



NON-CONTACT ULTRASONICS USED FOR IMPACT DAMAGE DETECTION ON LONG-TERM WATER IMMERSSED GFRP COMPOSITES

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Abstract: Traditional water immersion and Non-Contact ultrasonic C-Scan systems were used for damage detection and quantification on wet Glass Fiber Reinforced Polymer (GFRP) composites plates. Long-term immersion for up to 24 months, of low velocity impact damaged GFRP plates in hot water at 65° C and 93° C caused serious matrix and interface degradation. The water diffusion profile was followed by water uptake measurements. The use of water immersion single probe pulse-echo ultrasonics proved ineffective after long-term water immersion as damaged areas became ultrasound-invisible. The impact damaged part was filled with water thus acting in similar way to the rest of the undamaged material. The use of a pair of 400 kHz air-coupled through thickness ultrasonic probes was investigated for damage detection and evaluation. The contrast between impact damaged areas and water diffused areas was restored and damage size detection was possible. Calibrating the system for the group wave velocity of a dry condition specimen, a good qualitative and quantitative indication of the degraded state of specimens can be obtained. This system proved to be very promising for both the impact damage sizing and for the monitoring the degradation process.

Introduction

Modern polymer matrix composites have not been in service long enough for their properties and long-term environmental stability to be fully understood. The evaluation of their mechanical properties along with the long term stability under hydrothermal and other possible service environments has attracted much attention. Numerous studies in the past have demonstrated the degradation of the major properties when composite structures are used in a water environment [1–6]. The cause of degradation has been identified to be primarily due to water molecule penetration that causes swelling as well as plasticization of the polymer matrix and debonding at the fibre/matrix interface [7–9]. The matrix can also be degraded by a hydrolysis reaction of unsaturated bonds. Reviews of the subject revealed that generally there is a lack of understanding of the synergy between the different mechanisms of deterioration of the composites while there is a problem with the reliability of the long-term property prediction methods based on short-term accelerated tests [10,11].

Another concern with typical laminate polymer matrix composites is the significant reduction in residual strength after out-of-plane impact since the mechanical properties of this class of materials in the translaminal (through thickness) direction are relatively low [12]. The greatest reduction in strength is observed when impact damaged plates are subjected to in-plane compression loading [13]. The combination of impact damage with environmental exposure can yield very interesting results in terms of material performance. Since the main effect of the environment is on the interface and the matrix, the residual compressive strength is significantly degraded. The effect of water immersion on the impact-damaged composites with regard to their residual compression strength is a subject of importance for most marine and other structures in similar environments and it is an important issue to investigate.

Of paramount importance when studying composite materials after long-term exposure in water is the use of an effective technique for impact damage detection. In general, a lot of effort has been put in the past to identify the most reliable non-destructive evaluation (NDE) technique for the detection, location and the characterization of the size and type of damage.



Various methods are being used for damage detection however thermography, radiography and ultrasonics are the most commonly used techniques [14-17].

Because of its relatively inexpensive cost and the convenience of data acquisition, ultrasonic testing is one of the most widely used NDE techniques for quality-control and service-integrity evaluation. It is essential that the ultrasonic waves propagate efficiently between the transducers and the material under investigation. To ensure satisfactory acoustic transmission a coupling medium is normally required between the transducer and the component. Water is a good coupling medium, though various gels have been commonly utilised as well.

Recent technological advances in the field produced an ultrasonic technique in which water is no longer necessary as a coupling medium owing to the replacement of traditional transducers by new air-coupled transducers. This is an important achievement in ultrasonic NDE testing, which facilitates and in some cases, enables performing tests on previously impossible situations. During the last decade, air-coupled ultrasonic testing has been studied extensively for use in various manufacturing inspections and recently there has been an increased interest in using such systems for studying composite materials [18-20]. The principle of air-coupled ultrasonic technique is straight forward and very similar to water coupled ultrasonic technique. However, air has very low acoustic impedance and only around 1 % of the sound energy is transmitted, leading to difficulties in coupling energy into the material. This problem was solved with new transducer designs with careful attention of the sensitivity and bandwidth. Because of the tremendous difference in transmitted and received signal amplitudes, and the inherent difficulties in achieving adequate transducer/amplifier isolation and recovery, no current air-coupled NDT systems works in single probe mode.

