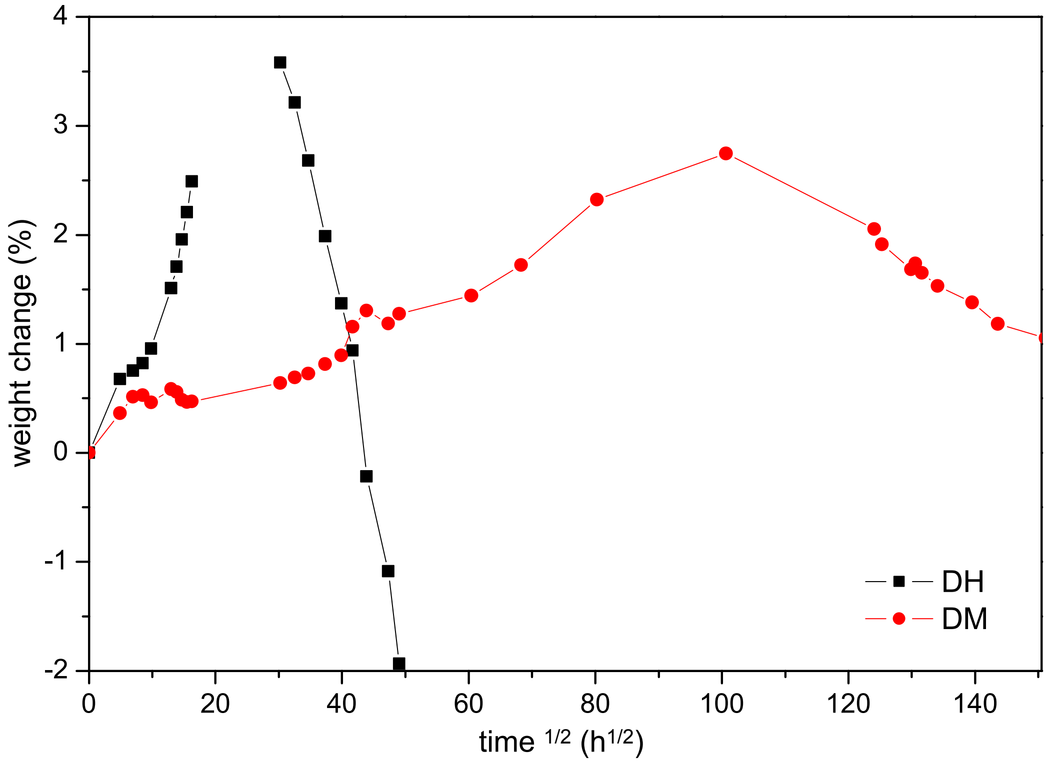

Figure 1 Water uptake results for specimens held at 65° C marked DM and at 93° C marked as DH.

Water absorption is seen to heavily damage composite laminates, by internal and surface distortion. Matrix cracks and interface damage between the matrix and the fibers are caused by water absorption, thus weakening the laminate and causing problems with damage detection. Such damage is seen in Figure 2.

Figure 2 Side view through the thickness of composite plate before, left and right after immersion in water at 65° C for 24 months. The change of colour of the resin is one of the changes after immersion. Extensive cracks can be seen on the exposed specimen. The thickness of the pictured plate material is 3.84 mm.

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Impact damage can initially, before water immersion, be visually observed. When this is not more a possible option, ultrasonic C-Scan is used to detect and size the extent of impact damage. The effects of prolonged water immersion can be seen on Figure 3. After extended immersion specimens loose transparency completely.

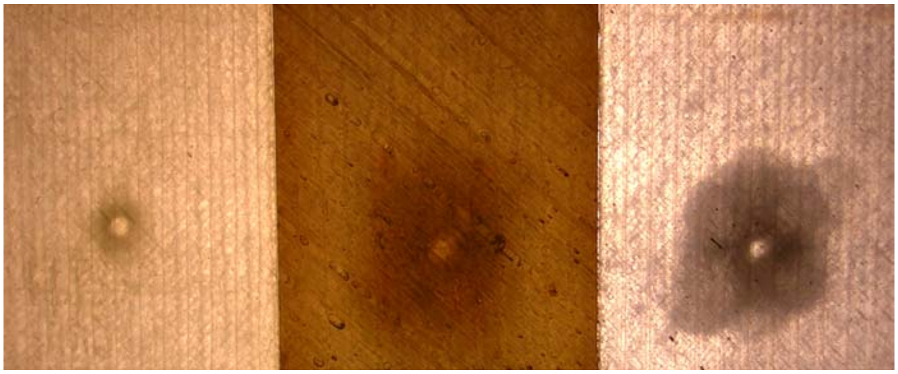

Figure 3 Colour change and loss of transparency of plates. The left most has been in water at 65° C for one week, the middle one has been in water for one week at 93° C and the right hand most has not been exposed to water.

