ACOUSTIC EMISSION OBSERVATION OF ULTIMATE ELASTIC WALL STRESS (UEWS) TEST UNDER PURE HYDROSTATIC PRESSURE FOR GLASS REINFORC ED EPOXY PIPE (GRE) PIPES

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الملخص

يعرض هذا البحث اختبارات الانبعاثات الصوتية (Acoustic Emissions) التي تم اجراءها لغرض تعزيز النتائج المتحصل عليه من تجربة اقصى اجهاد مرن لجدار الأنابيب المركبة $\pm 55^0$ من الالياف الزجاجية (UEWS) حيث تم اجراء اختبارات الانبعاثات الصوتية للأنابيب عند تعريضها لضغط هيدروستاتيكي نقي. أظهرت قياسات الانبعاثات الصوتية (AE) ان التشققات الدقيقة قد بدأت في الظهور في مراحل مبكرة من الاختبار، بينما حدث الانهيار قبل نقطة اعلي اجهاد مرن (UEWS). الظهور الواضح للانبعاثات الصوتية (AE) لوحظ فقط عند حدوث الانبعاج والذي تسبب في الانهيار الطبقي (Delamination) والانهيار الانفصالي (Debonding failure) متبوعا بانهيار للألياف الزجاجية بالسطح الخارجي للأنبوب.

ABSTRACT

This paper presents the Acoustic Emission (AE) observations made for enhancing the ultimate elastic wall stress (UEWS) results for ±55° fiberglass reinforced pipes. The acoustic emissions tests were implemented under pure hydrostatic pressure. The AE measurement of pure hydrostatic pressure showed that matrix cracks were initiated early in the tests and delamination failure has occurred before the UEWS point. Significant AE events were only noticed when buckling induced delamination and debonding failure, which was followed by fibre fracture at the outer surface of the pipe.

KEYWORDS: Debonding Acoustic Emission; Ultimate Elastic Wall Stress; Matrix Cracks.

INTRODUCTION

Recently acoustic emission AE analysis has been widely used in monitoring and evaluating the failure modes of materials in many applications. Acoustic emission techniques have been developed for use at the locations of areas and types of damage, based on recorded acoustic signals [1]. A number of studies have been carried out using acoustic emission techniques in order to evaluate failure mechanisms in polymer composite reinforced fiberglass.

Benmedakhene et al. [2] tested a double-cantilever beam specimen under monotonic pure mode (I) conditions with various displacement speeds. They installed the acoustic emission equipments, to detect crack initiation and to study mechanisms of crack growth. They reported that the strain energy release rate under cyclic loading increased as the applied load rate increased up to final failure. Furthermore, they found that the delamination process is a consequence of several types of damage, such as matrix cracking, interface debonding and fibre fracture. Combining acoustic emission analysis with enhanced microscopic observation helps to observe the crack paths, which appear to propagate through the resin along the fibre/matrix interface at high loading rate, as shown in Figure (1).

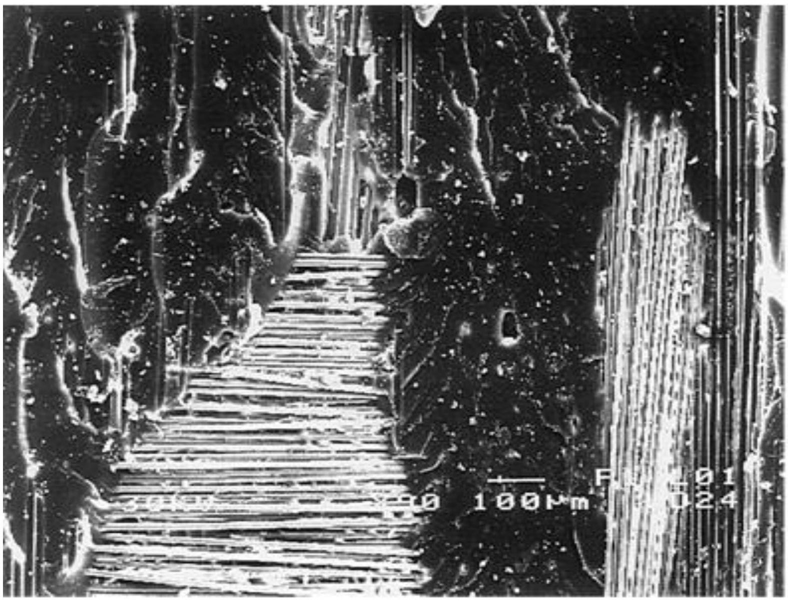


Figure 1: Shows a crack propagation in the resin and the interface [2].