The current study is focused in determining the behaviour of low energy impact damaged GFRP composites after long term water immersion using ultrasonic testing for damage detection and residual compression testing for mechanical strength reduction assessment. Since the degradation rate of composites at ambient water temperature can be very slow, accelerated degradation procedures were used instead. The laminated plates under study were impacted with three levels of low energy impact loading and immersed in distilled water at 65°C and 93°C for periods of up to 24 months. At certain time intervals the delamination damage was monitored using the water and air-coupled ultrasonic testing methods while the residual compression strength was obtained by compression tests on a CAI rig to determine the damage tolerance. A novel degradation monitoring method was developed using the air-coupled ultrasonic testing equipment by measurements of the acoustic wave velocity.

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, where a sharp increase in absorption is followed by a plateau is not observed. Similar results have also been previously observed by others and could be considered as typical for polymer composites immersed in water at high temperatures for extended time.

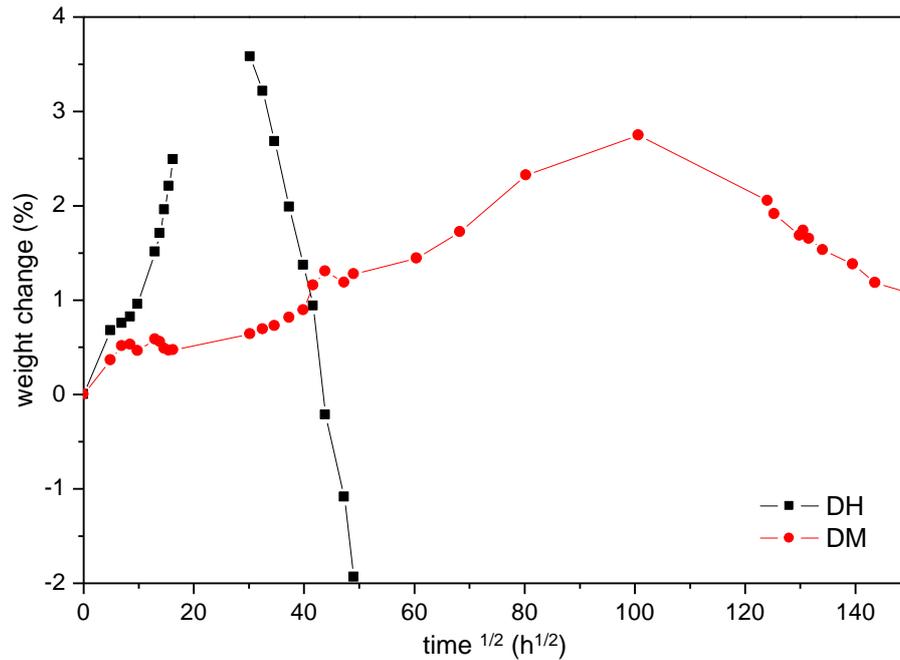


Figure 1 Water uptake results for specimens held at 65° C marked DM and at 93° C marked as DH.

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.

NDT

Impact damage can initially, before water immersion, be visually observed in some cases. When this is not a possible option, ultrasonic C-Scan is used to detect and size the extent of impact damage. The effects of prolonged water immersion as colour change can be seen on Figure 3. After extended immersion specimens lose translucency completely.

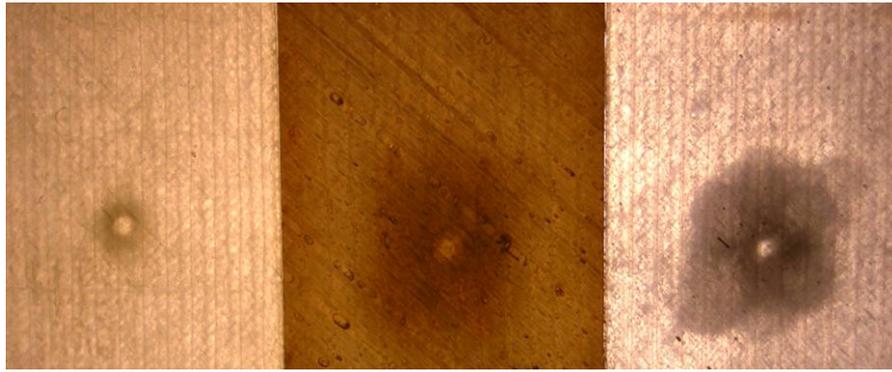


Figure 3 Colour change and loss of translucency of plates. The left most has been in water at 65° C for one week, the middle one has been in water for one week at 93° C and the right hand most has not been exposed to water.

