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Design by Analysis of Liquid Petroleum Gas Cylinder using Twice Elastic Slope Criteria to Calculate the Burst Pressure of Cylinder

Amruta Muralidhar Kulkarni
Research Scholar, M.E. (CAD/CAM/CAE)
KIT's College of Engineering,
Kolhapur, Maharashtra, India – 415124

Rajan L. Wankhade
Assistant Professor
Applied Mechanics Department
Government College of Engineering, Karad
Maharashtra, India – 415124

***Abstract*—Pressure vessels are used to hold gases under pressure and therefore are very important for various engineering applications. Liquid Petroleum Gas (LPG) cylinder is a thin pressure vessel used to meet energy requirements in household applications. Bursting of pressure vessel is disastrous and many fatal accidents are happened due to pressure vessel bursting. So prediction of burst pressure (B.P.) of a pressure vessel is necessary. In this paper, analysis of Liquid Petroleum Gas (LPG) cylinder is done to calculate the Burst Pressure (B.P.) of cylinder. The experimental data is taken from open literature. Finite Element Analysis is carried out using ANSYS commercial code. Burst Pressure (B.P.) is determined by applying Twice Elastic Slope Criteria (TESCA) of plastic collapse. Then the Mean Error (ME) is calculated between the experimental results and the results obtained by Finite Element Analysis (FEA).The FEA results showed the good agreement with experimental results.**

Keywords—LPG; B.P.; FEA; Twice Elastic Slope Criteria

I. Introduction

Liquid Petroleum gas (LPG) also referred to as simply propane or butane are flammable mixtures of hydrocarbons gases used as fuel in heating appliances, cooking equipment and vehicles. As its boiling temperature is below room temperature, LPG will evaporate quickly at normal temperature and pressure. So it is stored in pressurized steel vessels. Pressurized pressure vessels hold a large amount of energy at working pressure and also as LPG is flammable it will be disastrous if the pressure vessel (cylinder) bursts. Bursting of pressure vessel can cause extensive property damage, personal injury, environmental pollution and even loss of life. So prediction of burst pressure of a pressure vessel used in critical application is necessary.

Y. Kisioglu, J.R. Brevick, G.L. Kinzel (2001) has determined the burst pressure of DOT-39 refrigerant cylinders using both experimental and finite element analysis [1]. A Th. Diamantoudis, Th. Kermanidis (2004) studied comparison of design by analysis verses design by formulae of a cylinder to nozzle intersection by using FEA, author had calculated limiting load of pressure vessel and lead to conclusion that application of DBA (Design By Analysis) leads to much better results [2]. Y. Kisioglu, J.R. Brevick, G.L. Kinzel (2005) optimized Bottom End-Closure Design of DOT-39 Non-Refillable Refrigerant Cylinders [3]. M. Egemen Aksoley, Babur Ozcelik, Ismail Bican (2007) compared bursting pressure results of LPG tank using experimental and finite element method [4]. A. Kaptan, Y. Kisioglu (2007) has determined burst pressures and failure locations of vehicle LPG cylindrical fuel tanks using both experimental and finite element analysis (FEA) [5]. Y. Kisioglu, J. R. Brevick, G.L. Kinzel (2008) studied minimum material design for propane cylinder endclosures [6]. Peng-fei LIU, Jin-yang ZHENG, Li MA, Cun-jian MIAO, Lin-lin WU (2008) proposed a theoretical method using FEA to calculate the plastic collapse loads of pressure vessel under internal pressure and compares the analytical methods according to three criteria stated in the ASME boiler pressure vessel code[7]. Donald Mackenzie, Duncan Camilleri, Robert Hamilton (2008) studied design by Analysis of ductile failure and buckling in torospherical pressure vessel heads subjected to internal pressure. The purpose of this study is to investigate interaction between elastic plastic buckling and formation of GPD mechanism in a vessel. The plastic load is determined by applying the ASME twice elastic slope criteria of plastic collapse and alternative plastic criteria, the Plastic Work Curvature criteria [8]. Yasin Kisioglu (2011) determined the burst pressures and burst failure locations of the vehicle toroidal liquefied petroleum gas (LPG) fuel tanks using both experimental and finite element analysis (FEA) approach[9].Therefore very less work is reported to estimate the Burst Pressure of LPG cylinder by Design by analysis approach. So there is scope for work in this area. Also some Authors [8] used Twice Elastic Slope Criteria to estimate limit load so we can use that criteria to determine the Burst Pressure.

II. DESIGN APPROACHES

As far as design of pressure vessel is considered there are three main approaches used for designing, these are listed below:

A. *Design by experimentation*

In design by experimentation approach designers are carrying out experimental testing on actual model. But carrying out experimental test is costlier on actual model and results from prototype may not be same as that of actual model. Also accuracies of measurements and other factors are affecting on the results. Also it requires large number of experiments to rely on the results. Also experimentation is risky because if there is failure of equipment resulting in burst then it may cause danger to life hence special care needs to be taken while testing.

B. *Design by formulae or codes or rules [DBF]:*

In traditional design by formula method design activity is carried out by using formulae developed by researchers or code formulae, these formulae changes with change in loading, size, shape, location, material and some other factors. Method of design by formulae is unable to account nonlinearity.