Dogossy and Czigany [3] tested maize hull composites with applied tensile loads, in order to analyses and follow the failure process by acoustic emission observations. They reported that, it was possible to distinguish acoustic emission from the presence of three failure modes during the tests, which can be classified as matrix deformation (below 25 dB), maize hull pullout (26-40 dB), and maize hull breakage (over 41dB), as shown in Figure (2).

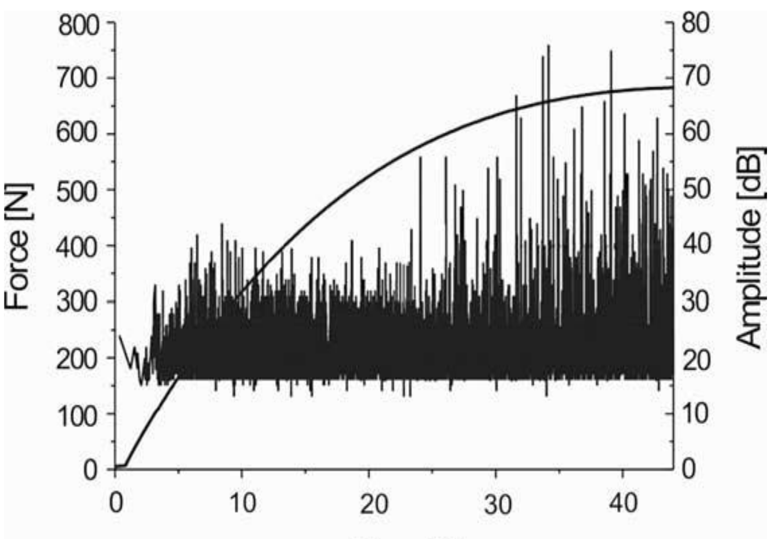


Figure 2: Characteristic tensile and amplitude curves of a PE composite [3].

Guillermo et al (2006) [4] presented a method for determining the endurance limit of fibre glass pipes under internal pressure using acoustic emission technology. They applied static and cyclic loads to 22 samples with 200 mm diameter and 1.5 m length. Pipes were tested to failure, which was defined as the weepage of liquid through the pipe wall.

They used the recorded data to plot cumulative signal strength versus time and showed the estimated pressure at the acoustic emission 'knee'. They concluded that, there are correlations between the acoustic emissions during the first loading of the specimens and the ultimate life under cycle loading. Moreover, they claimed that the collected results from acoustic emissions can be used to predict the long term cycle loading performance of reinforced fibreglass pipes. They also concluded that acoustic emission can be used to evaluate the effect on fatigue performance of factors such as changes in materials, fabrication, and methods.

Finkenstadt et al [5] tested polylactic acid (PLA) oil seed composites, and claimed that three different stages of deformation could be clearly discerned from acoustic emission evaluation. At first debonding of fibres from the matrix was recognized, and then the yielding of the matrix occurred as a second stage, followed finally by the ductile fracture of the matrix.

Khalifa and co-workers [6] performed mechanical characterization of lass/vinyl-ester composite pipes under axial loading by AE technique and tension test. The AE responses were found to distinctly correspond to the four damage modes observed in tension test: matrix cracking, interface debonding, delamination and fiber breakage.

EXPERIMENTAL WORK

Glass reinforced epoxy pipe (GRE) ±55° filament wound pipes were prepared and fitted in the designed rig for the UEWS tests as in Figure (3).

