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AN ESTIMATION OF STRUCTURAL INTEGRITY OF THE GFRP PRESSURE BOTTLES USING ACOUSTIC EMISSION TECHNIQUE

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ABSTRACT

Acoustic Emission (AE) is an upcoming NDT technique gaining ground in different fields as an on-line monitoring method for detection, location and characterization of various kinds of active degradations. This method has also made an impact as a tool for structural integrity evaluation and failure prediction.AE technique is highly sensitive and can find out degradations in FRP structures viz delamination, fibre crack, debonding and matrix crazing etc well before occurance of any catastrophic failure under dynamic service condition. In this present study, five identical GFRP hardware were taken up for the study and acoustic emission data is analyzed thoroughly and a lucid empirical relation is being developed to predict their burst performance. In this approach the failure is significant even at 50 to 60 % of maximum expected operating pressure (MEOP) with a reasonable error margin. Till date there is no method spelt out in the open literature for burst pressure prediction of composite pressure vessels. Acoustic Emission monitoring is carried out on 6- litre capacity cylindrical GFRP pressure bottles for four identical cases. An attempt is made on the fifth hardware to predict its burst pressure. This innovative methodology illustrates the structural behavior of GFRP pressure bottles in terms of AE parameters and its derivatives. In this approach AE data is acquired only upto 50% of the theoretical burst pressure and then the bottles are pressurized upto failure. An empirical relation was generated for the GFRP bottle which is subjected to cyclic proof pressure cum burst test on the basis of the governing AE parameters viz, count rate, duration rate, amplitude rate and felicity ratio exhibited. This methodology can possibly predict in real time the burst pressure of similar hardware if extended to other material systems.

Keywords: *Acoustic Emission, GFRP Pressure Bottles, Structural Integrity, Empirical Relation, AE Parameters, Prediction.*

1. Introduction

Acoustic Emission Technique (AET) is widely used for both materials research and structural integrity monitoring applications because of its unique potential for detection and location of dynamic defects under operating stresses [1,2]. In the past two decades, AE has been mostly used for testing pressure bottles undergoing proof tests. In aerospace composite structures, pressurised systems are made with low margins with their attendant light weight construction. With the rapid advances taking place in this area, there is a strong need for an NDT technique which can indicate the degradation that takes place during the course of the proof or acceptance pressure testing of pressurized systems [3]. There are cases reported in the literature that composite hardware that have successfully undergone proof pressure tests did fail during their actual test. In this respect, AE technique has assumed a unique role. More than evaluating the structural integrity of pressurized systems it has the capability to predict the burst pressure within certain limits [4]. It is well known that GFRP pressure bottles undergo degradation during acceptance/proof pressure test in view of resin crazing, delamination, fiber fracture, fiber pullout and debonding between the layers etc. Such degradations can be indicated through major AE parameters and their derivatives [5-8]. A methodology is being developed in this paper to estimate the structural integrity of GFRP pressure bottles.

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1.1 Filament winding: process technology

The process of filament winding is primarily used for hollow, generally circular or oval sectioned products. Fibres can either be use dry or be pulled through a resin bath before being wound onto the mandrel. The winding pattern is controlled by the rotational speed of the mandrel and the movement of the fibre feeding mechanism. Filament winding usually refers to the conventional filament winding process. However some industrial companies use a called 'Fast Filament Winder' for producing GFRP pressure vessels. Basically the processes are the same (the fibres are wound around a mandrel following a certain pattern), but the way the machines work and the way the mandrel moves differs. The Fig.1 shows the manufacturing process of filament winding.

