Low velocity impact on polymer composite plates in contact with water

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ABSTRACT

In this study, composite materials were tested in two different environments to determine the role of Fluid Structure Interaction with composites under a low velocity impact. This was done using a low velocity impact machine and polymer composite plates. The composite is made of laminated symmetrical plain weave E-glass fabrics. The test area of the composite plates is 30.5 cm by 30.5 cm with clamped boundary conditions. The testing was done using a drop weight system to impact the center of the test area. One testing was performed with composite plates in air, called dry impact. The other testing was conducted while composite plates were submerged in water, called wet impact. A Plexiglas box in conjunction with the impact machine was used to keep the top of the composite sample dry while it was submerged in an anechoic water tank, so called water-backed air impact. Output from the tests was recorded using strain gauges and a force impact sensor. The results show that an added mass effect from the water plays a large role in the Fluid Structure Interaction with composites due to the similar densities of water and the composites. The wet impact results in a larger impact force and damage than the dry impact under the same impact condition, i.e., the same impact mass and drop height.

1. INTRODUCTION

Composites are becoming more and more important in today's world. They have been popular in the aircraft industry for many years, and are currently attempting to make their way into the maritime industry as well. The application of these composites to the marine military environment is very appealing because of the high corrosion resistance offered by the composite. Another main reason for the use of composites is the very high strength to weight ratio. Similar composites have already made their way into the military marine environment. The U.S. Navy's DDG-1000 Zumwalt class destroyer has a superstructure made almost completely of composite materials. The use of composites on naval ships is gaining ground because they allow for lighter, faster, and corrosion free ships [1]. Other marine military applications include the use of composites to build ship's rudders. Composite rudders can be shaped and built from a mold which allows for a much lower cost than a steel rudder of the same design, while having similar strength properties [2]. The U.S. Navy has also looked into composite applications to rudders, propellers, stairwells, handrails, valves, and armors [3]. The downside to using composite materials for ship building and shipboard applications is the cost of construction and the cost of training for construction. It is estimated that ships made of composites can cost up to 20% more than a ship made of steel. However, the higher construction cost can be compensated by the lower maintenance and operation cost. It has been estimated that the cost of corrosion and corrosion related maintenance cost the U.S. Navy approximately $22 billion annually [4].

Fluid Structure Interaction (FSI) is very important in the application of composites to the marine environment. There is no FSI issue with using composites on parts of the ship that are above the water line because they are not in contact with water. However, a problem does arise when the composite is used in a place where a fluid such as water can interact with the composite. Especially, polymer composites have densities similar to that of water, as opposed to steel which has a much greater density than the water density. The similar magnitudes of densities play a larger role in FSI. The low velocity impact in water can be critical to the transient dynamic response of the composite. The added mass effect of the water causes a large amount of stress and strain on the composite that it would not encounter in air. This causes the composite to fail in water more rapidly. This problem is much less likely to occur in steel because there is much less of an added mass effect of the water because the density of steel is so large compared to water.

The objective of this study is to further the previous study of FSI and its effects on composite materials. Recently, experiments have been conducted to study the FSI on their respective composite samples [5–6]. In the research, FSI was studied under three different testing conditions. The first testing was a dry impact in air. There is no water contact in this case. This is the air-backed dry impact, or simply dry impact. The second and third cases had impacts while submerged in water. Both cases had the top surfaces of test plates, where impacted, in contact with water, but the bottom surfaces were different. The second case had a dry bottom surface, i.e., no water contact, which is called the air-backed wet impact. The third case had a wet bottom surface, i.e., in contact with water, called the water-backed wet impact. The second and third loading conditions represented impact on the ship hulls from the water side, which may be floating ice and sea animal impact on ship hulls. The three cases mentioned above are shown in Fig. 1(a) through (c). On the other hand, this study will continue that research for different loading condition such that the impact side is dry while the opposite side is wet, which is called the water-back dry impact as sketched in Fig. 1(d). This case is to simulate an impact from the inside of a composite hull such as ship-board equipments and sailors. In this paper, the two impacts are simply called dry and wet impacts, respectively.

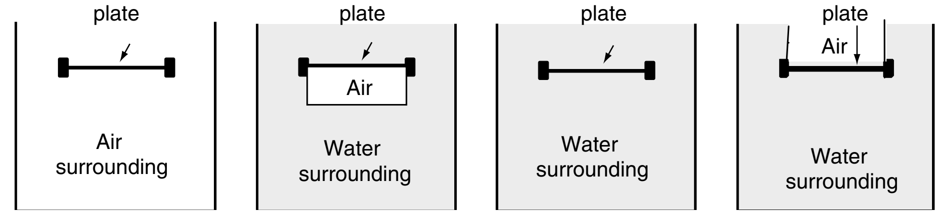

Figure 1 Comparison of different impact conditions with impact on the top side of composite plate: (a) air-backed dry impact (or simply dry impact), (b) air-backed wet impact, (c) water-backed wet impact, (d) water-backed dry impact.

2. EXPERIMENTAL METHODS

2.1. MATERIALS

There are two main materials used to form the composite and there are many other materials used as tools to accomplish the production. The two most important materials for the composite composition are the resin and the E-Glass woven fabrics. This section discusses about the material properties of the resin and the E-glass woven fabrics, as well as the other materials required to complete the process and how they are used.

The composite was made using a woven fiberglass cloth known as a 6 ounce E-Glass as shown Fig. 2. These types of woven fiberglass cloths are very common for marine composite construction and repair. The woven cloth was chosen for its uniformity and because of the fact that it is lightweight and is very common in small boat building. If this E-Glass is paired with the correct resin, it can maintain a high corrosion resistance and provide a water proof layer [7].

The resin chosen for this composite fabrication was a Vinyl Ester Resin known as Derakane 510A. As stated above, a smart choice of resin could improve the qualities of a composite material. This particular resin improves corrosion resistance and also has certain fire retardant properties which make it perfect for shipboard use as well as other marine applications. The method used for hardening of the resin is known as clear casting. Clear casting is accomplished by allowing the resin to cure at room temperature for 24 hours and then another 2 hours at a temperature of 120 degrees Celsius. The strength properties of the resin for clear casting are shown in Table 1 [8].

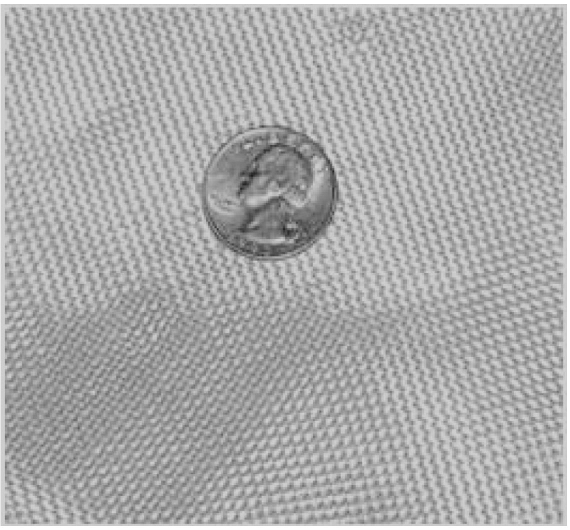

Figure 2 6 ounce E-Glass weave.

