REVIEW ON BURST PRESSURE ANALYSIS OF LAMINATED COMPOSITE PRESSURE VESSELS

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Abstract - *Pressure vessels are used for various industrial applications. To ensure safe operation of pressure vessels, it is important to know its burst pressure*. Burst pressure is the pressure *at which vessel burst/crack and internal fluid leaks. For light weight application pressure vessel are made of composite material. Payload performance /speed /operating range depends up on weight. Use of composites for pressure vessels improves performance and also offer significant amount of material savings. Stacking sequence is very crucial to strength of composite pressure vessels. Though different shapes of pressure vessels exist, most generally cylindrical and spherical shapes are used. Spherical vessels are theoretically two times stronger than cylindrical ones but due to the manufacturing difficulties, cylindrical ones are generally preferred in the industry. In this paper, a review on research work carried out for laminated composite pressure vessel are presented.*

Key Words: Composites, Pressure vessel, Burst pressure, Payload performance, Stacking sequence

1. INTRODUCTION

Pressure vessels are very important and they are used to store many liquids under high pressure. To prevent explosions as a result of rupture, special emphasis should be given to the strength of the pressure vessel. Codes for the safety of such vessels have been developed that specify the design of the container for specified conditions. Most of the pressure vessels are required to carry only low pressures and those types of pressure vessels are constructed of tubes and sheets rolled to form cylinders. Whereas some of the pressure vessels has to carry high pressures, and therefore thickness of the vessel walls must increase in order to provide adequate strength. Interest in studying of the shell arises from the fifties of twentieth century. The assemblies, containing thin shells, find wide use in the modern engineering, especially in ships, aircraft and spacecraft industry.

Composite pressure vessels find application in various fields ranging from households to industrial to aviation. They are critical component in various systems as their failure may lead to fatal accidents due to pressure differential. One of the important parameter to be calculated during design is burst pressure. Burst pressure is the pressure at which vessel burst/crack and internal fluid leaks. It is a design safety limit, which should not be exceeded. If this pressure is exceeded it may lead to mechanical breach and permanent loss of pressure containment. Many studies and research works were carried out by various researchers for the better understanding of structural performance of laminated composite pressure vessels. Cylindrical shells such as thin-walled laminated composite unstiffened vessels like deep submarine exploration housings and autonomous underwater vehicles are subjected to any combination of in plane, Out of plane and shear loads due to the high external hydrostatic pressure during their application. Due to the geometry of these structures, buckling is one of the most important failure criteria.

2. LITERATURE REVIEW

Alexis A. Krikanov [1999] conducted a study of composite pressure vessels with higher stiffness. A new method to design laminated composite pressure vessels under strain and strength constraints is proposed in this paper. A graphical analysis is presented to find optimum layer thicknesses for given fiber orientations. Replacing circumferential layer by second helical layer is suggested as a new way of strain suppressing among the commonly used ways for strain suppressing such as (1) addition of extra plies and (2) use of composite material with a higher stiffness. Numerical expressions and graphs are given to obtain optimum laminate configurations.

Jaroslav Mackerle [1999] gives review of finite element methods (FEMs) applied for the analysis of pressure vessel structures and piping from the theoretical as well as practical point of view. He classified his reference papers in to different categories: linear and nonlinear, static and dynamic, stress and deflection analyses; stability problems; thermal problems; fracture mechanics problems; contact problems; fluid–structure interaction problems; manufacturing of pipes and tubes; welded pipes and pressure vessel components; development of special finite elements for pressure vessels and pipes; finite element software; and other topics. Among the numerical procedures, finite element methods are the most frequently used.

Chang [2000] theoretically and experimentally analysed failure of the first laminate of composite pressure vessels. The experimental results were compared with theoretical results based on the Hoffman, Hill, and Tsai-Wu maximum stress criterions which accurately predicted the pressure in which the failure of the first layer occurs. Wu failure criteria can yield fairly good results with consistent accuracy for the laminated pressure vessels. In particular, the Hill criterion can predict first-ply failure pressure load with error around 1%.

Mohammad Z. Kabir [2000] conducted finite element analysis of composite pressure vessels with a load sharing metallic liner. A numerical analysis of filament-reinforced internally pressurized cylindrical vessels with over wrapped metallic liner is presented. The method uses the load-bearing liner approach and leak-before-rupture as design criteria. Numerical results are reported for the effects of different head shapes and the superiority of optimum geodesic head shapes in reducing the maximum stresses is also investigated. Incorporating the variable thickness in the analysis limits considerably the deformations of the structures. The metallic liner produces a remarkable drop in the principal on-axis stress, in both helical and hoop wound layers.

Levend Parnas et al. [2002] analytical procedure is developed to design and predict the behaviour of fiber-reinforced composite pressure vessels under combined mechanical and hydrothermal loading. The cylindrical pressure vessel is analysed using two approaches, which are thin wall and thick wall solutions. It is shown that for composite pressure vessels with a ratio of outer to inner radius, up to 1.1, two approaches give similar results in terms of the optimum winding angle, the burst pressure, etc. As the ratio increases, the thick wall analysis is required.

