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Investigation of Burst Pressure on Carbon / Glass Fiber Reinforced Polymer Metal Tube for High Pressure Applications

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Abstract

The objective of the work was to investigate the effect of burst pressure on fiber metal laminate (FML) cylindrical structures using high pressure test rig with acoustic gauge. Glass fiber / carbon fiber reinforced epoxy composite was wound on aluminum (Al) tubular structure at ±55° orientation using filament winding machine. The developed fiber metal cylindrical specimen was subjected to burst pressure using specially designed hydraulic pump with online monitoring acoustic emission (AE) to identify the initialization of crack on the surface of the cylinder. The results of burst pressure with respect to time showed four types of behaviour viz, elastic, elasto-plastic, peak and failure, irrespective of the type of fiber and thickness of fiber reinforced polymer (FRP). The carbon fiber based metal cylinders showed higher pressure absorption capacity than the glass fiber based cylinders. The initiation of crack, propagation of crack and surface burst were investigated using photographs, which were captured during testing.

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Keywords: fiber metal laminate; carbon fibers; glass fibers; aluminum tube; acoustic emission; burst pressure

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1. Introduction

Over the last decade, FRPs have been used for manufacturing circular tubes for various applications such as fuel tanks, rocket motor cases(Vasiliev et al(2003)), pressurized composite structure (Mertiny et al (2007)) etc due to their high specific strength, corrosion resistance and reduction in weight (Cho-Chung Liang et al (2002)). Although there is increasing usage of these materials in various applications, but its application in high pressure vessels is limited due to intrinsic problems of the material as proved by Levend Parnas et al (2002). The composite tubes fail to provide air tight protection under high pressure, which leads to leakage of gas / liquids from the composite tubes through fiber and matrix interface (Mertiny (2007)). To overcome this problem Luiz et al (2012) introduced metallic liner inside the composite tubes i.e. fiber is wound around the metallic tube to avoid leakages. L.M. Alves

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Et al (2013) introduced innovative tube and reservoirs made from metal liners, which are seamless and FRP skins are wound around the liner to enhance the strength.

Metal liners are normally made of elastic materials and FRP layer is made up of elasto-plastic materials such as carbon, glass or kevlar reinforced composites (Lifshitz (1995)). The pressure vessels designed with liners depend on the thickness of liner and on the load applied, such as elastomers used for no load condition, and metals used for load condition. David Cohen et al (2001) proved that the strength of the pressure vessel depends not only on material but also on orientation of fiber and winding techniques (David Cohen et al (1997)). For components requiring high energy absorption, filament winding has proved to be the most suitable manufacturing technique (Frank C. Shen (1995)). Most of the research work on filament winding proved an optimum winding angle of ± 55° for burst pressure (M. Xia et al (2001), Takayanagi et al (2001), Bakaiyan et al(2009)). Although many researchers have worked on composite cylinders subjected to high pressure, none of the work is focused to investigate the burst pressure on carbon FMLs and glass FMLs for high pressure test. Hence the objective of this research work was to investigate the effect of carbon fibers / glass fibers on burst pressure of FML tubes using acoustic burst pressure test rig. A still camera was used to study the damage analysis.

2. Specimen preparation

The cylindrical FML specimens with carbon fibers / glass fibers wound on Al tube at ±55° orientation were prepared using filament winding machine, as shown in Fig 1. The flexible mandrel with Al cylinder is fixed between the jaws. The flexible mandrel helps to attach and detach aluminium cylinder before and after winding. The fibers are impregnated with resin by passing through resin bath. The wetted fibers were allowed to pass through feed eye and then continuously wound on the Al cylinder. The process of winding a cylindrical FML specimen is shown in Fig 2. Any voids and excess resin present during winding are corrected during the curing process. The filament winding machine was continuously run after winding for five hours (up to gel formation) to avoid resin fall or segregation of resin due to gravity. The specimen was then allowed to cure for 24 hours at room temperature in the static condition. The cured specimen was trimmed off and faces cleaned using 1200 grid sand-paper with hand-held polishing machine. The thickness and diameter of the composite cylinder were measured using digital vernier. The blow holes and cracks were initially inspected by visual observation and then using ultra sound crack detector for microscopic defects. The defect free specimens were considered for characterization of burst pressure. The fabricated specimen had length 750mm, inner diameter 80mm and 1mm thick Al tube respectively. Carbon fibers and glass fibers are wound on Al tube for 2mm and 3mm thickness each.