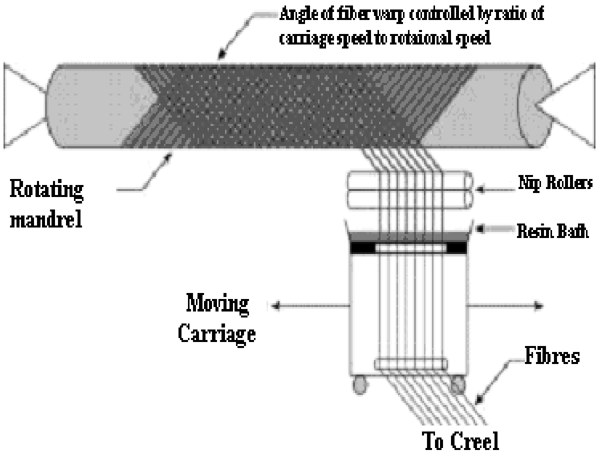

Fig. 1 Schematic Representation of the Filament Winding Process

After winding, the filament wound mandrel is subjected to curing and post curing operations during which the mandrel is continuously rotated to maintain uniformity of resin content around the circumference. After curing, product is removed from the mandrel, either by hydraulic or mechanical extractor.

2. GFRP Hardware Details and AE Instrumentation

The AE studies have been performed on five numbers of similar Glass epoxy pressure bottles. The Fig.2 shows the schematic view GFRP pressure bottle is being studied in this research.E-Glass fibres impregnated with epoxy resin are wound over an inner liner made of polypropylene.The bottles are built up of hoop layers and polar layers alternately placed in groups.The dome openings are equal and are closed with flat plates or special closures as the case may be for the pressure test purposes.The thickness of the composite wall is 5mm.The SG/AE instrumentation is shown in Fig.3.The sensitiveness of the sensor is verified and adjusted frequently at the end of every cycle with the use of Hsu-Nielsen pencil-break technique.The PAC-Disp 4 AE work station is used to monitor in conjunction with AE sensors R15(150 KHz,resonant type)and matching pre-amplifiers 40 dB with high pass analog filter range 20 KHz -400 KHz. Radiography (X-ray) test is conducted on each bottle to verify the uniformity in thickness of composite walls. Initially the threshold 45dB is set during the starting in order to avoid the system collapse.

3. AE Monitoring during Hydrostatic Pressure Test

The Emissions are captured with the use of four AE sensors.These AE sensors are mounted as per standard procedure [ASTM,1986], connecting co-axial cables with AE system. The deformation of the bottle is identified by fixing single element 350Ω strain gauges (ranges 0-18000με) and their locations are shown in the Fig.3.The pressure cycle is carried out upto 50% of their theoretical burst pressure in a cyclic mode.The pressure cycle is brought down to zero after every cycle.

In this paper AE signature is studied during the first repeat cycles.The pressure rate is maintained at 20 bar/min through- out the test. In the first test during pressurisation the hardware failed due to adaptor failure shown in Fig.5.In order to avoid this nature of failure, the remaining four hardware were gently machined at the cylindrical portion by 1 mm depth. The schematic view of experimental setup is shown in Fig.4.

Six numbers of strain gauges and three numbers linear potentiometers are mounted to find out the deformations and axial/diametrical dilations of the hardware. These data are acquired and analyzed for further developments of this research.

4. Pressurisation & Pressure History

Two sets of pressure schemes are used to pressurise 6- litre capacity,150 mm dia cylindrical GFRP pressure bottles-5 numbers.Initialy the first hardware is pressurised in cyclic steps upto 200 bar and the remaining hardware were pressurised upto 150 bar only. An air assisted hydraulic pump is used to pressurise upto 150 bars and for the higer pressurisation mechanical pump is used. The incremental pressure was 25 bar in all cases.The first time holds at various incremental pressures were for a minimum period of 1 min until the event rate declines.The maximum hold shall be for a period of 3 mins. In this paper, the emissions were studied only for repeat cycles. For every cycle, the AE parameters just before pressure hold are taken into consideration for developing the empirical relation predicting the burst pressure. In all cases, AE parameters were studied for a maximum pressure of 125 bar except for the first hardware. In the first hardware, cycling was done upto 175 bar.