Initially, a single probe, water immersion system by Physical Acoustics was available for this task, with a range of probes from 1 MHz up to a focused 15 MHz. The probe of 1 MHz was found the most useful for this work. A maximum of 400 V can be applied by the pulser. The accuracy of the method when the specimens were dry was tested against digital photographs taken with backlight, as in Figure 3. With time of water immersion increasing, the contrast between the damaged area and the rest of the material started reducing. Water penetrating the material through cracks and by capillary action at the interface of matrix and fibers filled most of the available space. The fact that water is used as the coupling medium seems that plays an important role in the problem faced. The more water found in the specimens the more acute is the problem. Also from the results obtained the amplitude reduction of the ultrasound through water filled specimens is reduced compared to that of dry specimens. Some specimens were allowed to dry in ambient temperature and then the contrast between impact damaged area and the rest of the material was restored. This practice of drying samples was not practical for the project objectives and alternatives were sought for the detection of impact damage condition.

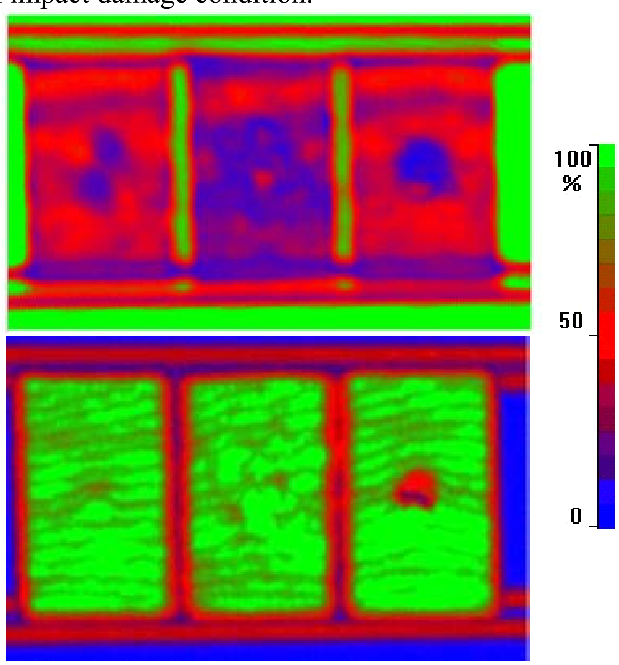

Figure 4 A series of specimens type D that have been impacted at 10 J. The first row depicts amplitude measurement with the gate at the bottom of the specimen. The bottom row has the gate set near the surface of the samples. The left most was impacted and exposed at 65C for 2 months. The middle has been impacted but not

conditioned. The top has been conditioned for two months and then impacted. On the bottom row the indentation caused from the impact after exposure can be seen on the right hand specimen

Due to the problems faced with water diffusion as in Figure 4, an air-coupled ultrasonic probe system was tested. A system by Airstar1 was obtained with a dual probe, for single through direct transmission. A set of ceramic transducer probes with nominal frequency at 400 kHz were used. Although the frequency of the probes is low compared with traditional water coupled or dry contact probes, the resolution was found to be ~ 1 mm and has also been reported by other authors as such [4]. The maximum pulser voltage can reach 800 V.