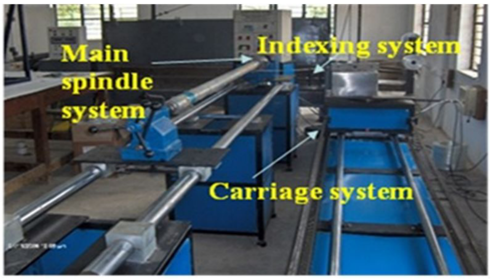

Fig 1- Filament Winding Machine

Fig 2- Winding Process for Composite Cylinder

Specifications of Filament Winding Machine

Maximum Length, mm	2200	Number of control axis	2 axes
Winding angle, Deg	0-90	Mandrel speed, rpm	60
No of winding spindle	Single	Carriage size (LBH), mm	5000 x 400 x 780
Feed rate, mm/min	1		

3. Experimental studies

The cylindrical FMLs fabricated using glass/Al and carbon/Al are tested for burst pressure using on-line acoustic emission (AE) monitor. The internal pressure tests for cylindrical FML specimens were performed according to the standard ASTM D1599-99. The component was mounted in the mechanical fixture with appropriate high pressure seals to prevent any leakage during pressurization. It was then filled with oil for easy detection of leakage or burst. A high pressure hydraulic pump, shown in Fig 3 specially designed for burst pressure test was used to apply internal pressure to the FML specimen. Six AE sensors of identical characteristics were mounted on the FML tube in the form of a rectangular array to cover the entire area of the component. Dynamic processes such as crack initiation, extension of cracks, fiber breakage or ply failure that originates in the inner layers and not on the outermost layer was not visible to the naked eyes during experimentation, but can be captured in an on-line monitoring AE setup and displayed in the monitor. This arrangement of sensors has the capability to detect and locate any real time active sources of failure mechanism in the component. The arrangement of six AE sensors in the rectangular array format is represented through points in the display of Fig 4.

Using the hydraulic pump pressure regulator the barrel was subjected to pressure cycles 0-10-0, 0-20-0, and so on until a defect was visible or a crack was audible. The peak pressure pattern for each specimen was conducted for five cycles. During all these pressure cycles, the acoustic waves released were detected by the individual sensors and the location of crack initiation was displayed on the monitor. This display helped to fix the camera in the location of crack initiation and continuously capture the process of bursting phenomenon.

Fig 3- Hydraulic pump setup

Fig 4- Acoustic Emission setup

4. Results and Discussion

Fig 5 and Fig 6 show the curves of 3 mm and 4 mm thick cylindrical glass FRP /Al and carbon FRP / Al composite structure for burst pressure as a function of time with photographs of crack propagation. The curves could be categorized into four regions, viz., a) Elastic behaviour, b) Plastic behaviour, c) Peak pressure and d) Failure. The sequence of crack mechanism is described below.

With reference to glass fiber based composite cylinder, a) at initial loading, up to a pressure of 25MPa, the slope is linear for both the thicknesses, indicating load absorption only by aluminium cylinder and no load is transferred to the outer fiber layers. The aluminium and FRP layers are subjected to elastic stress (straight line) without any visible crack initiating on the surface of the specimen (A) and no significant change in the dimension of the composite tubes is observed. b) After 25MPa, load is transferred to the outer glass fibers and stresses shift from elastic range to plastic region, the curve in this region is almost flat. Because of increase in pressure inside the cylinder, the fibers are stretched and the distance between fibers on the outer surface increases showing a wider outer diameter (B). Fringes or discolouring appear on the outer surface of the cylinder, due to equal stress distribution along the fibers. c) With further increase in pressure, the inner aluminium tube changes from elastic to plastic state. When pressure loading attains peak (C), small fiber breakages are seen, which represents the initiation of crack in the fibers. The previously visible fringes now disappeared showing stress relaxation, as the stresses get concentrated around the crack. But since no oil leakage was seen, it indicates that the metal layer is still intact (D). d) With further increase in pressure, the crack propagates in all directions and finally the aluminium cylindrical surface bursts leading to large amount of oil spilling out from the tube and the pressure drastically decreases (E).

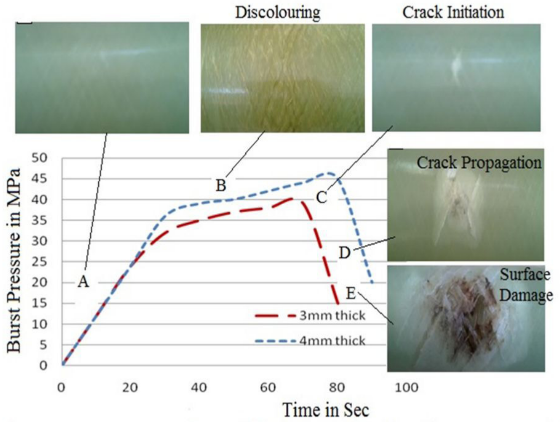

Fig 5 - Damage Sequence of GFRP/Al cylinder as a function of burst pressure and time