Table 1 Strength properties for clear casting of vinyl ester resin [8].

Property of Clear Casting at 25°C (75°F)	Value (SI)	Value (US)
Tensile Strength	86 MPa	12,300 psi
Tensile Modulus	3400 MPa	490 kpsi
Flexural Strength	150 MPa	21,700 psi
Flexural Modulus	3600 MPa	520 si

There are three main hardening agents used for the fabrication process of the composite sample. Two of them are always required and the third is only required if a faster cure time is desired. The first hardening agent is the Methyl Ethyl Ketone Peroxide (MEKP). The second is Cobalt Naphthenate 6%, and the third is Dimethylaniline (DMA). MEKP is a basic catalyst which is usually added to polyester and vinyl resins. The addition of the MEKP causes a chemical reaction and heat generation which begins the hardening process in the resin. The second hardening agent is a deep blue purple liquid known as Cobalt Naphthenate 6%. Since this is a cobalt solution, its main role in the process is as an oil drying agent, but it also adds some waterproofing to the composite material as well. It is used as a crosslinking catalyst during the hardening process of the fabrication and this particular catalyst is an oxidation dryer with the strongest drying activity. The Napthlenic acid is added to make the cobalt more oil soluble. Dimethylaniline is the third hardening agent used in the process. The DMA serves as a promoter to the curing of the resin during the fabrication of the composite. This hardening agent is used for a more rapid curing process of the resin and is only used when fast curing times are desired.

2.2. COMPOSITE CONSTRUCTION METHOD

The process used to fabricate the composite samples used in this research is known as Vacuum Assisted Resin Transfer Molding (VARTM). VARTM is a very common method used in low pressure composite molding production. This is done by constructing an air tight vacuum around the materials used to make the composite. A vacuum pump is used to expel all the air from the preform assembly of the composite. Once there is an air tight seal, the resin is pulled through the preform of e-glass weave from the bottom to the top. A distribution medium is used to accelerate the processing time of the VARTM and it also ensures total coverage of the preform [9].

There are many different materials needed to complete the VARTM process. A list of all the materials used is shown below; E-Glass, Vinyl Ester Resin, Airtech Resinflow 75 Distribution Medium, Teflon, Peel Ply, Stretchlon 200 1.5 Vacuum Bag Film, AT-200Y Sealant Tape, Plastic Tubing, and Resin Trap.

The distribution medium is a green mesh fabric that is used to evenly distribute the resin throughout the whole preform. The Teflon is used to prevent the resin from adhering to the glass which is used at the base of the set up. Peel ply is a nylon material that is placed between the distribution media and the E-glass weave for easy release after curing. The vacuum bag is made from a Polyolefin material and is used to cover the preform and adhere to the sealant tape to achieve a vacuum around the preform. The sealant tape is to hold down the vacuum bag. The plastic tubing is used to transfer the resin through the preform from the resin reservoir to the resin trap. Finally, the resin trap is used to collect any waste resin during the VARTM process.

The resin preparation is the most important part of the process. An incorrect mixture of resin and hardening agents will make the difference between a good sample and one that is not usable. The first step to the resin preparation is to pour the desired amount of resin into your resin bucket. For the composite samples made for this research, one liter of the resin was sufficient for the process. Once the desired amount of resin is in the bucket, it is important to measure out the exact amounts of hardening agents needed for the desired curing time. Table 2 shows the amount of each hardening agent needed for the desired cure time at the room temperature. The values given are in parts per hundred resin molding compound (phr).

Table 2 Typical Gel Times using MEKP, DMA, and Cobalt [8].

Gel Times at 25°C (75°F)	MEKP (phr)	Cobalt (phr)	DMA (phr)
15 +/− 5 minutes	2.00	0.30	0.05
30 +/− 10 minutes	1.25	0.30	—
50 +/− 15 minutes	1.00	0.20	—

It is important to note that the gel times of this mixture will vary based on the surrounding environment. This is why it is so difficult and important to come up with a mixture that works well and stick to that mixture. The gel times for approximately 50 minutes was used in this research. Furthermore, 1 drop of DMA from a 3 mL syringe was used as well. It was found that using a 30 minute gel time mixture made it difficult for the resin transfer process to completely cover the preform. When using the 50 minute gel time, sometimes the resin was unable to set and the vacuum began to pull resin from the preform after the transfer was stopped. The DMA was added to help the resin set faster into the preform.

Another important part of the mixture process is how to actually mix the components. It was discovered during the first couple trials that the MEKP and Cobalt react to one another if they are added at the same time. To fix this problem, the MEKP was added first and thoroughly stirred into the resin before the Cobalt was added. In addition, once all the required components are added to the resin, it is important to keep mixing it on and off for approximately 15 minutes to allow for a proper mixture. Once the air bubbles stop forming in the mixture, it is ready to go.

2.3. POST FABRICATION METHODS AND REQUIREMENTS

The curing process is relatively simple, but it takes some time. After the resin transfer is complete, the tube used on the resin side of the preform is clamped to keep the vacuum seal intact. Now the vacuum must stay on for 8 hours during the initial cure period. Then the composite must cure another 24 hours with the vacuum off. Both of these cure processes take place at room temperature. The last step in the cure process is to cure the composite for another 6 hours at an elevated temperature of 70°C.

Once the curing is complete, the samples will need to be cut down in size. The overall size of the composite must be able to fit into the impact machine, but there is no correct exact size. The only important part of the sizing is the 30.48 cm by 30.48 cm test area. To keep the test area consistent, a grid of 7.62 cm by 7.62 cm squares were drawn onto the sample. This allowed for a consistent placement of the strain gages on each composite sample.

The strain gages were an important part of this research. They gave great insight into the mechanics of what is actually occurring during the testing of each sample. They showed a quantitative difference between each of the testing environments which allowed for a better analysis of the results. The strain gage rosette measures the strain in the composite during the testing. The strain is measured in three different directions per strain gage. The measurement of strain in three different directions is important because they allow us to determine strains in any orientation.

This strain gages used for this research were from Vishay Precision Group. Each square composite sample had four strain gages placed throughout the surface of the sample. Figure 3 shows the strain gage rosette configuration. Figure 4 shows the arrangement of strain gages used for the square composites.

