METHODOLOGY TO EVALUATE IMPACT DAMAGE ON FIBER REINFORCED COMPOSITE TUBES

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SUMMARY: Impact and static punch tests on fiberglass pipes were conducted. The test specimens were 15.24 cm (6 in) ID. fiberglass pipes, with thicknesses varying from 0.635 cm (¼ in) to 1.27 cm (½ in). These specimens were subjected to static punch tests with different punch sizes to determine critical mechanisms, acoustic emission signatures and surface indications of damage. Following the static tests, other pipes were damaged by a low velocity impact load using two different contact areas and, impact energies. The specimens were instrumented with AE broad band sensors and monitored with digital equipment during all the stages of the testing program in addition to thermal emissions monitoring for determination of damage progression. In addition, source location studies on fiber reinforced plastics using acoustic emission records are done. This paper will present the tests results, and describe the use of acoustic emission as a tool to determine impact damage severity in composite pipes..

KEYWORDS: Acoustic, fatigue, nondestructive evaluation, impact.

INTRODUCTION

Composite materials in general engineering applications are becoming more popular in a variety of applications. Offshore applications are one of the areas where the use of composite materials is being studied in detail. With this increasing popularity, the need for a better understanding of the behavior of layered materials is also augmented. One of the areas of interest is the behavior of fiber composites subjected to impact loading. None-visual methods of evaluation for determining damage extent and residual capacity are of great interest in the field. The difficulty, in providing an accurate evaluation of damage based on a purely visual inspection, is well known in the aerospace and industrial applications areas. In addition, the majority of pipe applications are of relatively long lengths, making this type of inspection lengthy and tedious. Since the effect of an impact is very localized, global methods for monitoring stiffness would fail to provide with a reliable indication. The desire of making these inspections while the lines are operational is another constraint found regularly. The need for a global inspection method that will provide with information on the impact capacity characteristics, residual strength and location of damage is evident.

Traditional parametric acoustic emission (AE) has been successfully used in the monitoring of in service pressure vessels and railroad tank cars among other applications. This type of non-destructive evaluation is based on a statistical approach to damage assessment where precise identification of factors is not precise or reliable. This is a versatile tool if used properly and with the knowledge of the limitations of parametric AE. The development of high fidelity broad band sensors and digital capturing equipment provide AE with a new methodology [1,2] based on mathematical wave propagation. This wave analysis based approach in addition to parametric AE will provide with a reliable tool that not only will identify the damage and its effect on the capacity but also the location where it happened. This paper presents the preliminary results of an experimental program designed to develop methodologies based on non-destructive evaluation (NDE) techniques for the monitoring and strength prediction in tubular composite members. A description of the specimen and its properties as well as the testing program and results are presented in this paper. Preliminary results from AE monitoring of static penetrations and low velocity impact tests are presented; in addition, preliminary results from AE source location methods are also presented. A more complete in depth analysis of the test results is in progress and will be presented elsewhere.

SPECIMEN DESCRIPTION

The specimens used in this program were fiber reinforced epoxy pipes made by the continuous winding process. The reinforcement was E-Glass with 60% content by volume and a winding angle of +/- 60 degrees. The proportions of fiber in the specimens were verified by chemically digesting the resin, with a deviation in the results of less than 5%. For this paper, the results of three sets of specimens are presented. The difference between the sets is the wall thickness of the pipes. The inside diameter of both sets is 15.11 cm (5.95 in) with a total length of 0.91 m (3 ft) each. To minimize the variability in fabrication typical in composite materials, specimens of the same thickness were obtained from a single longer pipe. Each one of the longer pipes were 4.27 m (14 ft) in length, in addition to the 0.91 m (3 ft) specimens used; shorter sections were obtained at regular intervals for the fiber content tests. Before the pressure testing, the specimens were reinforced by providing a tapered buildup at the ends. This was to avoid the premature failures, typical in composite materials, of the specimens to be pressurized after impact loading. The buildup was provided by means of additional winding of glass/carbon fibers that tapered from zero at 20.32 cm (8 in) from the end to a thicker profile at each end of the pipe.