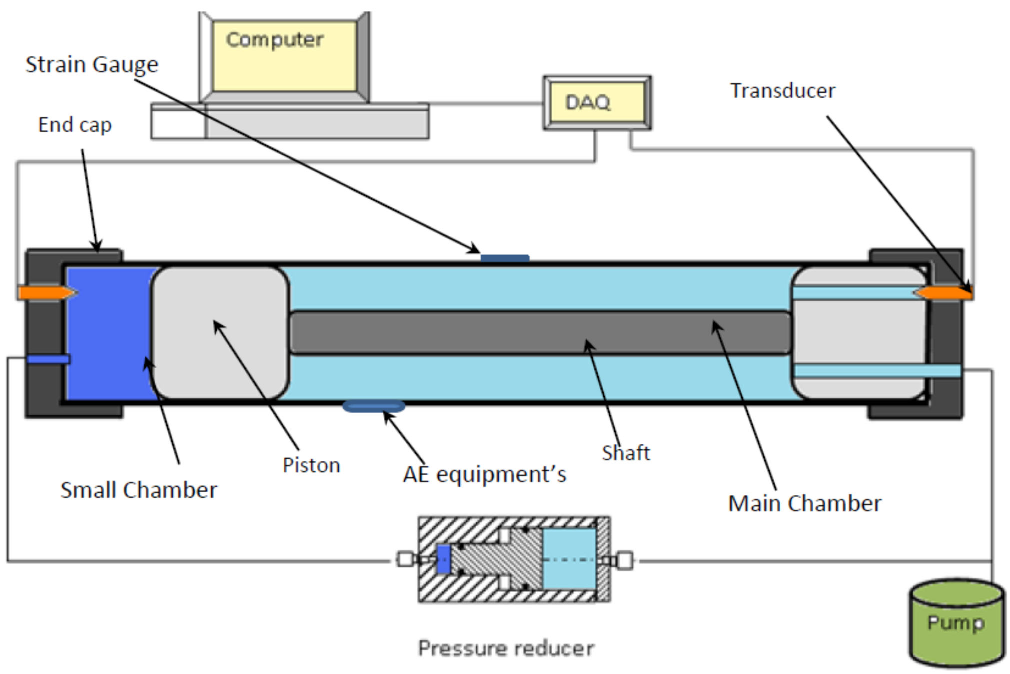


Figure 3: Schematic diagram of the rig for carrying out biaxial loading tests.

This rig enables additional axial stress to be applied up to pure axial loading. Axial stress up to pure hoop loading could be also minimized by controlling the pressure in both the main and small chambers inside the pipe. Therefore, it was unnecessary to add any external loads to the pipe wall to perform the test the rig was designed to perform the tasks involved in the biaxial tests under a variety of load and environmental conditions. The following criteria needed to be satisfied.

A nominal pressure rating (P_N) was determined, as well as the design cyclic test pressure (CTP) starting at 10% of the expected UEWS. The required bridge voltage was applied to the strain gauges due to the DAQ system as well as the acoustic emission equipments. Table (1) shows the physical and mechanical properties of the pipes.

Table 1: Physical and mechanical properties of the pipe.

Materials	Test Method	Value
Internal diameter		200 mm
Wall thickness		6 mm
Pipe length		2 000 mm
Epoxy Density		1.8 g/ml
Volume fraction (%)		59%
Axial Young's modulus (Ex)	ASTM D 2105	12 GPa
Axial strength	ASTM D 2105	75 MPa
Hoop Young's modulus (Ey)	ASTM D 2290	20 GPa
Hoop strength	ASTM D 2290	210 MPa
Shear modulus (Es)		11.5 GPa
Thermal conductivity		0.29 W/m. K
Poisson ratio axial/hoop	N_{xy}	0.65
Poisson ratio hoop/axial	N_{yx}	0.38