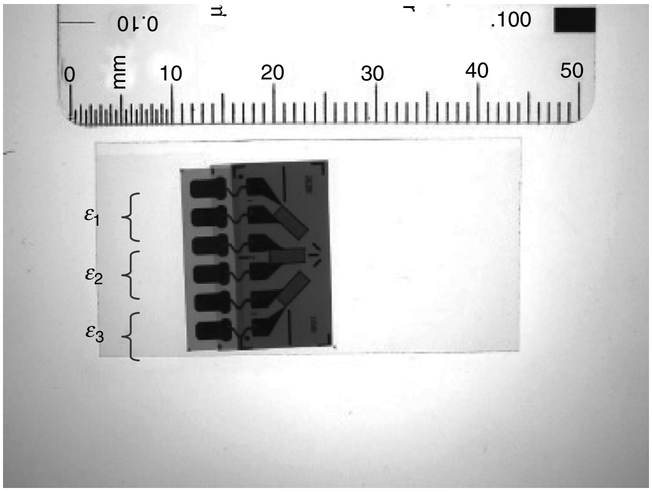

Figure 3 Square strain gage rosette showing $\varepsilon_{1,}$ $\varepsilon_{2,}$ ε_3.

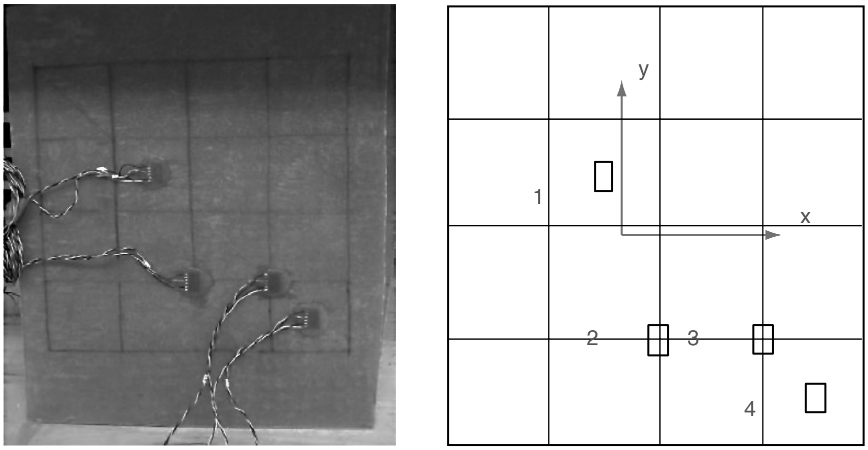

Figure 4 Strain Gage layout on composite samples.

2.4. TEST EQUIPMENT

The only piece of test equipment used in this research was a drop weight test machine designed and used in previous research [10]. The impact machine was used for testing composites used in this research. The impact machine is a simple drop weight system that allows the user to drop a desired amount of weight from a desired height. Figure 5 shows the apparatus. The test machine gets lowered into the anechoic water tank during testing to give the best stability possible. Both dry and wet impact tests are done in the tank. For the dry testing, water is drained from the tank while water is retained for the wet impact testing.

The drop weight apparatus has two main components. The first is a trigger that starts the data acquisition process at the same height for each drop. The second component is at the tip of the impactor itself. The impactor has a built in force sensor and for each drop the force data is acquired using a specifically designed LabVIEW program. The LabVIEW program

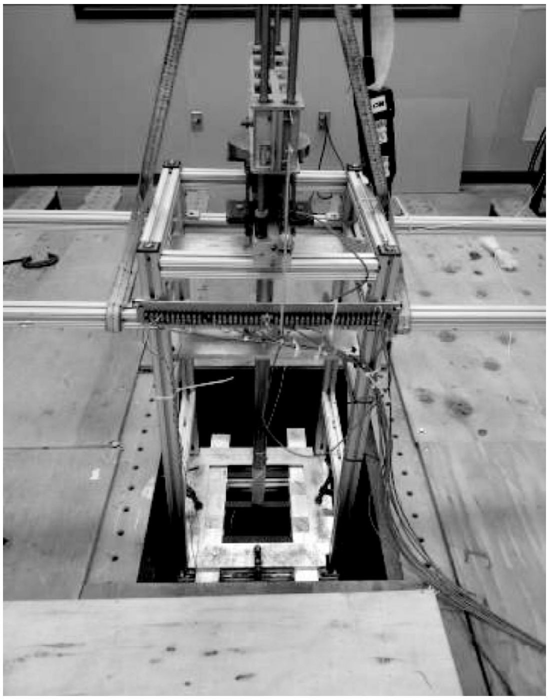

Figure 5 Impact test machine.

recorded 1000 samples of data over a 100 millisecond period of time. This was consistent throughout the testing of both composite samples.

2.5. TEST METHODS

A primary goal of this study was to determine the amount of force that initially caused damage to the composite sample. This allowed for the data before and after the damage to be analyzed and compared/contrasted. The damage was attempted to be detected visually after each drop. The initial damage is considered to be at the time the first delamination of the composite is visible. This testing gives great insight into when damage can be expected to occur and how that damage will affect the composite after more impacts are experienced.

The first test done was the dry impact test. This was done to use as a baseline test so that the differences in damage, force, and strain data could be compared between the two test environments. This test was repeated 3 times to show consistency in the data being obtained and determine its reliability. The results from the dry testing are shown in the next section.

The next test was done in the water environment. A Plexiglas box was fabricated to fit over the top of the composite sample in order to keep the top of it dry while being lowered into the water filled tank. The goal of this testing was to determine the FSI with the composite during impact testing with a water backed, dry top test environment throughout a set of different drop heights. For this testing, it was chosen to use the larger weight of 10.8 kg. The weights were dropped from a starting height of 7.62 cm (3 in) and ended with a drop height of 76.20 cm (30 in). These drop heights were chosen because it is known that from 7.62 cm (3 in) no damage will incur and at 76.20 cm (30 in) the impact sensor approaches the maximum force recording levels [6]. All of the drop heights are shown in Table 3.

Table 3 Drop heights used in the tests.

Drop Number	Height (in)	Height (cm)
1	3	7.62
2	4	10.16
3	5	12.7
4	6	15.24
5	8	20.32
6	10	25.4
7	12	30.48
8	14	35.56
9	16	40.64
10	18	45.72
11	20	50.8
12	22	55.88
13	24	60.96
14	26	66.04
15	28	71.12
16	30	76.20

3. RESULTS AND DISCUSSION

In order to determine the FSI effects on damage initiation and growth as well as their resulting dynamic responses of composite structures, an important aspect of this study is keeping track of the damage incurred by the composite so that we can determine when the composite fails and how this failure affects the composite's response to further impacts. The damage done to the composites can be hard to detect. Composite materials have distinct modes of failure depending on materials used to construct the composite. In laminated composites, delamination of the back side of the composite, where it is in tension after impact, is the most common place for the damage to occur. The most common causes of delamination are tensile and compressive fatigue loading and impact loading [11]. In recent literature there are many great reviews of published papers on the failure modes, and damage identification and significance which can be used as general references [12–15]. Small areas of delamination are capable of reducing the compression strength of composite materials by 50 percent. For this reason, after each impact on the composite sample, the backside was examined for any evidence of damage. All damages observed during this testing were delamination of the composites as expected.