EXPERIMENTAL PROGRAM

The program consisted in three phases of testing. The first test phase was a static punch series where three separate punch profiles were used. One profile was a round punch of 1.27 cm (½ in) of diameter and a spherical head. The other bearing surfaces were a rectangular narrow punch with dimensions 0.48 x 3.81 cm ($^{3}/_{16}$ x 1½ in), and a long one of 0.635 x 15.24 cm (¼ x 6 in). The static tests were to determine the AE signature of the failure mechanisms associated with each punch, in addition to the maximum load at failure. A picture of the setup for the static tests can be seen in Figure 1-A. The dynamic impact was performed with a pendulum setup. Figure 1-B shows the frame used for the impact testing along with the AE acquisition equipment. In order to maximize the use of each specimen, the pipes were damaged in two separate locations with two different impact profiles. Each impact was made at about 1/3 of the length of the pipe and the diametrically opposed locations and ends. After impact testing the pipes were subjected to internal pressure to determine the reserve leak/burst capacity. The initial tests were static to failure with cyclic tests to follow.

View A

View B

Figure 1 Setup for Static and Dynamic Punch Test

The seal system selected allowed for axial deformation of the specimen while maintaining a constant pressure. The acoustic emission system used in the test program consisted of two separate units and sensor types. Both resonant to 150 kHz and high fidelity broad band sensors were used to acquire AE data. The data acquisition systems used was by Physical Acoustics Inc (PAC). These were the Transportation Instrument for the resonant sensors and the Mistras-2000 for the digital information.

LOAD TESTS RESULTS

The results from the static punch tests on 6" ID specimens are shown in Table 1. As indicated before, three separate punch surfaces were used in the test. These surfaces are designated round, crease and large in the table. The specimen labels are H5, H15 and H20 to represent respectively the 0.33 cm (0.13 in), 0.94 cm (0.37 in) and 1.32 cm (0.52 in) specimens. Failure loads were determined as the loads where the deformation of the loading head increased without any increase in the measured load. The tests were repeated in separate areas of specimens to verify results.

Table 1 Static Punch Results

Specimen	**Thickness**	**Punch Dimensions**	**Max. Load**
H5	0.33 cm (0.13 in)	1.27 cm (½ in) round	2.22 kN (0.5 kip)
H5	0.33 cm (0.13 in)	0.635 x 3.81 cm(¼ x 1½ in)	3.56 kN (0.8 kip)
H15	0.94 cm (0.37 in)	1.27 cm (½ in) round	8.01 kN (1.8 kip)
H15	0.94 cm (0.37 in)	0.635 x 3.81 cm(¼ x 1½ in)	19.6 kN (4.4 kip)
H20	1.32 cm (0.52 in)	0.95 cm ($^3/_8$ in) round	17.8 kN (4.0 kip)

H20	1.32 cm (0.52 in)	0.635 x 6.35 cm (¼ x 2½ in)	37.8 kN (8.5 kip)
H20	1.32 cm (0.52 in)	0.635 x 10.2 cm (¼ x 4 in)	62.3 kN (14.0 kip)
H20	1.32 cm (0.52 in)	0.635 x 15.24 cm (¼ x 6 in)	84.55 kN (19.0 kip)

As expected, the damage mechanisms varied depending on the punch surface used. The damage associated with the round punch was initially of bearing type with matrix cracking and fiber breakage dominating the modes. The damage associated with the square punches was initially of matrix cracking but developed into a delamination mode and did not change during the subsequent loading stages. The delamination mode consisted on several planes that formed close to the ID of the pipe. Once they formed, the planes grew in the radial direction and meet with other surfaces in the same plane immediate above or below.

RESULTS FROM PRESSURE TESTS

Table 2 presents the results of the pressure test on damaged and non-damaged specimens. The tests presented on this table were static to leakage or burst.