The first cycle test pressure was applied with pressure increment from zero to the CTP_1 of wall stress of 5-10 MPa/ minute. Ten cycles were applied under CTP_1 holding for one minute at the given pressure and one minute at conditions of zero pressure.
The pressure was then uniformly increased to the second group of cycles, which can be determined by adding 10% of the expected UEWS as follows:

$$CTP_{i+1} = CTP_i + 0.1 * P_{UEWS\ exp.} \quad (1)$$

The procedure was repeated until Weeping or failure of the pipe. Strain measurements as well as pressure readings were taken at the end of the first and tenth cycles. The UEWS was investigated when the difference in strains between the 1st and 10th cycles of the same cycle group exceeds 5%.

$$\varepsilon_{10i}/\varepsilon_{1i} > 1.05 \quad (2)$$

Two cycle groups after the UEWS point using the same procedure were required for clarify the exist of UEWS. Figure (4) shows pressure versus time and cycle group definition.

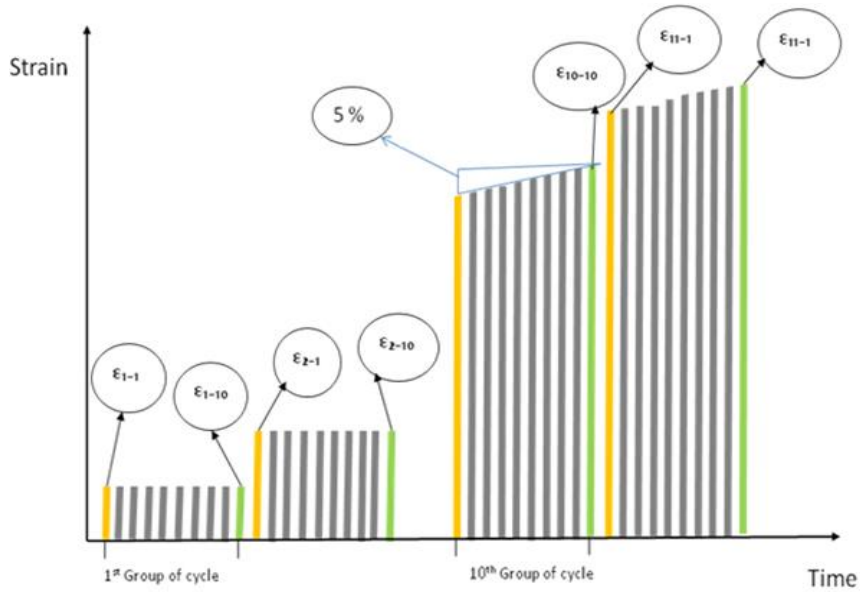


Figure 4: Definition of test cycles and cycle groups.

RESULTS AND DISCUSSION

In this test, the pipe ends were both sealed with steel end caps, which were not constrained from movement resulting in the hoop stress being twice the axial stress. The pressure was gradually increased up to the cycling test pressure (CTP1), was held there for one minute and then released for another minute. This was repeated ten times and then the cycle test pressure was increased to the level of the subsequent cycle group. The distinction between cycle groups was manually marked in order to analyse independently the AE signals for each group.

Figure (5) shows the pipe performance under pure hydrostatic internal pressure (2:1) at room temperature. The relation between stress and strain clearly shown to be linear, and both hoop and axial strains are positive.

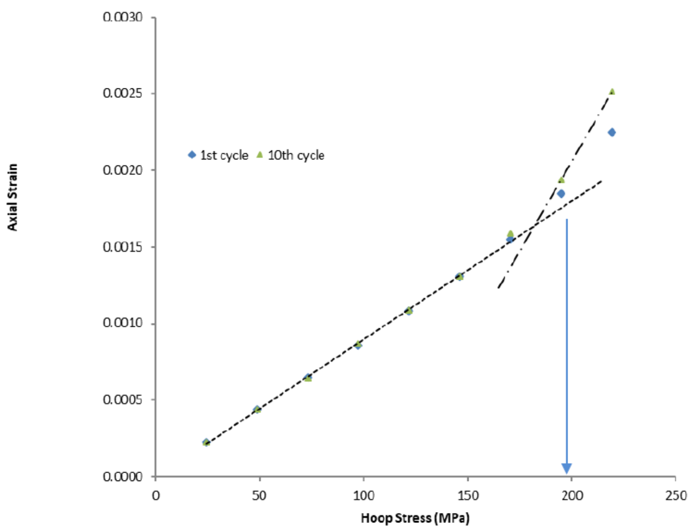


Figure 5: Stress-strain relationships and UEWS points under pure hydrostatic internal pressure (2:1) for ±55° fibre/glass epoxy pipes.

