Finite Element Analysis to Calculate Bursting Pressure Using Ramberg-Osgood Model

Puneet Deolia and Firoz Ahmed Shaikh

***Abstract*— Pressure vessels are very common structural component which are used to store fluid under pressure in many industries such as process, petrochemical, power and aviation. This structure can be a simple geometry or complex geometry containing many geometrical discontinuities. Vessels are usually required to operate in complex loading conditions such as internal pressure, external forces, thermal loads, etc. Because of these complex loading conditions vessel tend to store large amount of energy. Hence it would be disastrous if a vessel bursts. An accurate prediction of burst pressure is necessary in chemical, medical and aviation industry. To numerically calculate burst pressure material curve is essential and accuracy of predicting the burst pressure is dependent on the strain energy under the curve. There are various material models which are used to define material curve, amongst them Ramberg-Osgood is very popular. Ramberg-Osgood accurately capture material curve in strain hardening region. This approach is applicable for different material grades. In this paper a finite element method is used to predict burst pressure using Ramberg-Osgood equation. The finite element analysis is a non-linear analysis which includes the geometry and material non-linearity in the model and it is solved using the Newton Raphson algorithm. These results are then compared and validated with results obtained by experimental results.**

***Index Terms*— Pressure Vessel, Burst Pressure, Ramberg-Osgood.**

I. INTRODUCTION

BURST pressure is the pressure at which vessel burst/crack and internal fluid leaks. An accurate prediction of burst pressure is necessary in chemical, medical and aviation industry. It is imperative to find bursting value of vessel which is the pressure at which vessel burst/crack and internal fluid leaks. It is a safety limit, which should not be exceeded. Ductile instability and brittle fracture are two failure modes for a cylindrical pressure vessel. With improvement in manufacturing processes and enhancement in material, a vessel is more likely to experience a ductile burst failure. Hence, in this paper only ductile instability failure mode is considered. Bursting a ductile vessel involves large plastic strain. To predict the bursting pressure has long been an important aspect in the design of vessels. To ensure high safety performance, the design and manufacturing of vessels are governed by various mandatory national standards, codes and guidelines. Most pressure vessel design codes assume a membrane stress state condition for the determination of the smallest shell thickness and large safety factors at areas of geometric discontinuities. Large safety factors lead to increasing the material thickness, while safety is not necessarily increased as fracture toughness decreases with increasing thickness. Also stress corrosion cracking at components operating in corrosive environments is expected to be higher in thicker parts [1, 2]. Considerable work has been reported by various researchers on this subject and many formulas have been proposed for calculating the burst pressure of a pressure vessel depending on their type and manufacturing process. Engineering solutions using experimental methods are well defined for this problem, but burst data from experimental models are limited. Many researchers suggested to use of the finite element method for predicting the bursting pressure since the configurations that can be examined are unlimited and the effort and expense required are relatively minimal.

T. Aseer Brabin et al. [1] examined various existing predictive equations used to predict bursting value of vessels. According to them amongst various formulas, Faupel's bursting pressure formula is simple and reliable in predicting the burst pressure of thin and thick-walled steel cylindrical vessels. Zheng Chuan-xiang et al. [2] experimentally studied large number of mild steel pressure vessel and presented new modified Faupel formula for calculating the burst pressure. The applicability of this formula is limited to mild steel pressure vessels only. A.Th. Diamantoudis et al. [3] did a comparative study for design by formula and design by analysis approaches for a cylinder to nozzle intersection which is part of vertical pressure vessel with skirt support by using finite element techniques. Materials used in their study were ductile P355 steel alloy and high strength steel alloy P500QT. Theoretical formulas used for evaluation of bursting value gives conservative results when compared with finite element analysis results. Similar kind of comparative study was done by Usman Tariq Murtaza et al. [4] for PWR reactor pressure vessel. They observed an increase of 17.70 % in maximum allowable pressure when vessel is designed by design by analysis approach. They used multi-linear material model for analysis. Amruta M. Kulkarni et al. [5] calculated burst pressure of liquid petroleum gas cylinder by numerically by using commercial software ANSYS 14. They compared there