Initially, a single probe, water immersion system by Physical Acoustics was available for this task, with a selection of 1 MHz and 5 MHz probes. 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.

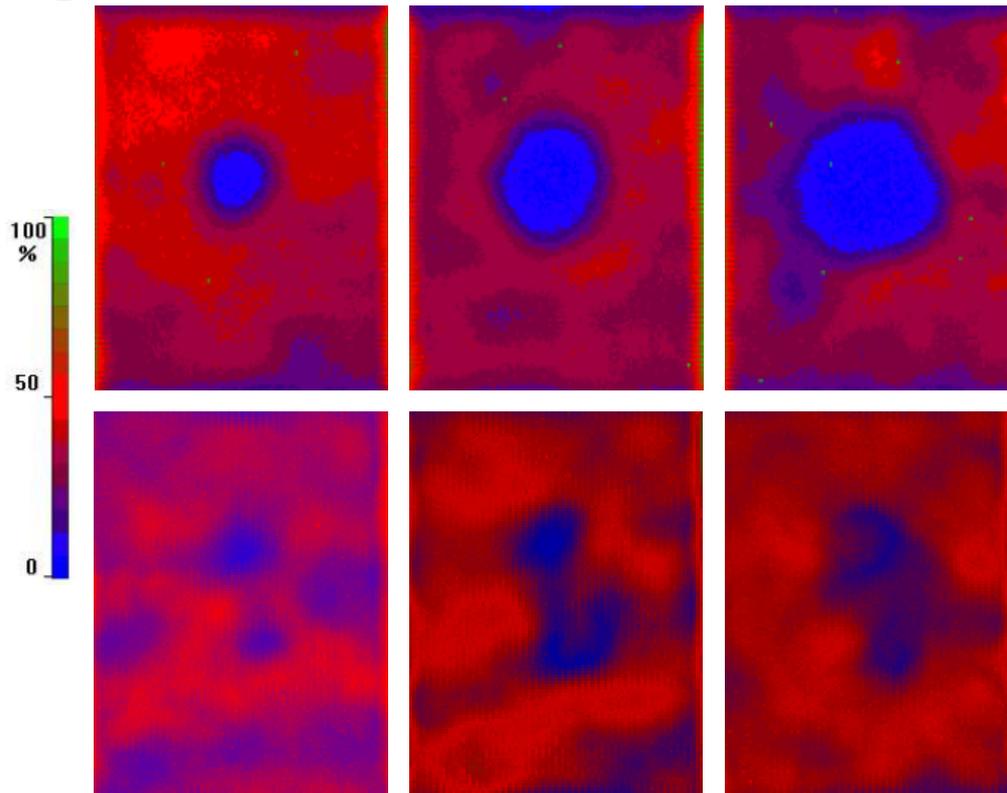


Figure 4 Comparison of C-scans using the water-coupled ultrasonic testing equipment. The top row shows dry specimens impacted with 2.5J, 5J, and 10J and the bottom row shows water immersed specimens held for 24 months at 65° C and impacted with 2.5J, 5J, and 10J prior to immersion.

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 [21]. The maximum pulser voltage can reach 800 V.