For all the samples tested, measurement was conducted to track the visible damage of delamination in the samples. Delamination occurred at a significantly lower drop height during the submerged testing versus the dry testing. Figure 6 shows an example of the delamination occurring at the underside of the impact zone.

After a total of six tests, three in water and three in air, the data proved to be consistent from one sample to another. Figure 7 shows the consistency of the data for two of the samples tested under the same impact condition.

There is plenty of information available from the force data that is collected during the testing. First, the impact force experienced in a water submerged environment is higher than the force in a dry environment for the same drop height before damage occurs. Figure 8 shows that the wet impact force for a 15.24 cm drop height has approximately a 350 N higher

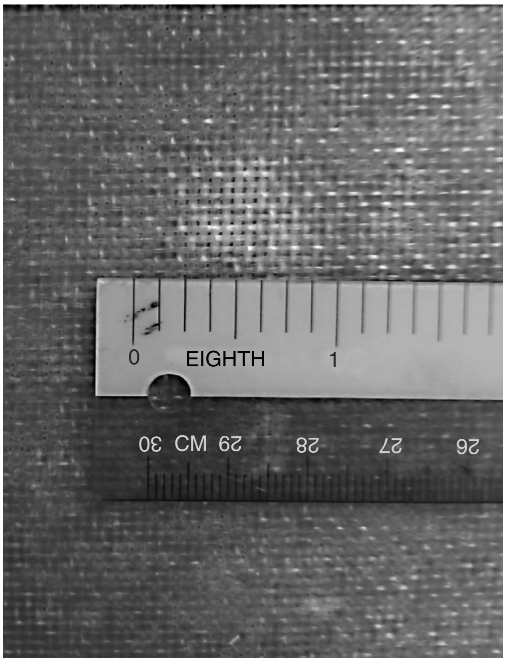

Figure 6 Close up of delamination under impact zone of wet sample.

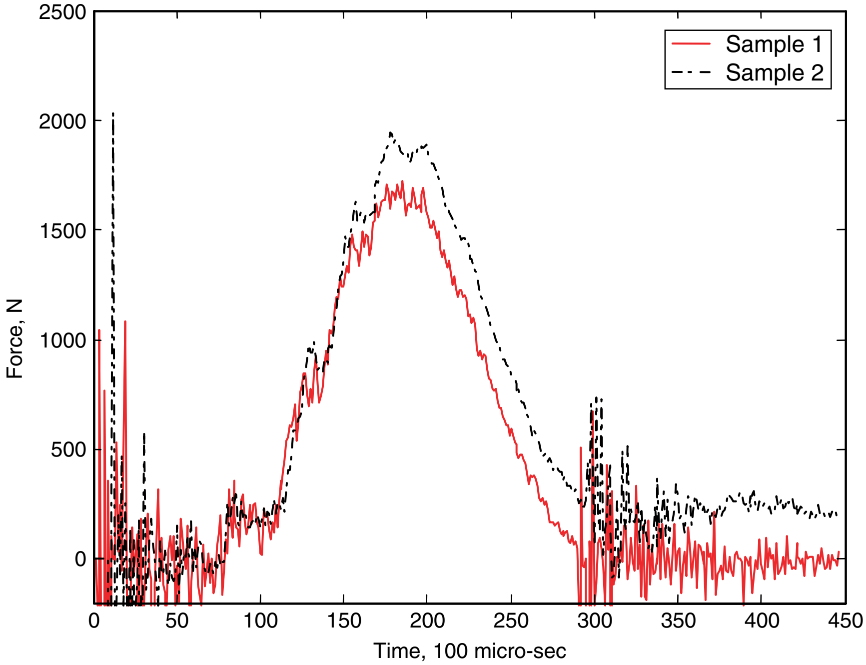

Figure 7 Force comparison between two samples with 30.48 cm drop height dry testing.

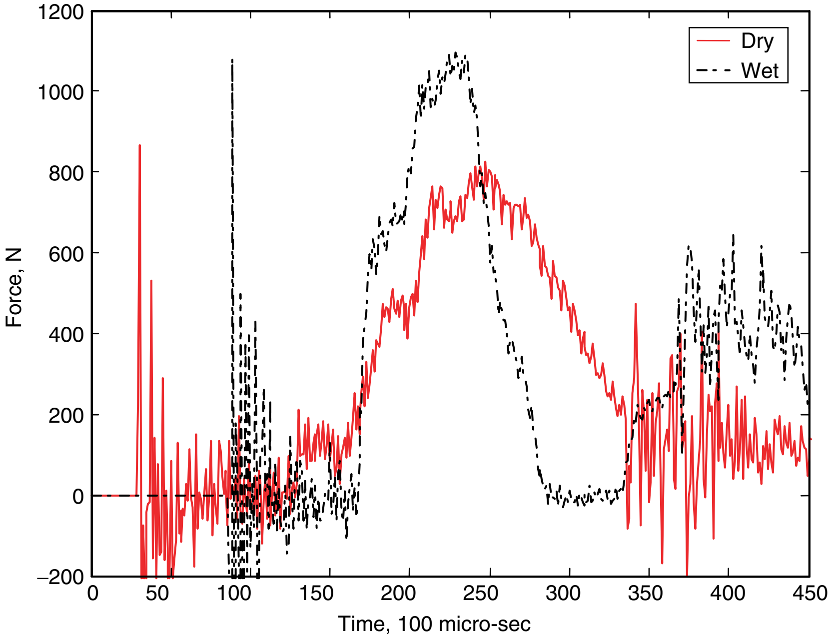

Figure 8 Impact force comparison between wet and dry testing with drop height of 15.24 cm.

than the dry impact force. At this drop height, the wet impact began to initiate delamination at the underside of the sample while there was no sign of delamination for the dry impact.

The fact that this drop height is the first sign of delamination is significant, because after this point, the impact force for the wet samples will no longer be greater than the dry impact force. As the drop heights increase, the dry impact force becomes greater than the wet impact force. This is because the damage induced from the wet impact results in a reduced stiffness of the structure, eventually leading to reduction in the impact force. This fact that the change in impact force occurs after damage is significant because even if no visible damage is detectable, the force data can be analyzed to determine m any internal damage has occurred to the composite sample.

In every case, the damage occurred earlier in the wet sample versus the dry sample. In all cases for the wet impact test, a drop height of 15.24 cm resulted in initial damages. However, in all cases for the dry impact test, initial damages occurred between drop heights of 55.88 cm and 71.12 cm. Thus, the dry impact produced damages at approximately four to five times greater impact heights than the wet impact. In other words, the FSI induced damage at much lower impact height or impact energy since the same impact mass was used for both dry and wet tests. Figure 9 shows the delamination damage size as a function of drop height for both the wet and dry samples. The plot shows that delamination under the wet impact grew in a step-like function rather than a continuous function as the impact height increased. A similar but less distinct behavior can be also observed for the delamination growth under dry impact.