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results experimental results. They performed nonlinear finite element analysis by using plane 42 axisymmetric elements to reduce computational time. They found a strong correlation between numerical and experimental results. Christopher J. Evans et al. [6] investigated by using nonlinear finite element analysis to determine the failure location and failure pressure for pressure vessels. The method they to predict the pressure-vessel failure point is 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. Failure pressure prediction for symmetrically shaped component and a non-symmetric shaped component were in good agreement with experimental results. Variation in burst location prediction for non-symmetric shaped component was attributed to variation in material properties both in the weld and the location where the vessel was predicted to fail. Liping Xue et al. [7] predicted burst pressure of cylindrical shell made of Q235A material subjected to internal pressure accurately by using finite element method. They performed nonlinear static analysis by using 3-D 20 node solid element type. They also found that the Barlow equation can be used to predict burst pressure analytical. Yasin Kisioglu [8] predicted the burst pressures and burst failure locations for toroidal shaped liquefied petroleum gas fuel tanks using both finite element analysis and experimental approaches. Experimental burst test investigations were performed hydrostatically by him where the cylinders were internally pressurized with water by him. In FEA modeling processes, these liquefied petroleum gas fuel tanks were subjected to incremental internal uniform pressure and nonlinear analysis was performed. Numerically 8.77 MPa burst pressure was calculated by author that was in agreement with experimental value of 8.50 MPa of burst pressure. From literature it was observed that most researchers have used true stress-strain curve obtained after material testing [3, 6, 7, 8]. Masayuki Kamaya [9] proposed a procedure for estimating true stress-strain curves of the Ramberg-Osgood type for which only the yield and ultimate strengths are required. Author applied the estimation procedure to eight materials to investigate validity of estimations to assess structural integrity of cracked pipes. It was shown that the change in failure load derived by using the stress-strain curves which were estimated increased as the yield strength was decreased. He concluded that by using the proposed procedure change in failure load could be limited to less than 5%. In this paper a new methodology is proposed to perform finite element analysis. Material curve used to perform non-linear static analysis is obtained by using Ramberg-Osgood equation. This methodology eliminates necessity of material testing in preliminary design stage. Thus it is helpful in saving cost and precious time. Results obtained were compared with experimental results.

II. DIMENSION OF CYLINDRICAL PRESSURE VESSEL

Vessel is made of mild steel material. All major dimension of vessel are enlisted in table below. The vessel is designed to safely operate at 17-23 bar pressure range. This vessel is considered to be thin pressure vessel as r/t >= 10.

Table 1. Physical Property of Mild Steel

Sr. No.	Physical properties	Dimensions
1	Outer diameter (mm)	204
2	Inner diameter (mm)	200
3	Length without end cap (mm)	400

III. MATERIAL PROPERTIES

Mild steel is used as material for manufacturing the pressure vessel. It possesses high toughness, plasticity and good weldability. Also it is being inexpensive and easy available and mainly used for the production of various industrial vessels. Material test was performed as per ASTM E8 standard to calculate its mechanical properties. From the test it is observed that the material is having young’s modulus of 205,000 MPa, the yield limit of 337 MPa and ultimate limit of 391 MPa with 32 % strain at rupture. Detail material graph obtained from the test is shown in Figure 1. These material properties are used in Ramberg-Osgood equation to achieve the true stress-strain curve which is further implemented in FEM.

Fig. 1. Experimental Material curve for Mild Steel

Ramberg-Osgood equation is used to describe the non-linear relationship between stress and strain. It is especially useful for metals that harden with plastic deformation.

Original form of Ramberg Osgood equation can be written [9]:

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{\sigma_y}\right)^n \qquad (1)$$

Where ε and σ are total strain and stress in MPa respectively. E is Young's Modulus of the material in MPa. Estimation of parameter n is proposed to simplify the definition of material. Although there were numerous approached to estimate this parameter, the following equation is widely accepted

$$n = \frac{ln(e_{us}/0.002)}{ln(\sigma_U/\sigma_Y)} \quad (2)$$

Where e_{us} is uniform strain at max load i.e. at σ_u σ_u and σ_y are yield stress and ultimate stress of material respectively.