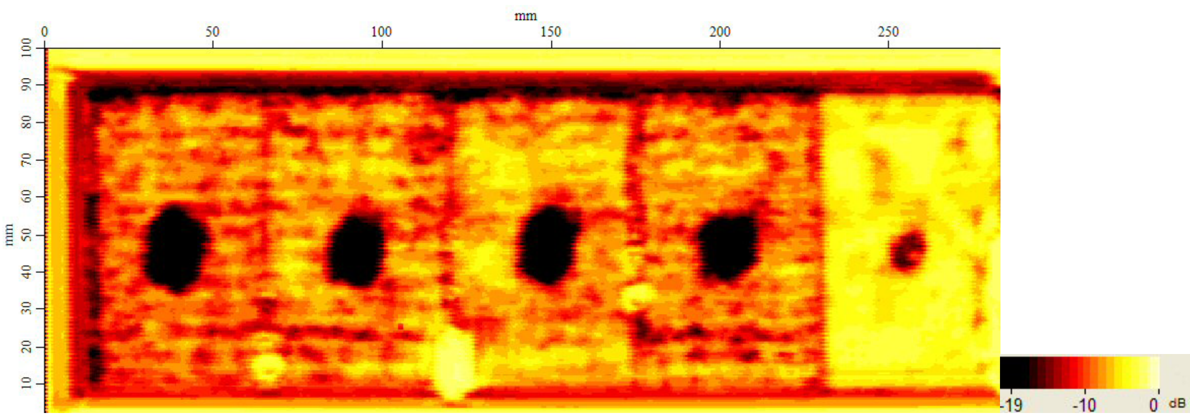

Figure 5 A series of specimens scanned after 24 months in water at 65° C. The last specimen on the right has not been exposed to water. The four specimens in the left have been impacted with 5 J prior to immersion in water. The unexposed specimen has been impacted at 2.5 J. Scan step size 0.8 mm, scan speed 25 mm/sec. The very bright spot between the four specimens on the center is due to some gap between the specimens allowing direct transmission to the receiver probe.

From Figure 5 it can be clearly be distinguished the difference between the water exposed samples and the reference unexposed one on the right. The difference measured was found to be in the range of 6 dB.
The change in the velocity of the acoustic wave was also tested for some specimens after immersion in water.

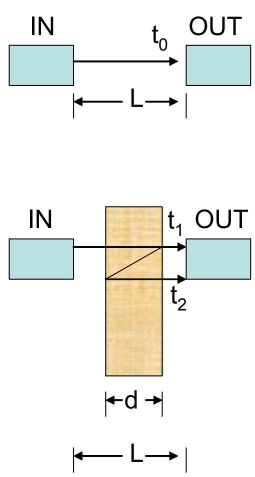

Figure 6 The acoustic wave velocity measurement set up.

The methodology is explained in Figure 6. Assuming that:

$$Va = \frac{L}{t_0} \text{ then}$$

$$Vc = \frac{(2t_0 - 3t_1 + t_2)Va}{t_2 - t_1}$$

where Va the air velocity, L the distance between the probes and Vc the velocity in the composite. The results of the measurements are seen on Figure 7.

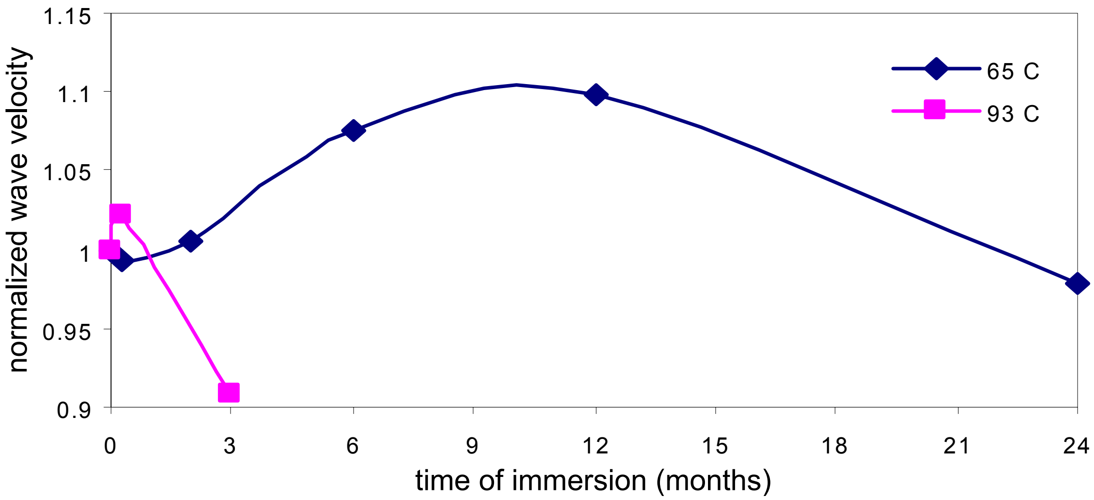

Figure 7 Normalized wave velocity through the material with respect to time of immersion. Normalization is against the dry sample, at time 0.