Table 2 Internal Pressure Test Results

Label	**Energy Round**	**Energy Long**	**Max. Pressure**	**Location of Failure**	**Type**
H5	NA	NA	14.5 MPa (2100 psi)	Middle	Leak
1H5	40	80	10.34 MPa (1500 psi)	Long Punch	Burst
2H5	60	180	5.5 MPa (800 psi)	Long Punch	Burst
3H5	130	220	2.76 MPa (400 psi)	Round Punch	Burst
H15	NA	NA	37.92 MPa (5500 psi)	Middle	Leak
1H15	130	190	37.92 MPa (5500 psi)	Round Punch	Burst
2H15	350	700	28.27 MPa (4100 psi)	Round Punch	Burst
3H15	400	800	26.89 MPa (3900 psi)	Round Punch	Burst
H20	0	NA	82.73 MPa (12 ksi)	Middle	Leak
1H20	840	NA	68.94 MPa (10 ksi)	Round Punch	Burst

The companion specimens that were not damaged failed by leakage through the matrix with isolated fiber breakage. By producing an impact damage in fiberglass pipes, this difference between leakage and burst is reduced and in most cases burst becomes the dominant mode of failure.

For the information on Table 2, the values for the impact energies were normalized to t^2 (where t is the pipe thickness). Energy round is the energy from the round punch and energy long from the rectangular punch. Energy values are in Joules. Following Figure 2 shows the respective reduction in capacity. The plots contain results of tests performed in this study and results from a test by Oden et all [3] on pipes with similar material properties. The sharp drops from the points represented by H5 specimens and Oden specimens are the result of the impact damage causing through thickness cracking before pressurization tests. Failure modes in test performed for this study were of burst when impact did not cause through thickness cracking before pressurization.

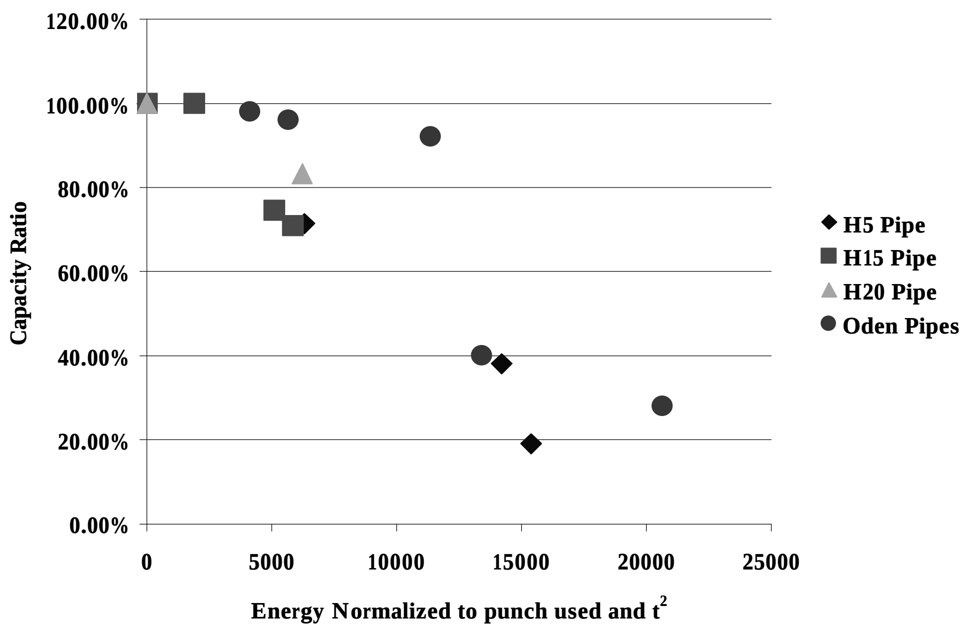

Figure 2 Capacity Ratio Normalized

Before impact, the control specimens failed by leakage produced by extensive matrix cracking. No considerable damage on fibers was observed in these cases. Impact damage to fiber specimens in this program, no matter how small, reduced the ultimate capacity of the component to values that are in some cases smaller than the leakage capacities.