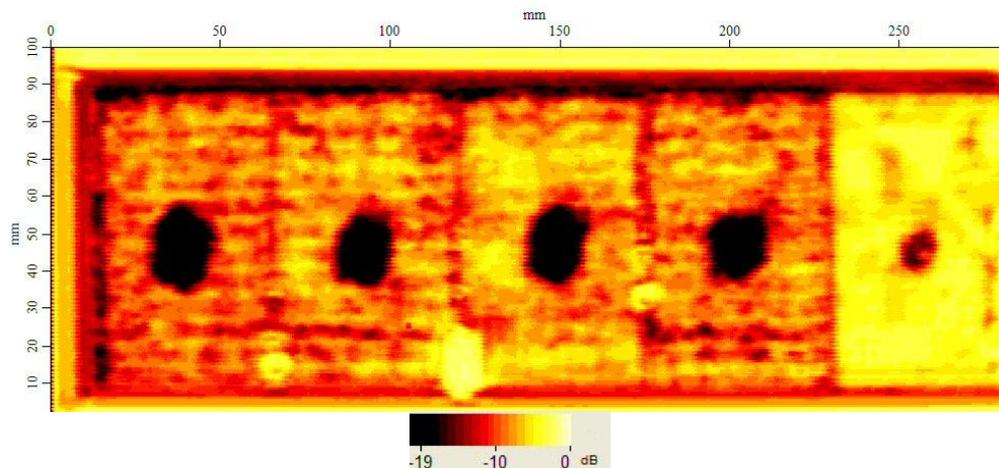


Figure 5 A series of specimens scanned after 24 months in water at 65° C. The last specimen on the right has not been exposed to water. The four specimens in the left have been impacted with 5 J prior to immersion in water. The unexposed specimen has been impacted at 2.5 J.



Scan step size was 0.8 mm and 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.

Using the air-coupled system allowed to find impact damage after long-term water immersion only when the pulser voltage was considerably raised in comparison to what was needed for dry specimens, as shown in Figure 6.

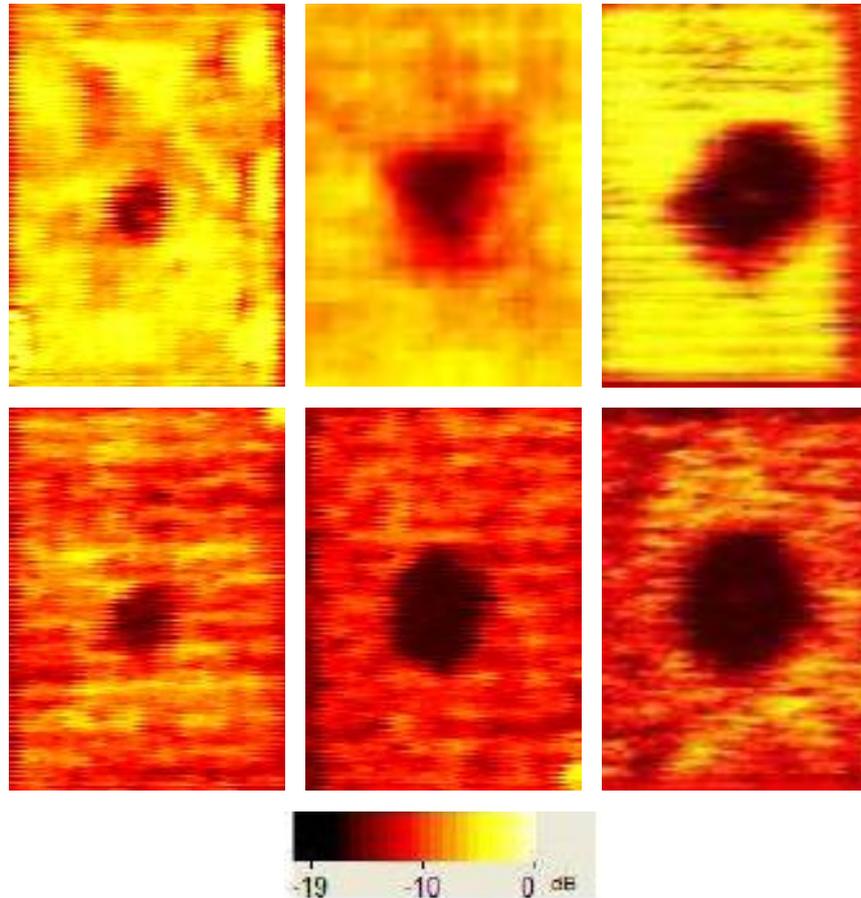


Figure 6 Comparison of C-scans using the air-coupled ultrasonic testing equipment. The top row shows dry specimens impacted with 2.5J, 5J, and 10J and the bottom row shows water immersed specimens for 24 months at 65° C and impacted with 2.5J, 5J, and 10J prior to immersion.