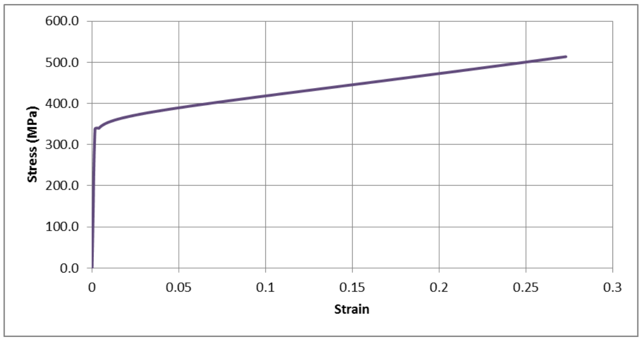

Fig. 2. Ramberg-Osgood Material Curve used for FEM analysis

IV. EXPERIMENTAL SETUP

Manufactured vessel is shown in Figure 3. Total of two vessels has been manufactured and tested to get the average burst pressure and to evaluate the experimental accuracy of burst pressure test. Details of experimental set up are shown in Figure 3. Prior to perform the burst test, the pressure vessel is filled with the water. To avoid the air bubble trap inside the vessel, priming has been done by removing air bubble from the vessel. Single bubble trap inside the vessel may lead to the explosion of the vessel. To perform the priming pressure gauge has been removed temporarily and water pumped in the vessel using lever which removes the bubble from the dial gauge opening. This procedure is repeated till no bubble is coming from the opening. After priming operation dial gauge is fitted and water pumped in using the lever till the vessel burst.

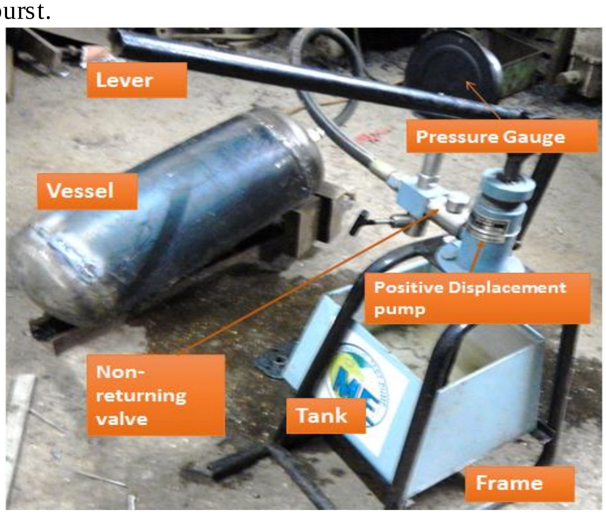

Fig. 3.Details of Experimental Setup - Burst test

V. FINITE ELEMENT METHOD

Commercial software Hypermesh 12.0 is used as pre-processor and post processor whereas Commercial Software NASTRAN 2012 is used as solver. Static nonlinear finite element analysis of vessels was performed to calculate burst pressure. As the vessel under consideration is thin, stresses across the thickness are neglected. The midsurface of vessels were extracted which were considered to mesh the vessel with 2D FEA shell model. This is expected to reduce the solving time. The shell element, Tria3 element type was used to mesh the model of vessel which comprises of node count of 4741 for pressure vessel. Weld of 3mm is modeled in the vessel to consider the effect of welded joint.

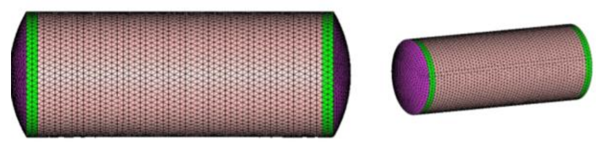

Fig.4. Meshed Model of vessel in Hypermesh

A. *Loading and boundary condition*

Loading - Pressure of 1 bar is applied inside the vessel and load is incremented in steps until the non-linear or von-Mises equivalent stress induced in vessels exceeds ultimate strength of material. Pressure at which induced stresses exceeds ultimate strength of material is considered to be the burst pressure of the vessel.