Fig. 2 GFRP Pressure Bottles being Studied in the Program

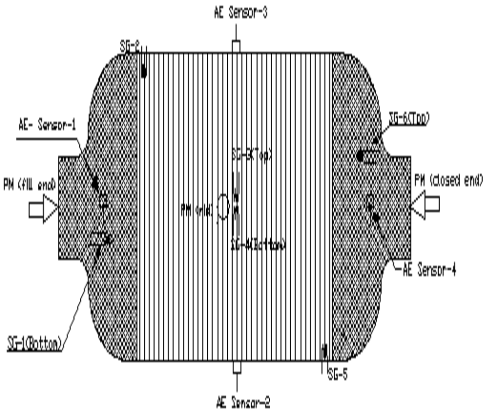

Fig. 3 SG/AE Instrumentation on GFRP Pressure Bottles

5. Empirical Relation

The empirical relation is nothing but a relation connecting the dominant four AE parameters with expected burst pressure and internal pressure at which the prediction is attempted. This relation is developed in the first hardware itself, after that, the same will be refined after every remaining hardware test. The general form of empirical equation is assumed as:

$$\mathbf{N^{-\alpha} \times D^{-\beta} \times A^{-\gamma} \times R^{a} = F \times P^{-b}} \qquad (1)$$

Where,

N = Ring down Counts in numbers/sec
D = Duration rate in µs
A = Amplitude rate in dB
R = Felicity Ratio
F = Tentative burst pressure in bars (ksc)
P = The internal pressure (in bars) at which prediction is attempted
α, β, γ, a, b= Empirical constants

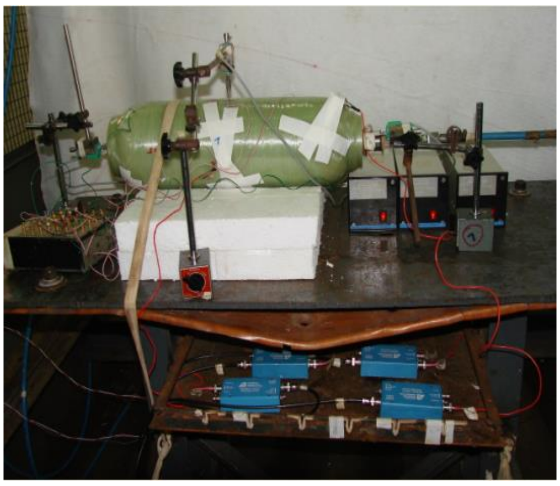

Fig. 4 Experimential Setup

6. AE Parameters

In this analysis the major derived AE parameters chosen were count rate, duration rate,amplitude rate and Felicity ratio(F.R). The pressure at which significant emissions start during first repeat cycle is considered as ‘P_1’. The maximum pressure reached during the previous cycle, is say, ‘P_2’. Thus F.R=P_1/P_2. The other parameters are chosen just before the pressure hold that follows during the first repeat cycle. The solution of each hardware is found out by MATLAB software. The unknown constants are arrived at by substituting all the major AE parameters into the empirical relations. In any hardware, the tentative burst pressure is arrived at by substituting the other hardware’s constants. In the first bottle, initially the emissions were very low. Therefore, the equation is formed from 75 bar pressure cycle onwards. The authors also observed that the machined hardware exhibited burst earlier than the first hardware failure.

7. Results and Discussion

In the case of one of the hardware,say,GFRP-02, for the first repeat cycle at 75 bar, the values of derived AE parameters and pressure at which prediction was attempted are substituted into their equations corresponding to 75, 100, 125, 150 & 175 bars respectively. The solution initially gave low burst values in comparison with the actual burst pressure of 299.5 bar.