From Figure 5 it can be clearly 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.

Based on the assumption that water absorption causes changes in the material, it was envisaged that the ultrasound velocity through it would follow these changes. The measurements were performed using a paired set of 400 kHz probes in single through transmission mode. The change in the velocity of the acoustic wave was also tested for some specimens after immersion in water.

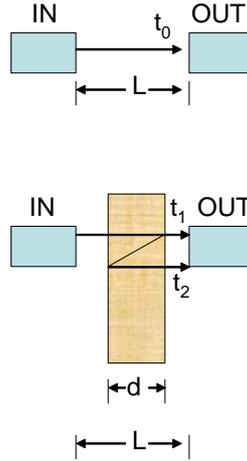


Figure 7 Schematic of the probe arrangement for the measurement of the ultrasonic wave velocity through the material. L is the distance between the faces of the probes, t_0 is the time it takes for signal to cross when no sample is present, t_1 and t_2 refer to the time taken for first and second pass respectively through the material and d is the thickness of the material.

The set-up used for measuring ultrasonic wave velocity through the composite material plates is shown in Figure 7. 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. The values used for the calculations are shown on Table 1.

Table 1 The values used for the calculations, where λ_{air} is the ultrasound wavelength in air, f the frequency of the emitted ultrasound by the probes used and L the distance between the probes.

L	0.075	m
λ_{air}	$0.85 \cdot 10^{-3}$	m
f	$0.4 \cdot 10^6$	Hz
Va	340	m/s
t_0	$220 \cdot 10^{-6}$	s

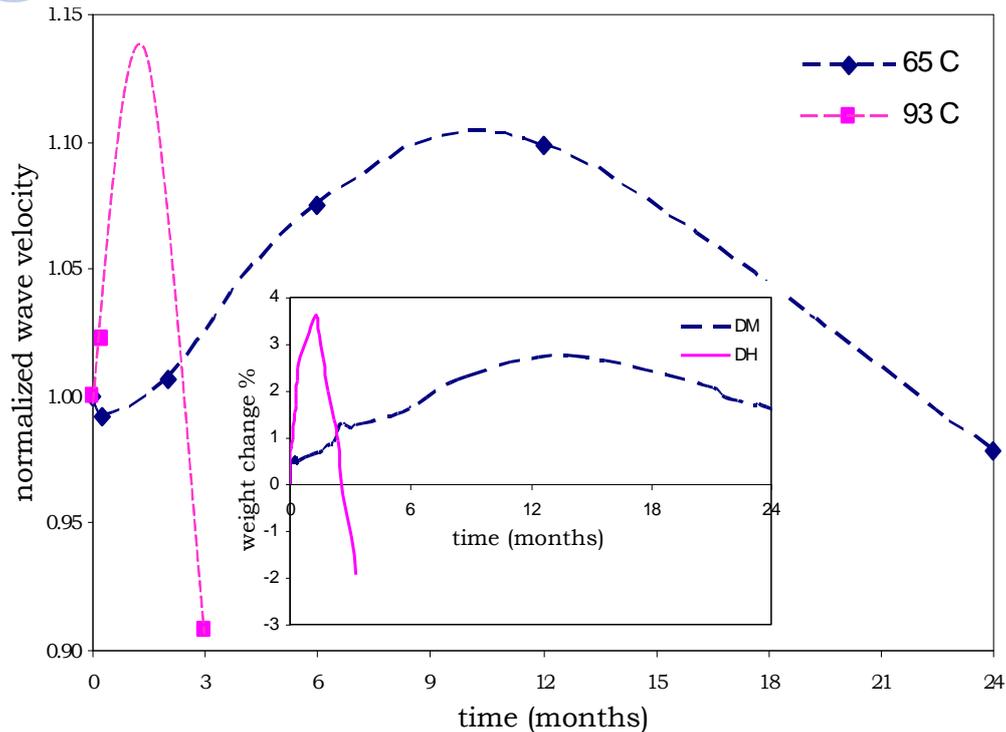


Figure 7 Normalized wave velocity through material type D with respect to time of immersion. Normalization is against the dry sample at time $t=0$. In the inset figure the weight change for the same material immersed in water at 65°C noted as DM and 93°C noted as DH.