Kim et al. [2005] presented an optimal design method of filament wound structures under internal pressure. They used the semi-geodesic path algorithm to calculate possible winding patterns taking into account the windability and slippage between the fiber and the mandrel surface. In addition, they performed a finite element analyses using commercial code, ABAQUS, to predict the behaviour of filament wound structures. The optimal dome contour was studied in ANSYS with a trial design.

Zheng Chuan-xiang et al. [2006] presented new modified Faupel's formulae for calculating the burst pressure. According to the author formulae is derived based on bursting experiment on hundreds of mild steel pressure vessel and based on analysing the data as Faupel formulae is having the error in the calculation. Error in the calculation is reduced after using the modified Faupel formulae and hence the value is more closely match with the experimental data.

Koppert et al.[2007] conducted experimental investigation along with finite element modelling on the composite pressure vessels made by dry filament winding method. They represented that the results of finite element model for vessels with one or two layers is consistent with experimental results but there are high errors for vessels with three or four layers.

Onder et al. [2009] studied burst pressure of filament wound composite pressure vessels under alternating pure internal pressure. The study dealt with the influences of temperature and winding angle on filament wound composite pressure vessels. Finite element method and experimental approaches were employed to verify the optimum winding angles. The hygrothermal and other mechanical properties were measured on E-glass–epoxy composite flat layers. Some analytical and experimental solutions were compared with the finite element solutions, in which commercial software ANSYS 10.0 was utilized; close results were obtained between analytical and experimental solutions for some orientations.

P. Xu et al. [2009] conduced finite element analysis of burst pressure of composite hydrogen storage vessels. In this research, a 3D parametric finite element model is proposed to predict the damage evolution and failure strength of the composite hydrogen storage vessels, in which a solution algorithm is proposed to investigate the progressive damage and failure properties of composite structures with increasing internal pressure. The maximum stress, Hoffman, Tsai–Hill and Tsai–Wu failure criteria which are employed respectively to determine the failure properties of composite vessels are incorporated into the numerical method as individual subroutines. Parametric studies in terms of the effects of different failure criteria are performed and the calculated failure strengths of composite vessels are also compared with the experimental results.

T. Aseer Brabin et al. [2011] examined different existing predictive equations which are used to predict burst pressure by utilizing test data on different steel vessels. They found that Faupel's bursting pressure formula is simple and reliable in predicting the burst pressure of thin and thick-walled steel cylindrical vessels. They suggested that variation in burst pressure values may be attributed to variation in strength properties of vessel material.

E.S. Barboza Neto et al.[2011] investigated the behaviour of pressure vessel liner under burst pressure testing. They used liner with polymer blend of 95% LLDPE and 5%HDPE which is to be used in all composite carbon/epoxy compressed natural gas shell manufactured by filament winding process. Designing and failure prediction of composite laminate shell and liner were based on Tsai-Wu and Von Mises criteria respectively. Liners of different thickness were tested in hydrostatic burst pressure testing machine. FEA simulations were conducted using

ABAQUS/CAE6.8 in which model was meshed by using CAX4R element type. Authors conducted preliminary simulation by using sub-laminate with different orientation and found 400 orientation to be best in regards of strength. They concluded that ideal thickness of liner which can with stand the pressure of 2-2.2 MPa lie between 15-16 mm. In order to account for manufacturing tolerances, a 15.3 mm nominal thickness was chosen for the liner. The hydrostatic pressure limit of the actual liner was 2.0 MPa and the characteristic fracture behaviour changed from brittle to ductile.

Haris Hameed Mian et al.[2013] studied optimization of composite material system and lay-up to achieve minimum weight pressure vessel. The work elucidates the procedure to optimize the lay-up for composite pressure vessel using finite element analysis and calculate the relative weight saving compared with the reference metallic pressure vessel. The determination of proper fiber orientation and laminate thickness is very important to decrease manufacturing difficulties and increase structural efficiency. The lay-up sequence, orientation and laminate thickness (number of layers) are optimized for three composite materials S-glass/epoxy, Kevlar/epoxy and Carbon/ epoxy. Finite element analysis of composite pressure vessel is performed by using commercial finite element code ANSYS and utilizing the capabilities of ANSYS Parametric Design Language and Design Optimization module to automate the process of optimization. For verification, a code is developed in MATLAB based on classical lamination theory; incorporating Tsai–Wu failure criterion for first-ply failure (FPF). The results of the MATLAB code show its effectiveness in theoretical prediction of first-ply failure strengths of laminated composite pressure vessels and close agreement with the FEA results.