ACOUSTIC EMISSION RESULTS

Table 3 shows comparative values of AE signature characteristics typically used in traditional AE monitoring of structures. The determination of the AE knee was made when the point was reached where the Felicity ratio was less than one.

In the table, specimen 2H5 is marked as NA in the columns. During testing of this specimen, a problem with the equipment prohibited data acquisition. Results in the table that show a Felicity Ratio of 1.0 indicates that the specimen did not show signs of permanent damage as recorded by the AE until leak pressure was achieved. By combining the use of digital systems and parametric AE, a methodology can be developed to evaluate impact damage severity in in-place structures. As it can be seen in Table 3, AE is able to flag damage intensity based on parametric AE, independently of the mechanisms involved in the process. Nevertheless, this is only possible if the damage is located within the structure.

Table 3 AE Comparison Table

Specimen	**Pressure**	**AE Knee at First Loading**	**Felicity Ratio**
H5	14.5 MPa (2100 psi)	4.14 kPa (600 psi)	1
1H5	10.34 MPa (1500 psi)	1.4 kPa (200 psi)	0.5
2H5	5.5 MPa (800 psi)	NA	NA
3H5	2.76 MPa (400 psi)	689.4 kPa (100 psi)	0.1
H15	37.92 MPa (5500 psi)	22.1 MPa (3200 psi)	1
1H15	37.92 MPa (5500 psi)	7.6 MPa (1100 psi)	1
2H15	28.27 MPa (4100 psi)	6.89 MPa (1000 psi)	0.8
3H15	26.89 MPa (3900 psi)	6.89 MPa (1000 psi)	0.6
H20	82.73 MPa (12 ksi)	27.56 MPa (4000 psi)	1
1H20	68.94 MPa (10 ksi)	27.56 MPa (4000 psi)	0.95

SOURCE LOCATION

Source location was carried out on two pipes. First, the conventional source location approach based on differences in time of arrival was used on 1H5 pipe. The wave velocity and attenuation rates in different directions were measured. The results showed that this approach was very difficult to apply to composite pipe structures since waves travel at different speed in different direction. Waves propagate at the highest speed along fiber, together with a very low attenuation rate in this direction, the signal tends to propagate mainly through the fiber and reaches sensors [8]. These are main factors that complicate the conventional source location approach. Therefore, an innovative approach using neural network was developed to solve to problem. This approach was applied to 2H20 pipe. Presented in a selected reference [8] the theory and optimization method for the network can be seen in more detail.

MLP NEURAL NETWORK

The network used in this program is the Multi-layer perceptron (MLP) using error back propagation. A schematic diagram of the final network model is shown in Figure 3. The network is composed of 9 inputs from three sensors. Input combinations of amplitude, duration, and rise time has shown a very good sensitivity to the change of outputs. Twelve hidden units were used with four nodes of output in terms of circumferencial rows. In order to obtain a correct value of weighting function (Wij and Vij), the process required training data with known outputs (also called supervised training). First, the weighting function was randomized by a computer, after the network was trained, error generated by the network was compared to the real output. Then, this error was back propagated through the network to adjust the weighting values in order to obtain a correct output. This process is known as error back propagation.