Figure 10 compares impact forces at 20.32 cm, just after damage occurred in the wet sample but no damage for the dry sample. Their impact force magnitudes are almost identical. The damaged sample experienced a loss of stiffness and therefore the impact force decreased. Since these low drop heights have caused damage in the wet samples but not for the dry samples, the impact force for the dry samples becomes larger than the wet samples until

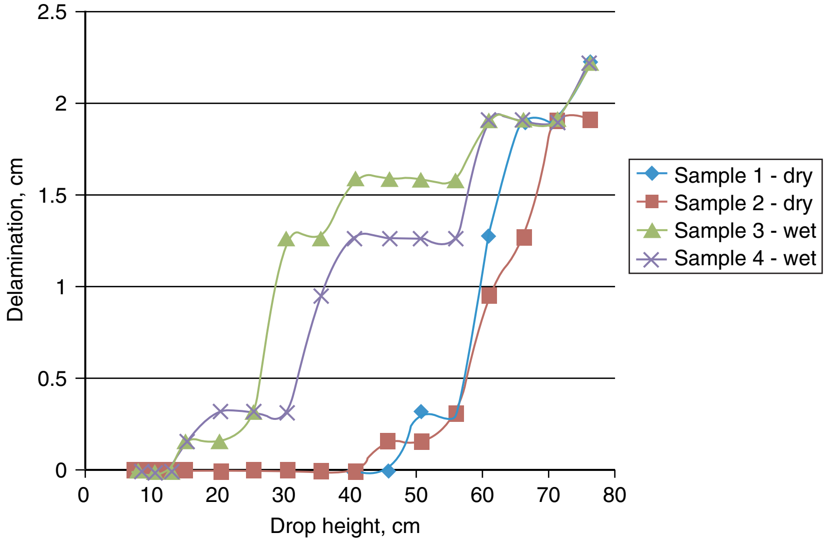

Figure 9 Damage size as a function of drop height for both wet and dry samples.

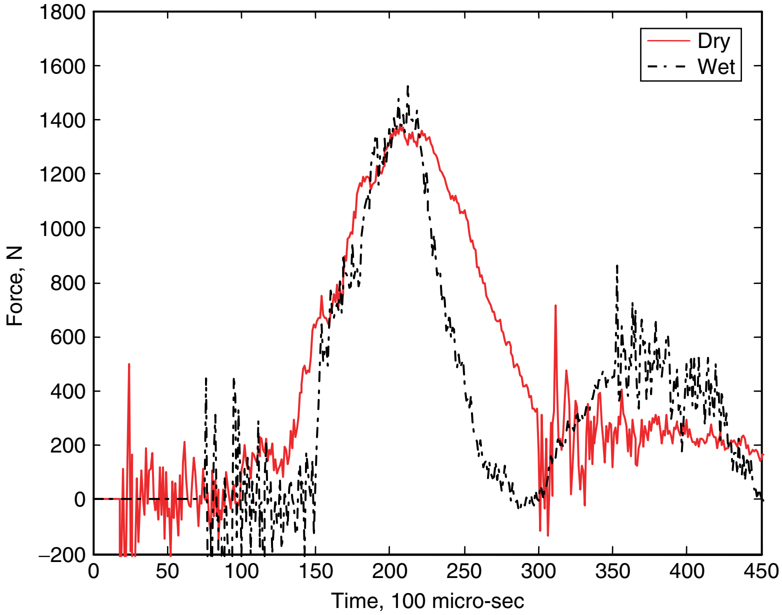

Figure 10 Impact force comparison showing same impact force due to damage in wet sample with a drop height of 20.32 cm.

damage is incurred for the dry samples. Figure 11 shows how the dry impact force is now much larger than the wet impact force because the dry samples still do not have any damage.

During the testing of the dry samples, visual damage was not noticed until about the 66.04 cm drop heights. Hence, if the wet vs. dry impact forces are compared at that drop height, it is expected to see the impact forces to be similar again because they have both

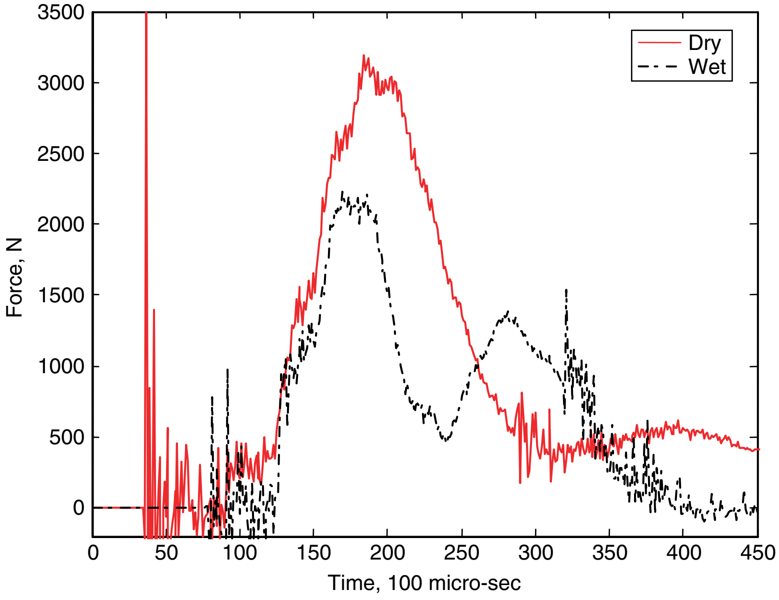

Figure 11 Impact force comparison showing the dry force larger than the wet force at 50.80 cm drop height.

sustained damage. Figure 12 shows the comparison at a drop height of 71.12 cm and the results are what is expected. At that impact height, the delamination size was almost the same between the dry and wet impacts as shown in Fig. 9, which shows the average delamination

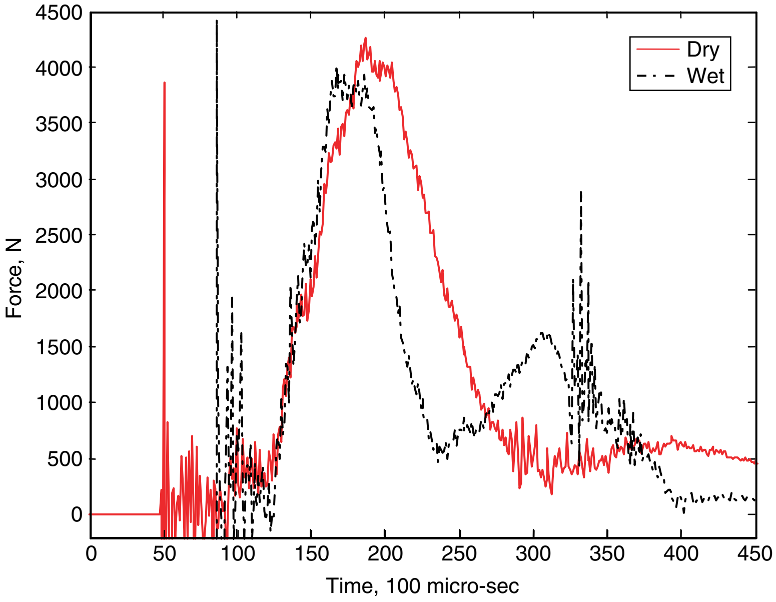

Figure 12 Impact force comparison showing impact force magnitudes becoming similar again due to damage sustained in both samples for drop height of 71.12 cm.

growth slope (i.e. change of damage size divided by the change of the impact height) is higher for the dry impact than the wet impact even though the former started the damage initiation at a larger impact height.