However, at pressures above 170 MPa a well defined transition to non-linear behaviour occurred up to final failure at about 220MPa. The departure from linearity in the stress-strain curve is due to the interaction of transverse and shear stresses and by exceeding the critical value of these stresses. Pipes under loading of 2:1 hoop to axial stresses provided the longest-lasting linear behaviour before plasticity was observed among all the conducted stress ratios. This level of performance found agreement with Acoustic emission observations.

Figure (6) illustrates the AE counts as a function of both time (seconds) and pipe wall stress. The loading was halted at a stress level of 223 MPa, when intensive leakage made it difficult for any further increase in pressure to be applied. The amplifier sensitivity was set at 40dB, and therefore any AE signals lower than 40 dB were filtered out. AE events started at quite an early stage of loading, suggesting that matrix microcracking took place because of the stress being increasingly taken up by the fibre reinforcement. These events increased up to the corresponding wall stress of 74 MPa and then stabilized with negligible subsequent increase of AE event rate detected, indicating that a constant rate of damage occurred up to the eighth cycle at a wall stress of 149 MPa. At this stress level progressive development and a sudden increase in acoustic events were noted. It is likely that, as load increases transverse cracking and delamination have initiated. After that, there were only slight decreases in AE events during crack propagation compared to those generated due to their initiation. At a wall stress of 204 MPa an increase in acoustic events indicated that debonding occurred and cause a pathway for liquid to weep.

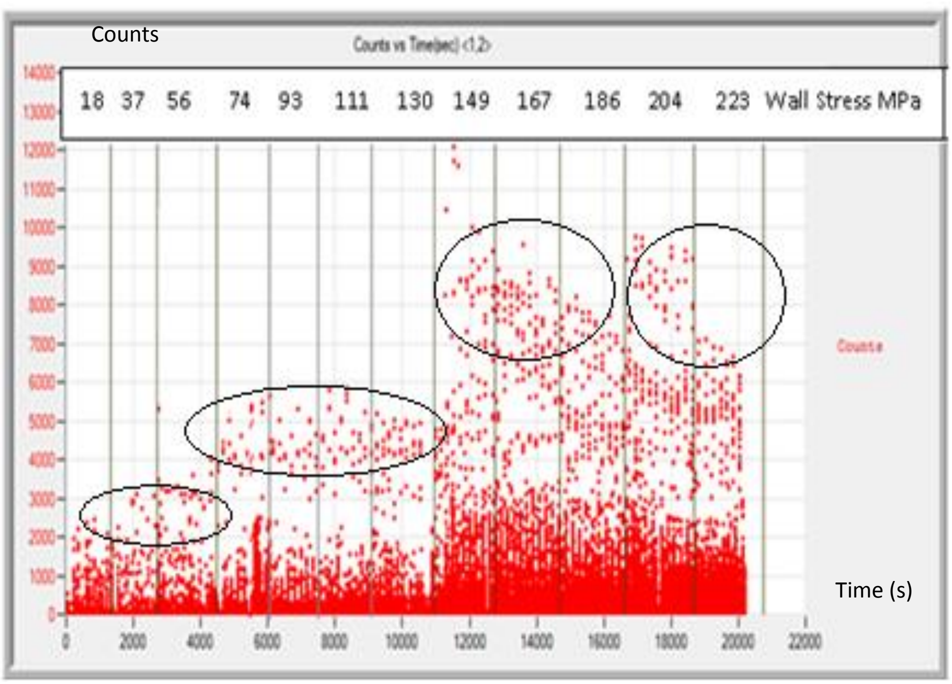


Figure 6: AE counts vs. time and hoop stress, for ±55° GRE pipes under internal pressure of 2:1.