Amruta M. Kulkarni et al. [2015] calculated burst pressure of liquid petroleum gas cylinder used in household application by using twice elastic slope criteria. Authors have compared results of two design approaches which are design by experiment and design by analysis in which they consider both material and geometry nonlinearity. They performed nonlinear finite element analysis using commercial software ANSYS 14. They also suggested using Plane 42 axisymmetric elements to reduce computational time. They found mean variation between experimental and numerical simulation to be - 0.5741% and thus establishing a strong correlation between numerical and experimental results.

Christopher J. Evans et al. [2015] used nonlinear finite element analysis to determine the failure location and failure pressure for pressure vessels. The method investigated by this paper is to predict the pressure-vessel failure point by identifying the pressure and location where the total mechanical strain exceeds the actual elongation limit of the material. Authors used a symmetrically shaped component and a non-symmetric shaped component for their research. Authors compared their FEA results with experimental data and found them to be in agreement for symmetrically shaped component, however, for the nonsymmetrical shaped pressure- vessel, the FEA software predicted the failure pressure within a reasonable range, but the component failed at different location than predicted location because of variation in material properties in both the weld and the location where the vessel was predicted to fail.

Usman T Murtaza et al. [2015] compared two different design approaches suggested by ASME for a PWR reactor pressure vessel which was made up of nuclear grade steel "SA-508 Gr.3Cl.1". Authors performed FE analysis using ANSYS and used twice elastic slope criteria to determine the collapse load, element used for the analysis is Solid 186 i.e. higher order 3-D 20-node solid element. Maximum Stress concentration was obtained around nozzle-cylinder junction. Authors suggested to not rely on theoretical design to avoid unnecessary conservatism and use design by analysis approach to predict burst pressure of pressure vessel.

Zhi-Min Li et al. [2015] studied buckling and postbuckling of anisotropic laminated cylindrical shells under combined external pressure and axial compression in thermal environments. The buckling and postbuckling analysis for an anisotropic laminated thin cylindrical shell of finite length subjected to combined loading of external pressure and axial compression using the boundary layer theory is presented. Postbuckling response of perfect and imperfect, anisotropic laminated cylindrical shells with respect to the material and geometric properties and load-proportional parameters under different sets of thermal environmental conditions are numerically illustrated. The analytical model developed can be used as a versatile and accurate tool to study the buckling and postbuckling behaviour of composite structures.

A.M. Kamal et al. [2016] investigated analytical and finite element modelling of pressure vessels for seawater reverse osmosis desalination plants. A pressure vessel (PV) which contains the membrane elements of seawater reverse osmosis (SWRO) desalination has been modelled using analytical solution and finite element modelling (FEM) to optimize the PV design parameters. Two types of PV materials have been compared namely; stainless steel and fiber reinforced composite materials. Von-Mises yield criterion and Tsai-Wu failure criterion are used for the design of stainless steel and composite PVs respectively. E-glass/epoxy and carbon/epoxy composite materials are considered in this work. In addition, hybrid composite materials are introduced for layers through the vessel thickness. The results have shown that the composite PVs have lighter weight than the stainless steel PVs. The carbon/epoxy PVs introduce the optimum weight savings but in terms of the total PVs cost, the hybrid composite PVs can be used.

S. Sharifi et al [2016] conducted numerical and experimental study on mechanical strength of internally pressurized laminated woven composite shells incorporated with surface-bounded sensors. In this study, strain deformation of three types of internally pressurized laminated composite shells (hemispherical, ellipsoidal, and torispherical) with two types of woven roving (WR) stacking sequence (WR $[0]_6$ and WR $[0/45]_3$) was studied numerically and experimentally. The regions at which the critical strain occurs were determined by using finite element analysis (FEA). Vacuum infusion process (VIP) was employed for the composite shell fabrication. The surface-bounded sensors were used to measure strain values occurring at the outermost ply. In general, a good agreement between strain variation rates derived by the two approaches was observed. However, some discrepancy was observed for strain magnitude, particularly the ones close to the boundary. Furthermore, the effect of staking sequence and geometrical shape on the mechanical strength of laminated woven composite shells was investigated. Laminated composite shells with WR $[0/ 45]_3$ were found to be the preferred choice over WR $[0]_6$.

3. CONCLUSIONS

From the literatures it is find out that, many researchers conducted studies on laminated composite pressure vessels. Failure of pressure vessels are mainly caused by buckling. Researchers used different approaches to evaluate burst pressure namely analytical, experimental and numerical. They suggested avoiding use of analytical approach to avoid unnecessary conservatism. Amongst various formulas available, Faupel formula gives most reliable results. Experimentally evaluating bursting pressure is costly and dangerous. Composite pressure vessels Tsai-Wu failure criteria gives best results and maximum bursting strength. The analytical method developed can be used as a versatile and accurate tool to study the buckling and postbuckling behaviour of composite structures. The determination of proper fiber orientation and laminate thickness is very important to decrease manufacturing difficulties and increase structural efficiency.

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