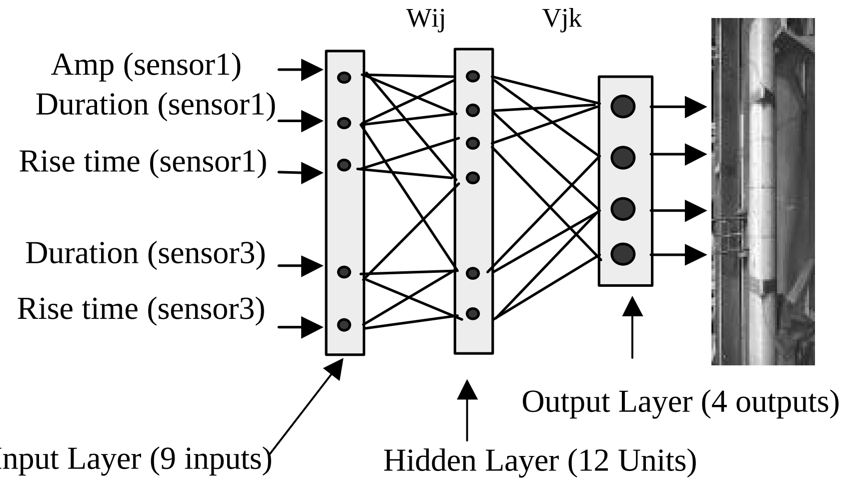

Figure 3 Final Network

NEURAL NETWORK RESULTS FROM IMPACT TESTS

From the impact test, the damage location was located exactly between row 2 and row 3. Forty five data points (events) were obtained from this test. The data is real emissions from fiber breakage and matrix cracking, and noises. Most of the noise came from the vibration of the pipe right after the impact. After filtering out the noise events, there are 5 useful data points left for inputting to the trained network. The results for these 5 data points are shown in Table 4.

Based on the rounded output in Table 3, it indicated that all damage locations are row 2 and row 3, which is essentially correct.

NEURAL NETWORK RESULTS FROM INTERNAL PRESSURE TESTS

The final step of the experimental program was an internal pressure testing of the pipe. The objective of this test in the source location part is to obtain more useful emissions. Although, the pipe was expected to fail at the impact location by fiber break through, other type of emissions such as delamination and matrix cracking at other unknown places was also expected. Due to the expectation of a severe explosive failure, all sensors were removed and the monitoring was stopped when the load reached 8.22 MPa (1200 psi). 198 data points were obtained from the test. Unfortunately, most of the data points are not complete (only one sensor picked up the signal). Only 54 complete data points were used to input the trained network. The exclusive summary of the results is in Table 5.
Ambiguous output, in this case, means that the results show that 2 rows were possible sources

Table 4 Output (in terms of row)

	Output from Network	**Rounded Output**
Data 1	0.04, 0.87, 0.89, 0.00	0, 1, 1, 0
Data 2	0.02, 0.93, 0.86, 0.01	0, 1, 1, 0
Data 3	0.12, 0.85, 0.79, 0.00	0, 1, 1, 0
Data 4	0.13, 0.83, 0.87, 0.09	0, 1, 1, 0
Data 5	0.16, 0.87, 0.89, 0.12	0, 1, 1, 0

Table 5 Summary of Results

Location of damage	**Number of data points**	**Percentage (%)**
Row1	31	57.4
Row2	8	14.8
Row3	6	11.1
Row4	1	1.8
Ambiguous Outputs	8	14.8
Total	54	

of emission. The results from the network showed that most of the emissions came from row 1 that is the end of the pipe connecting to the water hose (the inlet for water pressurization of the pipe). It is difficult to justify the outputs yielded from the network in this particular test because emissions could be from anywhere in the pipe. Since the test was not carried to complete failure, there was no obvious damage.

SUMMARY

A series of impact tests on tubular specimens were performed for this phase. Two of them were used for the source location study. Preliminary results show promising indications of the possibility of using AE/NDE methods for the damage monitoring and strength prediction in composite pipes. The main characteristic of the method selected is its ability to inspect large areas in a short amount of time. In addition to providing with indications of the existence of damage, AE showed promise in the determination of residual capacity after damage is produced. A parallel study using the same impact specimens is aimed towards the development of source location techniques based on AE. Two source location approaches were studied. The conventional source location technique based on the difference in time of arrival was difficult to apply in the composite structure. A new approach using MLP neural network shows a very promising result. This would present with a useful tool for monitoring the damage progress in a particular location once a zone is identified. Further detail analyses are underway to better understand the measured response of the test specimen and further evaluate strength and behavior of large-scale composite elements with NDE techniques. Ambiguous output, in this case, means that the results show that 2 rows were possible sources of emission.

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