In the pressure range 100/125 bar, it gave reasonable percentage of error, say, 2.67. The felicity ratio is estimated using corresponding data sets as described earlier. The chosen values are also verified with the sixth equation at 200 bar. In this case, it indicates the values of burst pressure with an error margin of -1.42%. Using these equations one could find out the constants with the help of MATLAB software. This software displays the output for any {mxn} matrix, where m=n. Similarly, for the other hardware the AE parameters are acquired from 25 bar internal pressure onwards at an incremental pressure rise of 25 bar.

The mathematical procedure is same for all the hardware. For each of the pressure bottles the dominant AE parameters preceding the failure can be detected at around 75% of MEOP. From the acquired data, a set of multiple parameters can be developed with a small error margin. The initial emissions are more for all the bottles except for the first bottle. The prediction attempted in the GFRP-03 pressure bottle gave the percentage of error from -6.11 to 3.22% at 100/125 bar pressure cycle.

Its constants gave a prediction of -15.37 to 21.9% at 100/125 bar pressure cycles. The constants of GFRP-01 and GFRP-05 pressure bottles exhibited reasonably low error margins at -0.64 to 3.22% and -19.2 to 6.43% respectively at 50 / 75 bar cycle range. The failure mode of GFRP-05 is shown in Fig.6. GFRP-04 pressure bottle failed at very low pressure (125 bar) compared to all the remaining hardware. Substituting the GFRP-02 hardware constants gave a prediction for this hardware with an error margin of 16.9% at 75 bar cycle.

This particular hardware failed during the 3 mins hold period. E.V.K.Hill and T.J.Lewis [9] found this trend to be characteristic of bad pressure vessel. Due to the continuance of AE activity during the pressure hold and creeping to failure would indicate a bad vessel cause huge error margin. This methodology can be extended for other types hardware like Kevlar-epoxy, Carbon- epoxy etc.

If we compare the performance of all the hardware it can be identified that the failure of GFRP hardware is preceded by high count rate, large number of long duration events, high amplitude rate and a very low felicity ratio. The authors observed from the mathematical analysis that the predicted burst pressure error margin is high at lower pressure and it is reasonable in the range 75 bar to 100 bar.The optimum results of each bottles were shown in bar charts as below (Refer Fig.7 to Fig.11).