The strain data gathered can help determine what is occurring locally in each sample and it gives a great insight into the fluid structure interaction occurring at each impact height. Being able to compare the dry versus wet strain data at the exact same drop height and weight combination is very important in determining how the fluid structure interaction deforms each composite sample. It is expected that the deformation in the wet samples would be higher at each strain gage throughout the sample than that of its dry counterpart. Strain data for the x and y directions were recorded at the four different strain gages on each sample as shown in Fig. 4.

Figures 13 through 17 show the strain results for all four strain gages along the x- or y-direction at the 15.24 cm drop height. If the strains in the x- and y-axis are similar, only one strain component is plotted. As can be seen at each strain gage, the strain magnitude of the wet composite sample is greater than that of the dry sample in all locations. This is because the wet impact produced a greater impact force than the dry impact before damage occurs. The differences in strain responses between the wet and dry impacts vary from the strain gage location to location. While the difference in strain magnitude as well as its shape in the strain-time history is smaller at strain gage #1 (i.e., near the center of the composite plate), it is much larger at the gage #4 (i.e., near the clamped boundary edges). This result suggests that the FSI effect is not uniform over the clamped plate and is more significant near the clamped boundary. The latter fact can be further confirmed by comparing the x- and y-strain at the gage location #2 (i.e., Fig. 14 vs. Fig. 15). The y-strain is much more different at that location because that component is more affected by the clamped boundary.

Once the damage occurs only for the wet sample, the impact force at the same impact height is greater for the dry impact, which can result in a larger strain for the dry impact. On the other hand, the wet sample has a reduced stiffness with the damage, which can

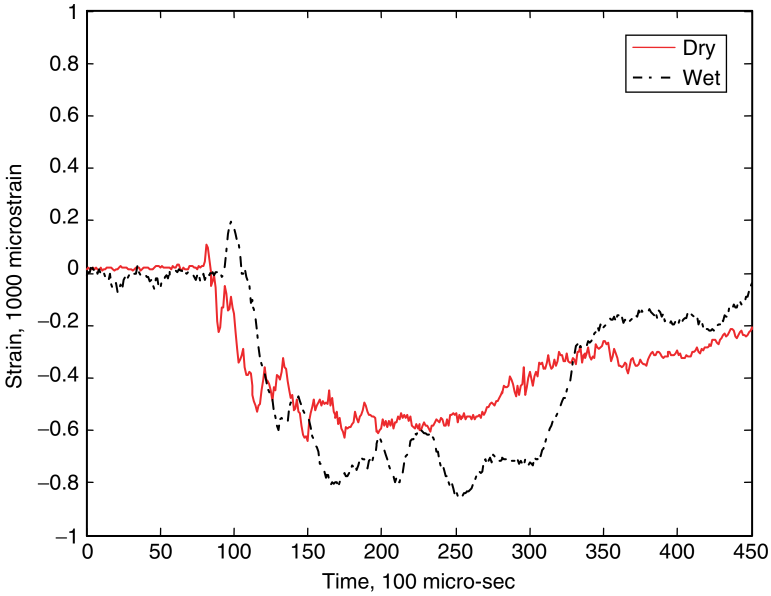

Figure 13 Strain along x-direction at strain gage #1 with impact height 15.24 cm.

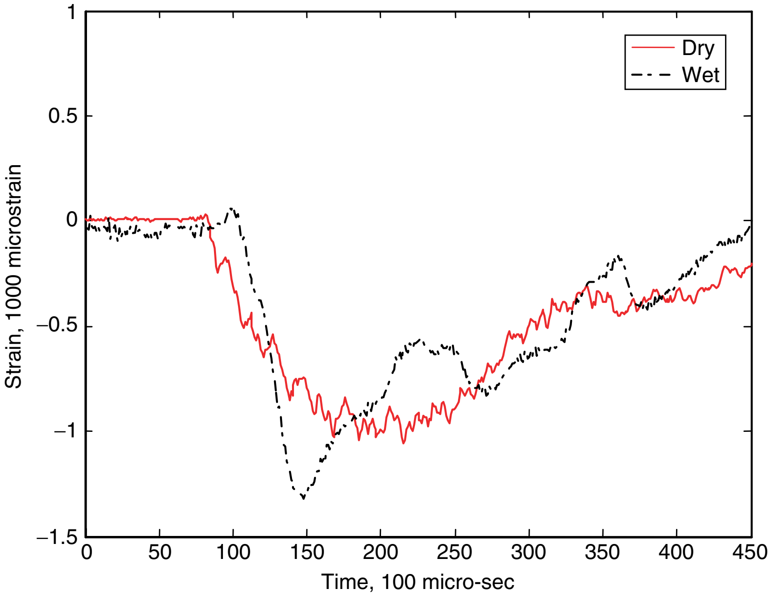

Figure 14 Strain along x-direction at strain gage #2 with impact height 15.24 cm.

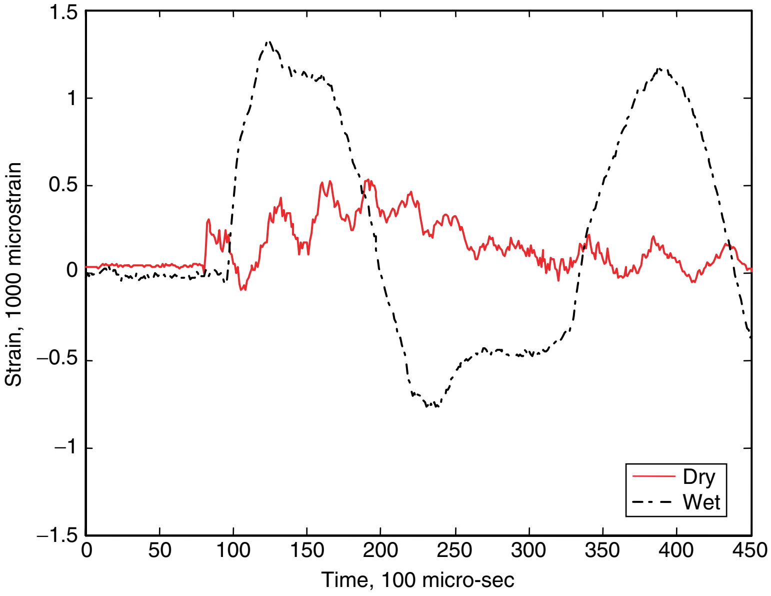

Figure 15 Strain along y-direction at strain gage #2 with impact height of 15.24 cm.