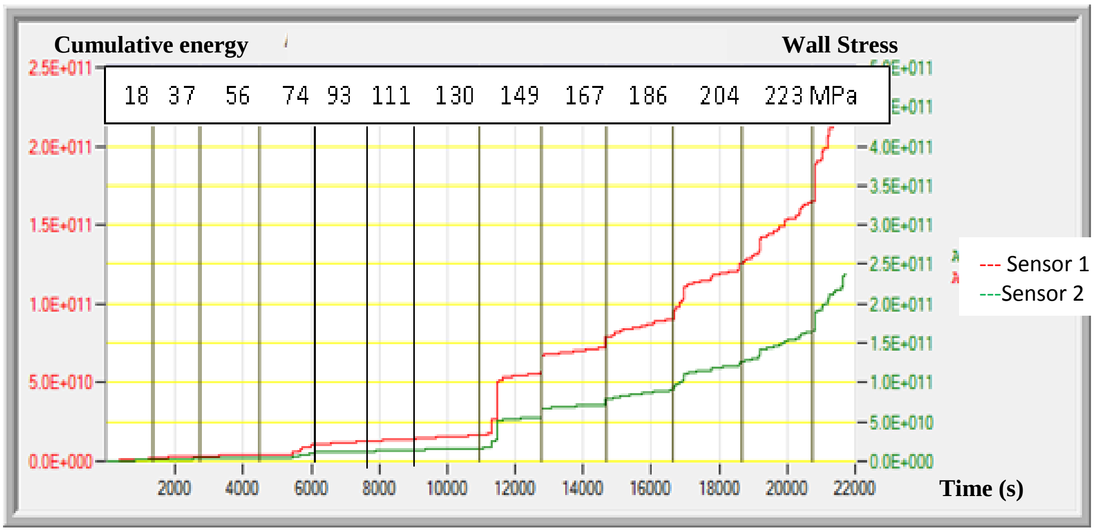
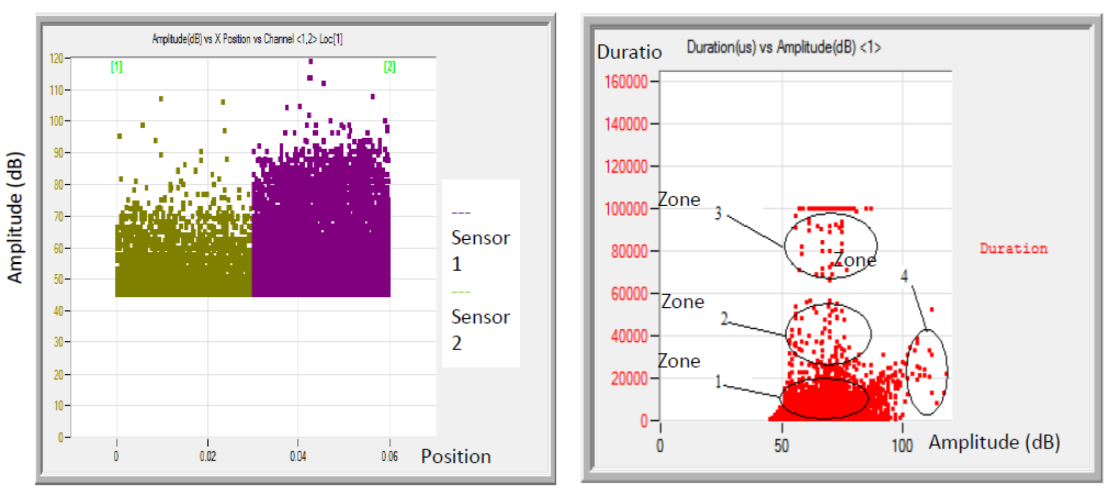


Figure 7: AE cumulative energy release rate vs. time and wall stress, for ±55° GRE pipes under internal pressure of 2:1.