Fig. 5 Failure Mode of GFRP-02

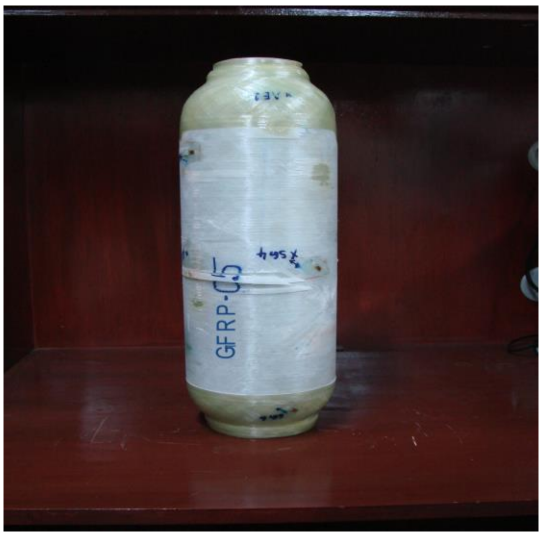

Fig. 6 Failure Mode of GFRP-05

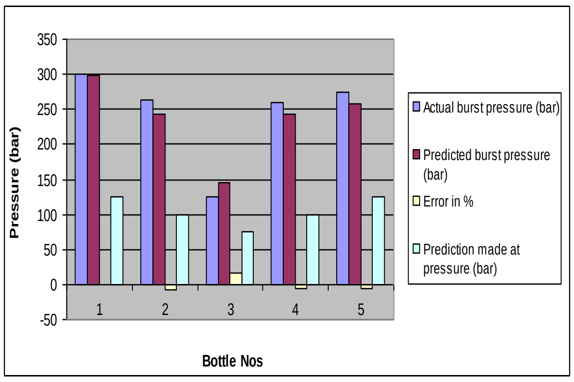

Fig. 7 Optimum Results using GFRP-01 Constants

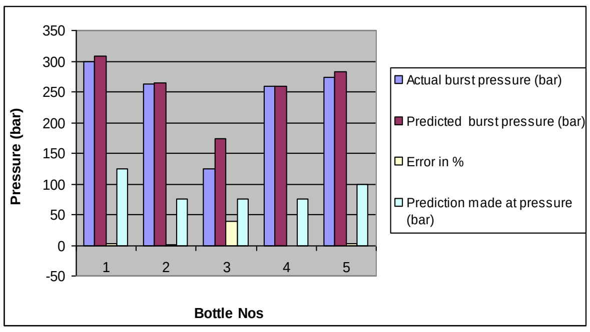

Fig. 8 Optimum Results using GFRP-02 Constants

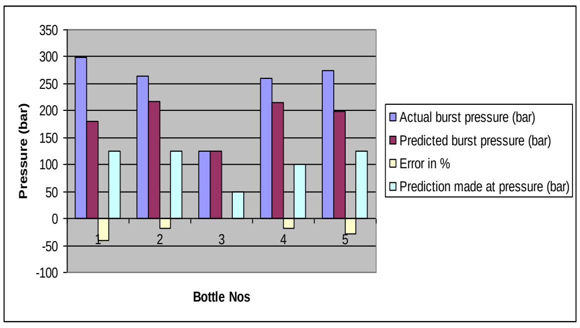

Fig. 9 Optimum Results using GFRP-03 Constants

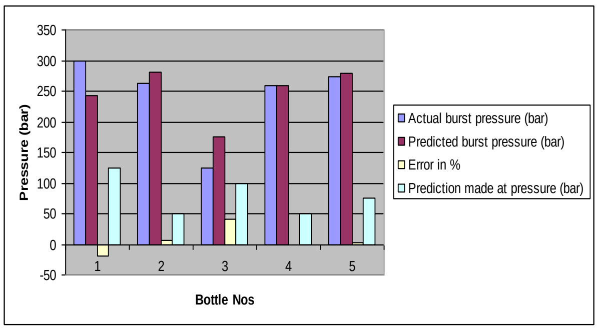

Fig. 10 Optimum Results using GFRP-04 Constants

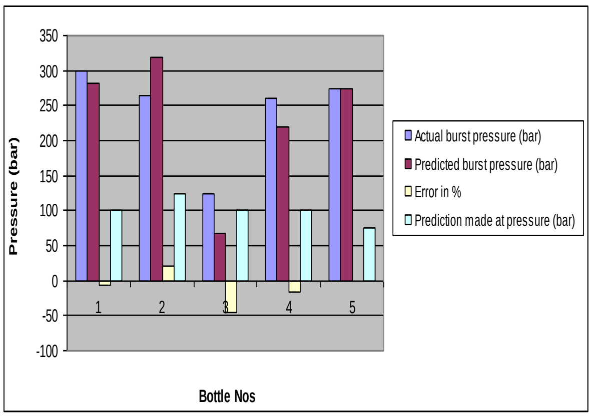

Fig. 11 Optimum Results using GFRP-05 Constants

8. Conclusions

The authors have clearly verified that the prediction of burst pressure is possible in the case of GFRP pressure bottles with a lucid empirical relation. The correlation of all the five hardware is reasonably better with an acceptable error margins at –0.64% to 2.18% and for the worst case the percentage of error prediction is -19.2% to 16.9% at around 75% of MEOP. The major AE parameters like count rate, duration rate, amplitude rate and felicity ratio exhibited during first repeat cycle could substantially facilitate accurate prediction of failure. This innovative approach can be extended to any other material system to predict the structural integrity and can send out warning signals well ahead of failure.

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