result in a larger strain for the wet impact. As a result, the two facts act against each other. However, the reduced stiffness effect with the wet impact is larger on the strain response than the larger impact force with the dry impact. Hence, the wet impact results in always

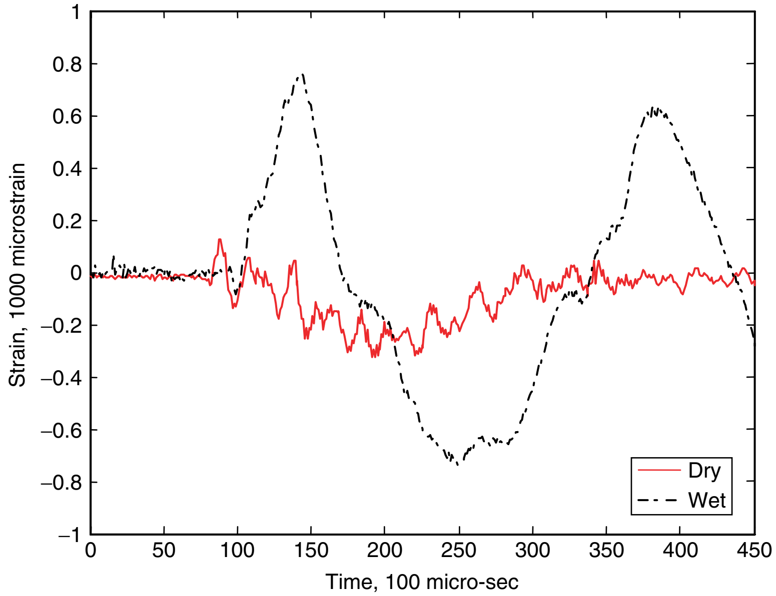

Figure 16 Strain along x-direction at strain gage #3 with impact height 15.24 cm.

larger strains regardless there is damage or not. Besides, the strain-time history plots change in terms of their frequencies and shapes along with damage. Figures 18 through 22 show the strain plots after both wet and dry impact has a similar size of damage at the drop height of 76.20 cm. These figures can be compared to Figs. 13 through 17,

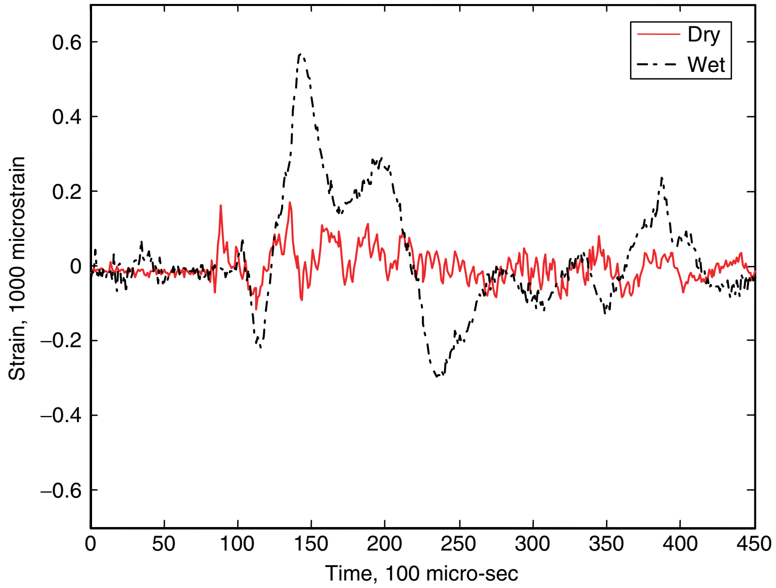

Figure 17 Strain along y-direction at strain gage #4 impact height 15.24 cm.

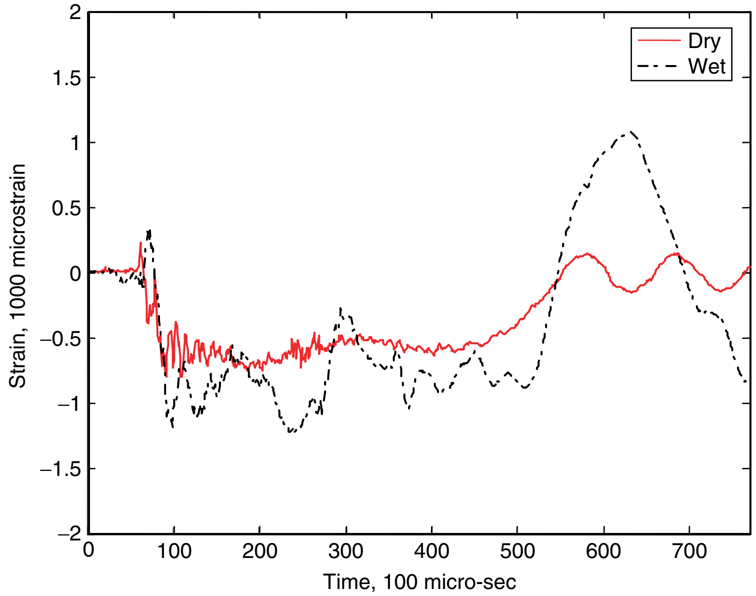

Figure 18 Strain along x-direction at strain gage #1 with impact height of 76.20 cm.

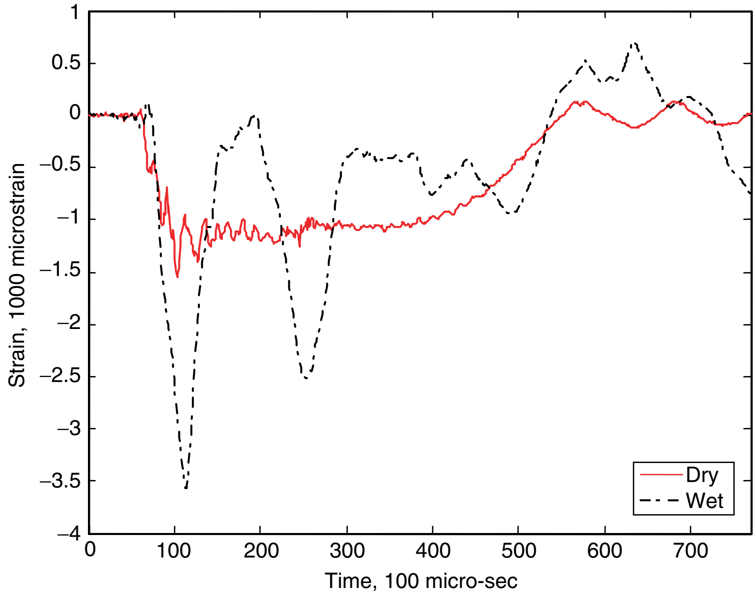

Figure 19 Strain along x-direction at strain gage #2 with impact height of 76.20 cm.