Figure (8a) shows that the failure is taking place closer to channel 2 probe. Most of the acoustic emission was low duration events between 40 dB and 80 dB amplitude (zone 1 in Figure 8b). Such behavior is normally associated with matrix cracking and indicates that matrix cracking was taking place throughout the test. There are also three other distinct zones of events evident. Zones 2 and 3 are intermediate and high duration events with amplitude between 50 dB and 80 dB. High duration events are normally associated with friction and therefore could arise from fibre pullout. Intermediate duration events could be attributed to delamination. Zone 4 is characterized by high amplitude low duration events, which is associated with debonding and the possible of presence of fibre fracture.



(a) (b)

Figure 8: AE absolute dB versus position of channels 1and 2 (a), and AE duration versus amplitude dB (b) for ±55° GRE pipes under 2:1 stress ratio.

Figure (9) is a record of the AE amplitude vs time, from both channels, for the pipe sample tested to failure. The plot shows that up to 130 MPa there is a low amplitude activity associated with matrix cracking. There is also a small burst of activity at around 74MPa of events with amplitude between 60 dB and 70 dB that could be attributed to matrix microcracking. Above 130 MPa there is a higher amount of AE activity and a distinct band of events is recorded between 70 dB and 90 dB amplitude.

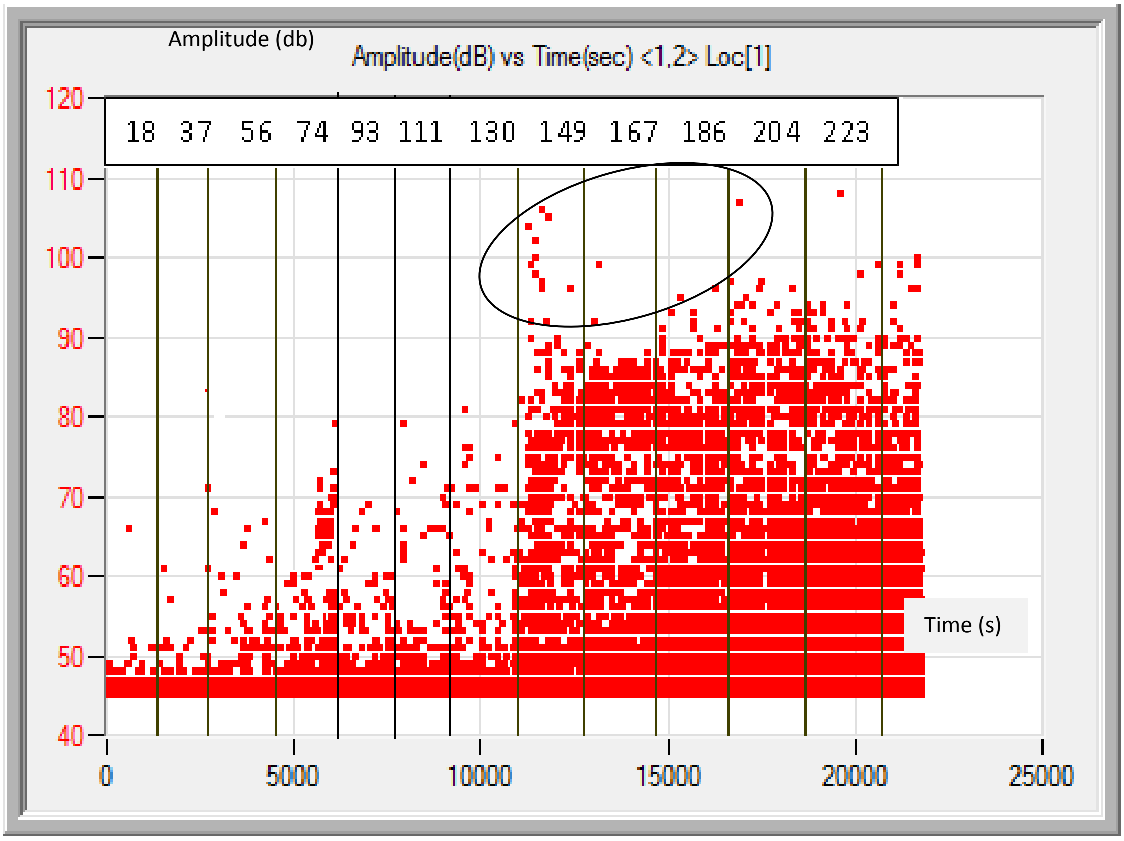


Figure 9: Signal amplitude vs. time for the ±55° GRE pipe under internal pressure of 2:1.