For each sample tested the average value from five point measurements was taken. The measurements were performed directly on the computer screen, using the digital oscilloscope capabilities of the Gauge Analog to Digital (A/D) card available. The normalization of values as plotted on the graph is done against the wave velocity measured for the dry specimen. Inset in Figure 7 is the result of water absorption for the same material at the given temperatures.

A similarity between the water absorption curves and the wave velocity measured was observed and plotted in Figure 7. The material response as a result of the immersion in different water temperatures with respect to time is evident. At 93°C after just 1 week immersion a significant increase is found. In the water absorption plot, specimens exposed at 93°C show a higher peak than those exposed at 65°C . This has not been observed in the measurements taken for wave velocity. But this can probably be attributed to the fact that measurement of peak is after 1 week only of immersion. In the weight change plot the peak is observed after about 4 weeks. The response at 65°C is slower as expected. The very interesting issue here is that the degradation process evident from the mass reduction measured during water diffusion experiments is also evident here. The peak wave velocity for exposure at 65°C is at about 11 months, compared to about 13 months for the peak in water absorption. Since thickness changes are excluded by the method used for velocity measurements, changes observed must be attributed to the state of the material. So, this method can be used to evaluate the residual condition of the material.

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.

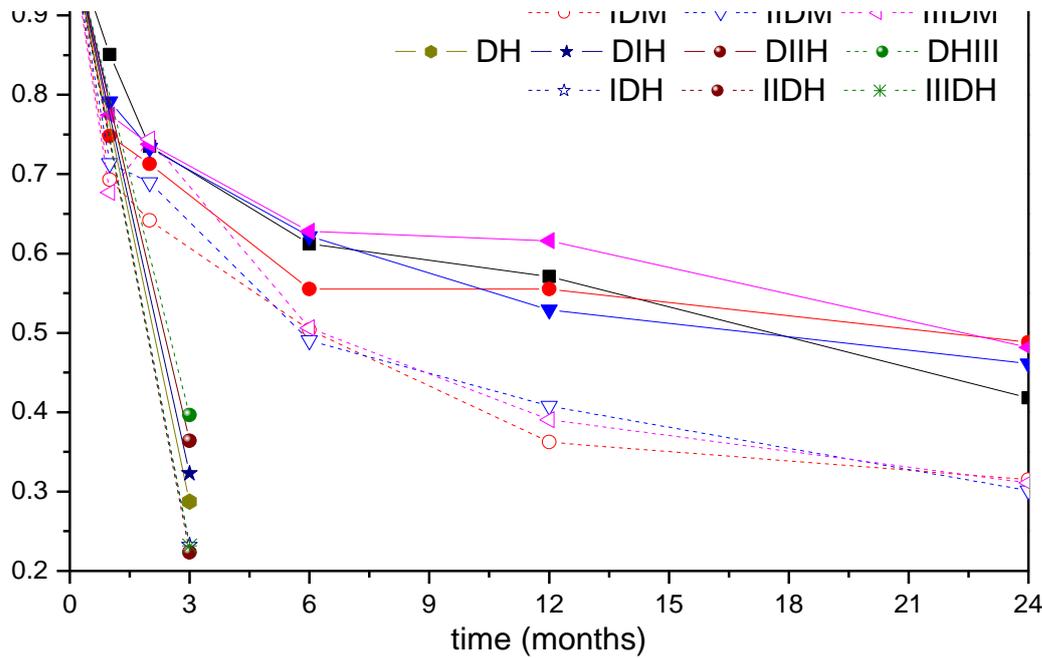


Figure 8 Normalized compressive strength for specimens immersed in water at 65° C marked M and 93° C marked H, with respect to time. Specimens with dashed lines correspond to results obtained for specimens impacted after water immersion. The roman numerals I, II and III relate to the impact level 2.5, 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, 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. 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 experimental work should be directed towards this scope in order to link these two mechanisms and their effect on the residual strength.

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