respectively. At the gage location #1, the strain responses of both wet and dry impacts do not change much between the two impact heights except for the magnitude as compared in Figs. 13 and 18. The gage #2 shows a big difference between the dry and wet responses as the impact height increases. The strain with wet impact is much greater than the dry

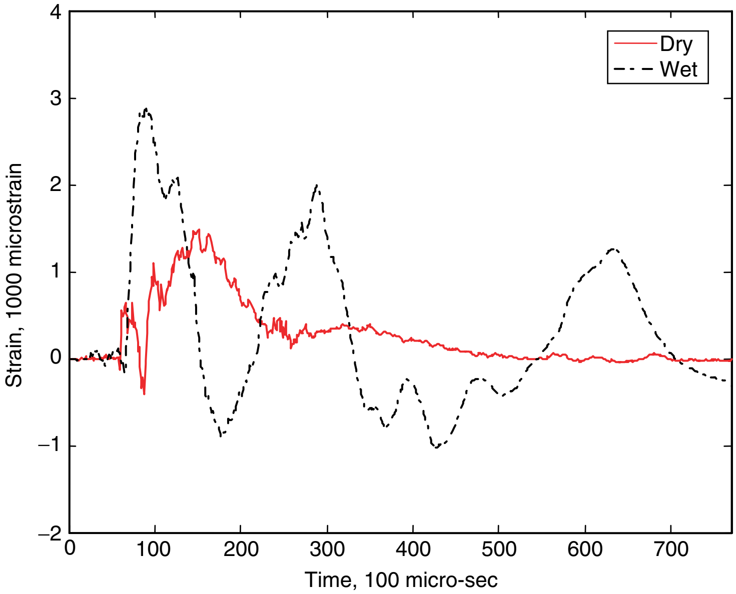

Figure 20 Strain along y-direction at strain gage #2 with impact height of 76.20 cm.

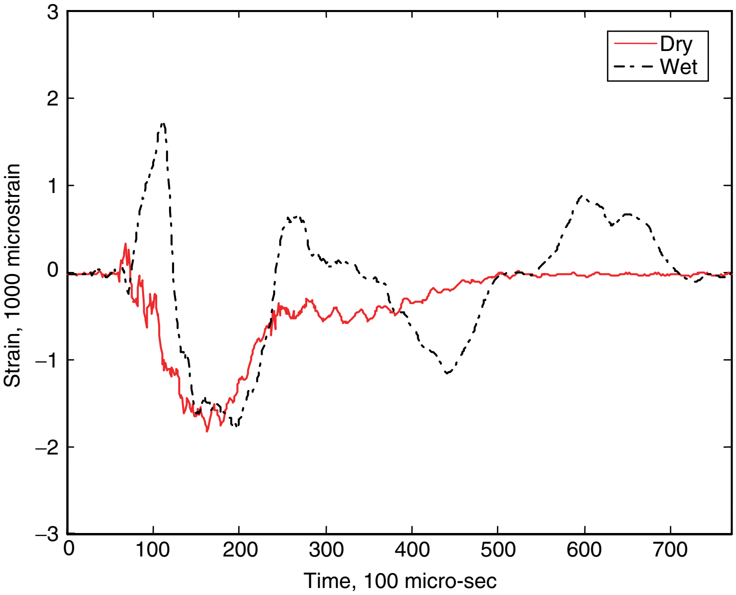

Figure 21 Strain along x-direction at strain gage #3 with impact height of 76.20 cm.

impact at the drop height of 76.20 cm. On the other hand, the magnitude of the compressive strains becomes similar between the wet and dry impacts at the impact height of 76.20 cm. The change in the strain responses between the two different drop heights is the severest at the gage location #4 as shown in Figs. 17 and 22.

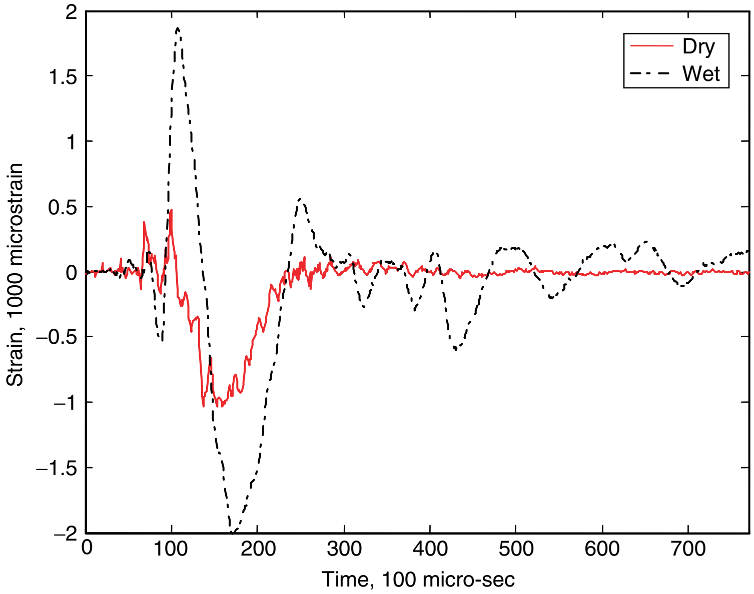

Figure 22 Strain along y-direction at strain gage #4 with impact height of 76.20 cm.

4. CONCLUSION

This study was undertaken to pursue a better understanding of FSI effects on composite materials made from a woven fabric E-glass cloth. In order to investigate the dynamic response of the composite materials with FSI effects under impact loading, two impact conditions were considered. The conditions were dry impact and water-backed dry impact.

Since the composite materials have a very similar density to water, the FSI effects are very significant on the impact force and dynamic response of the plates. Due to the added mass effect of the water, the wet impact force is larger than the dry impact force before any damage occurs in both cases. As a result, the wet impact is more detrimental to the composite material than the dry impact. It is possible to show a quantitative explanation of the added mass effect by calculating Added Mass Factor. This can be seen in the analysis done by Ref. [5]. However, it was found that the added mass effect was not uniform over the whole surface of the plate. This was discovered through the comparison of strain gage responses between the dry and wet impacts at different locations. A location near to the clamped boundary shows a larger FSI effect.

In summary, the experimental results show that the dynamic response in a water environment is significantly different than in a dry environment. The impact force experience in water is larger than the force experience in air which leads to an earlier onset of damage. The strain deformations clearly show that a water environment will produce larger strains than an air environment. Neglecting the FSI effect in composite structures in contact with water would result in the non-conservative design and analysis leading to a pre-mature failure.

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