Boundary Conditions - Some nodes are identified in the models which were constrained to keep the models in equilibrium in such a way that no reactions are observed at constrained location. This boundary conditions are applied to avoid singularity in Finite Element Model.

VI. RESULTS AND DISCUSSION

From the experimentation, average burst pressure is achieved at 91 bar i.e. at which the leakage start and pressure start to drop in the gauge. To understand the acceptability of Ramberg-Osgood method pressure vessel were analyzed. Stress plot of the vessel is shown in Figure 5. Where, the stresses for the vessel exceeding the ultimate limit are considered as the burst of the vessel.

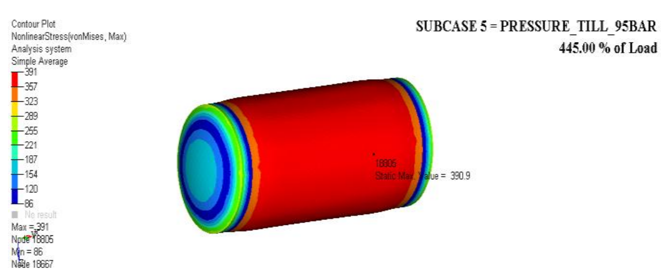

Fig. 5. Stress plot of vessel

FIGURE 6 SHOWS THE BURST LOCATION OF VESSEL WHICH IS NEARLY SAME AS OF EXPERIMENTAL LOCATION. IN THE FE

ANALYSIS THE VESSEL IS EXCEEDING THE ULTIMATE LIMIT OF MATERIAL AT 87 BAR. MAXIMUM PERCENTAGE ERROR OBSERVED IS 4.39%, WHICH GIVES GOOD AGREEMENT BETWEEN THE EXPERIMENTAL AND FE RESULT.

Fig. 6. Burst Location of vessel

Table 2. Results

Sr. No.	Experimental Results(Bar)	FEM Results(Bar)
1	92	87
2	90	87

VII. CONCLUSIONS

THE VESSEL IS SUBJECTED TO AN INCREMENTAL INTERNAL PRESSURE TO DETERMINE THE EXACT BURST PRESSURE AND BURST FAILURE LOCATION WERE EVALUATED USING BOTH EXPERIMENTAL AND FE SIMULATION WITH RAMBERG-OSGOOD MODEL. BASED ON THE GENERATED RESULTS, THE FOLLOWING CONCLUSIONS CAN BE MADE.

- REASONABLE AGREEMENT IS ACHIEVED BETWEEN FINITE ELEMENT RESULTS AND EXPERIMENTAL RESULTS. ANALYZING THE RESULT, RAMBERG-OSGOOD MATERIAL MODEL SHOWS BETTER CORRELATION WITH THE EXPERIMENTAL RESULT. BURST PRESSURE RESULT OBTAINED FROM FEA WAS ABOUT 87 BAR, WHEREAS THE BURST PRESSURE RESULT FROM THE EXPERIMENTATION WAS 91 BAR. ERROR OF 4.39% IS OBSERVED BETWEEN THE RESULTS WHICH IS SURELY A GOOD AGREEMENT IN THE RESULT.

- ANALYZING THE RESULT, RAMBERG-OSGOOD MATERIAL MODEL SHOWS BETTER CORRELATION WITH THE EXPERIMENTAL AND ACTUAL MATERIAL CURVE.

RAMBERG-OSGOOD MATERIAL MODEL CAN BE USED FOR ANY MATERIAL WHICH HAS INFORMATION REGARDING YIELD LIMIT, ULTIMATE LIMIT AND STRAIN AT RUPTURE. THIS METHODOLOGY WILL EVENTUALLY SAVE THE TIME AND COST OF ACTUAL TESTING. DISCREPANCY IN THE PREDICTION USING RAMBERG-OSGOOD MAY BE DUE TO VARIATION IN THE MECHANICAL PROPERTIES OF MATERIAL USED FOR THE EXPERIMENTATION.

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