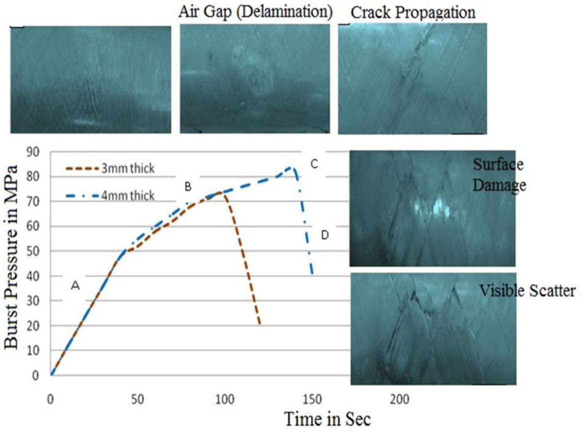

Fig 6 - Damage Sequence of CFRP/Al cylinder as a function of burst pressure and time

In case of carbon based FML, the load absorbed by the same aluminum tube, along with carbon fibers is up to 50MPa. Beyond 50MPa, the load is transferred to the outer carbon fibers. The higher stiffness of the carbon fibers exerted on aluminum tube increases the load bearing capacity of tubes, as proved by Jung-Seok Et al (2011). Similar nature of bursting behavior as that exhibited by glass FRP is shown in Fig.6 for carbon FRP/ aluminium tubes, except the difference in slope at region B. At region B, the elasto-plastic behaviour is observed and hence the pressure increases linearly with time, but for different slope of elastic region (A). At the end of region B, air patch or delamination can be seen on the surface. During this process the failure modes that can be seen is detaching of ply from other ply and leading to failure in the outermost carbon layer. The only difference between carbons based FML and glass based FML is that the failure is concentrated at single point for glass based FMLs and scattered in carbon based FMLs, as shown in region E.

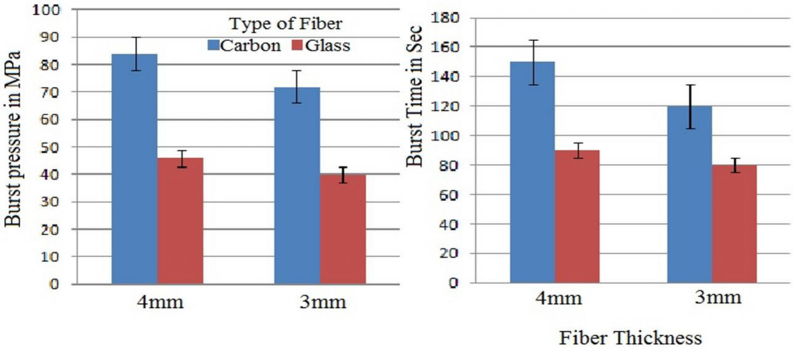

Fig 7 – (a) Peak Pressure and (b) Burst Time for FRP thickness of 3mm and 4mm

The peak pressure and burst time of glass based and carbon based Al composite tubes for 3mm and 4mm thickness are presented in Fig 7(a) and (b). It can be observed that beyond the elastic behaviour exhibited by aluminum tubes, the pressure absorbed by 4mm thick cylinder is 17% more in case of carbon / Al cylinder and 15% more for glass /Al cylinder, compared to the composite cylinder of 3mm thick. For glass fibers based composite cylinders of 4mm and 3mm thickness, the peak pressure is attained at 46MPa and 40MPa and for carbon fibers based cylinder at 84MPa and 72MPa. The surface burst occurs at 90sec for 4mm thick glass fiber based cylinder compared to 80sec for 3mm thick cylinder. In case of carbon cylinder for 4mm and 3mm thicknesses, burst occurs at 150sec and 120sec respectively. This indicates that the type of fiber wound on the cylinder and thickness of FRP does influence the pressure holding capacity of a composite cylinder (David Cohen Et al (2001)). The initiation of crack, crack propagation and surface burst in glass based FML is concentrated at a single point resulting in stress concentration around the crack, while in case of carbon based FML it is scattered, resulting in visible matrix cracking. The elaborate fracture in carbon based tubes is due to improved load bearing capacity and higher stiffness of carbon fibers (Jung-Seok et al (2011)).

Higher the thickness, higher is the load at which failure occurs. This is an expected result considering that carbon fibers are much stronger and stiffer (David Cohen et al (2001), Jung-Seok et al (2011)) than the glass fibers and burst performance increases with increase in the thickness of the composite layer. Also pressure tests done by Pinar Karpuz (2005) reveal that the carbon fiber reinforced composite tubes exhibited a better burst performance compared to the glass fiber reinforced tubes.

5. Conclusion

Based on experimental results, the following conclusions were drawn:

- The burst pressure of carbon / Al FML cylinder showed 80% and 82.61% higher than glass / Al FML cylinder for 3mm and 4mm thicknesses respectively.
- The burst strength enhancement due to increase in thickness of FRP layer is 16.67% and 15% for carbon / Al FML cylinder and glass / Al FML cylinder respectively.
- Failure in glass fiber based FMLs is concentric, while it is scattered in carbon fiber based FMLs.
- The bursting of tubular surface occurred at 90sec and 80sec for glass fiber based cylinder and at 150sec and 120sec for carbon fiber based cylinders of 3mm and 4mm thicknesses respectively.

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