Residual compressive strength

A new miniaturized Compression After Impact (CAI) test fixture was designed and used for these tests. The residual compressive strength after water immersion was tested at various time intervals, for up to 24 months exposure. Specimens were loaded to failure and the maximum compressive load sustained was used for the calculation of the compressive strength.

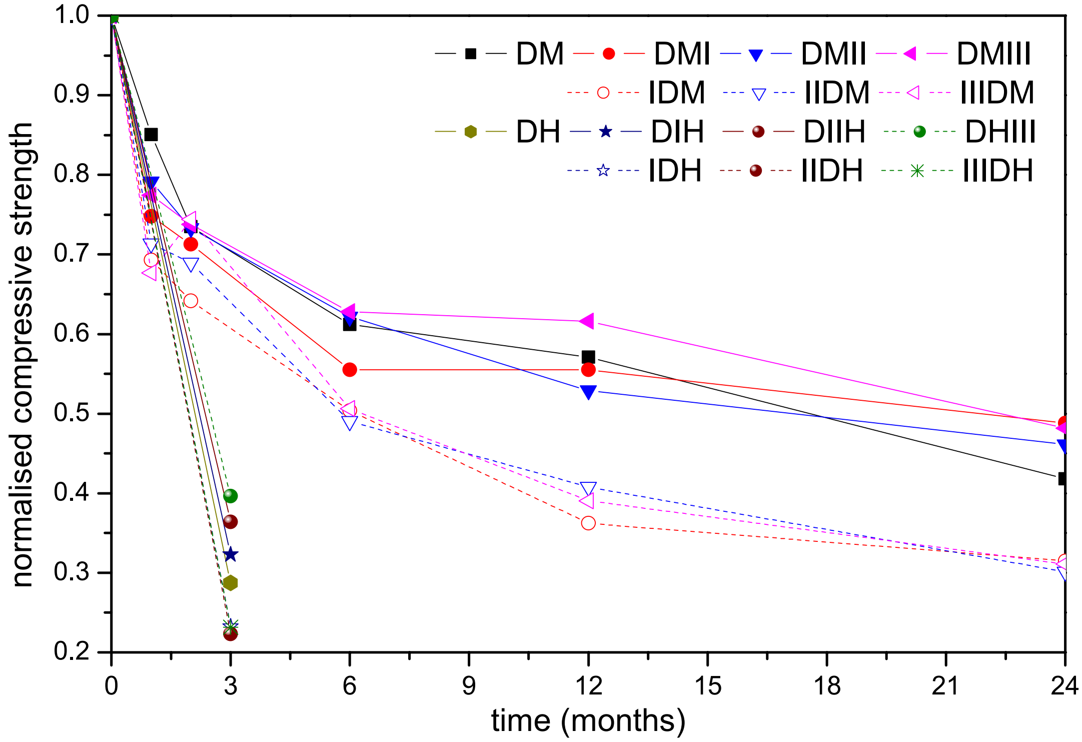

Figure 8 Normalized compressive strength for specimens immersed in water at 65° C marked M and 93° C marked H, with respect to time. Specimens with dashed lines correspond to results obtained for specimens impacted after water immersion. The roman numerals I, II and III relate to the impact level 2.5, 5 and 10 Joules, when before the specimen name correspond to impact after water immersion.

Discussion: Water diffusion plays an important role in the degradation of composites. As yet there is no established method to predict the diffusion under most circumstances. A series of experiments are needed to establish the general profile and then extrapolations are performed. There is also no direct link between residual strength and water absorption. Dielectric NDT methods can measure the water content of laminates [5], but not directly relate to residual strength. Ultrasonics have been used in the past for the determination of mechanical strength with water content being of prime concern [6]. A symmetry between the change in acoustic velocity through the material and the weight change due to water absorption has been established. More work is needed to extend this relationship to changes in the mechanical residual strength of the composites after water immersion. The significance of the prediction using NDT is emphasized by the fact that specimens impacted after water immersion fail at much lower stress than previously impacted specimens. Thus by establishing the condition of the material the seriousness of a possible impact can be established.

Conclusions: Extended exposure of GFRP to hot water at 65° C and 93° C causes a severe drop in residual compressive strength. The effect of impact after water immersion is more detrimental. Water coupled ultrasonics have reduced efficiency for the detection of impact damage for samples after extended exposure in water. Air coupled ultrasonics are not so sensitive to this problem. A correlation between the weight change of composites due to water absorption and the change in the velocity of the sound wave through the material was found to exist. More work is needed to link these two mechanisms and their effect on the residual strength.

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