This suggests that a second failure mechanism is developing, in addition to matrix cracking, which seems to involve delamination and debonding. Some events of high amplitude (100 dB) are normally associated with fibre fracture. Undoubtedly some fibre fracture is taking place but this is very limited. The latter statement is supported by the fact that the failure of the pipe took place be weep age and not bursting which would have involved substantial fibre failures.

More events noted in Figure (10) from the tenth cycle group up to weep age indicated that significant debonding in the fibre/matrix interface took place. This debonding occurred alongside rapid transverse cracking in the later stages of loading, eventually resulting in weep age.

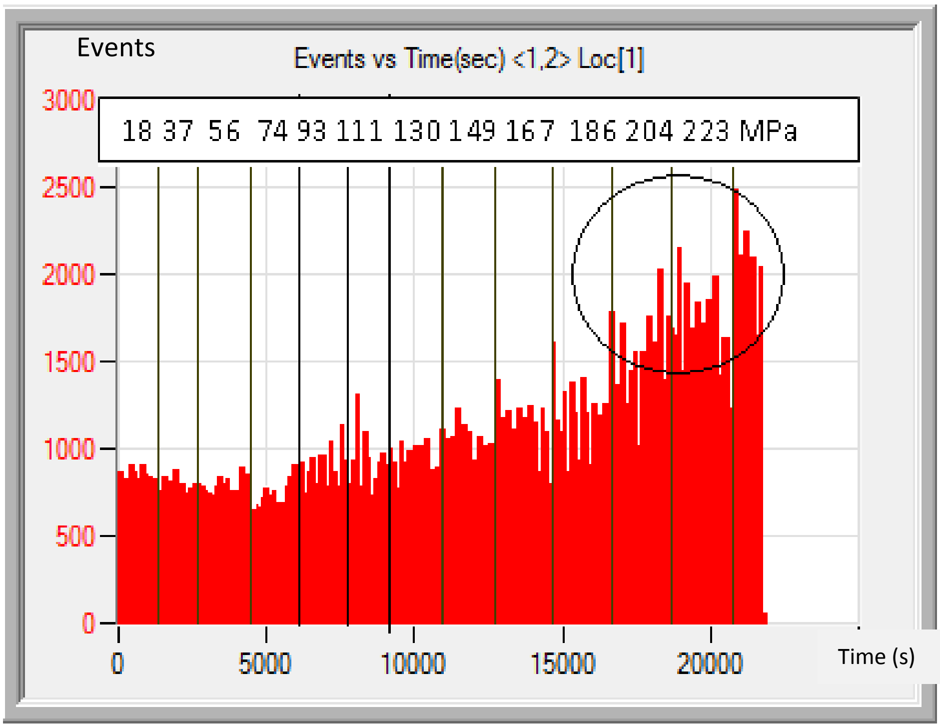


Figure 10: AE events vs. time for the ±55° GRE pipe under internal pressure of 2:1.

CONCLUSION

AE measurements were conducted during the UEWS tests under hydrostatic. The ultimate elastic wall stress was measured at 160 MPa. However, acoustic emission results show that matrix cracks were initiated and had progressed to delamination immediately before the UEWS point at about 140 MPa. The AE test provides satisfactory results for the damage mechanism in GRE pipes. Nearly stable AE measurements were recorded due to the relatively high shear stress. Significant AE events were only noticed when the bending of the pipe just before buckling induced massive delamination and debonding failure followed by fibre fracture on the outer surface of the pipe. Through the analysis, the AE results do give good accounts for the states of damage mechanisms and progressions involved based on the distinct AE signatures throughout the test. The results hence suggest that, with further work, AE can be used as the monitoring tool to provide an early warning system for glass-reinforced plastics pipe failure.

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