C. *Design by analysis [DBA]:*

It is using all the knowledge in engineering mechanics, theoretical as well as practical and all the practical experience with numerical methods and with commercially available hardware and software for simulation of the behavior of structure under various actions.DBA approach started in 1992, this new approach is now laid down in normative annex B of part 3 of Design of horizontal vessels standard EN (European Norm) 13445 for unfired pressure vessels. Design by analysis is classified in three categories. These are as follows:

1) *DBA- linear analysis*
2) *DBA without considering geometrical non linearity but considering material non linearity*
3) *DBA- Direct route (DBA-DR)*: It is the non linear analysis considering all kinds of non linearity

III. PHENOMENON OF BURSTING (STRESS STRAIN CURVE)

The stress-strain diagram for a ductile material like steel is shown in this Fig. 1,

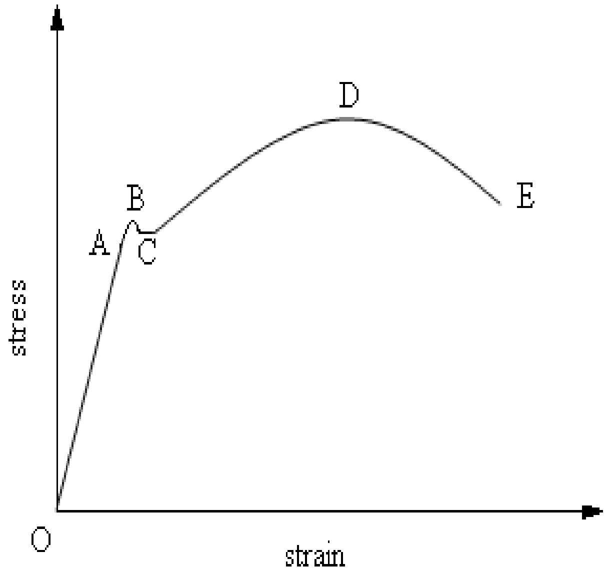

Fig.1. Stress-strain curve for ductile material

Part OA is linear. In this region the stress is directly proportional to strain. If a specimen is loaded within this limit and gradually unloaded, it returns to its original length without any permanent deformation. This is linear elastic region and point A denotes the limit of proportionality. Beyond A, the curve becomes slightly nonlinear. However the strain up to point B is still elastic. Point B, therefore, represents the elastic limit. If the specimen is strained further, the stress drops suddenly (represented by point C) and thereafter the material yields at constant stress. After D, further straining is accompanied by increased stress, indicating work hardening. This work hardening continues up to the point E. Point E is the ultimate stress and it is the highest value of the stress that the material can bear without fracture. Then up to the ultimate strength, the deformation in the material is uniform along the length of the material and then at the maximum stress localized deformation or necking occurs in the specimen and load (stress) falls of as area decreases and failure occurs. In case of any type of pressure vessel it can take load up to UTS and further increase in load cause decrease in shell thickness and vessel bursts.

IV. TESC (TWICE ELASTIC SLOPE CRITERIA)

In elastic plastic analysis the GPD (gross plastic deformation) load or limit (bursting) load is defined by applying a criterion of plastic collapse to a characteristic load – deformation curve calculated for pressure vessel. The ASME TES (Twice elastic slope) criterion is based on an empirical procedure for calculating collapse loads in experimental stress analysis of pressure vessels and is illustrated in Fig. 2 given below. The plastic load corresponding to the intersection of the load- deformation curve and a straight line called the collapse limit line, emanating from the origin of the load deformation curve at angle $\varphi=\tan^{-1}(2\tan\Phi)$. Factor of safety based on this limiting load will be used for deciding factor of safety. In this procedure stresses are allowed to exceed yield limits hence lesser thickness will be used for same pressure resulting in economical design. The Twice Elastic Slope Criterion of plastic collapse is shown in the Fig. 2,

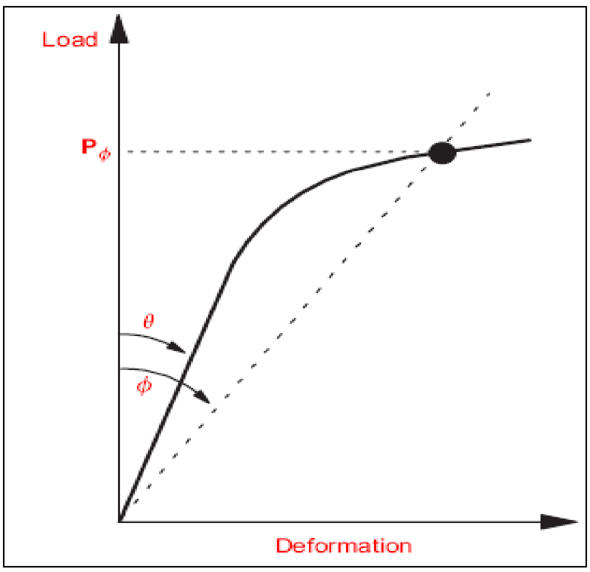

Fig.2. Twice elastic slope criterion of plastic collapse

V. ANALYSIS OF LPG CYLINDER

In this section nonlinear analysis of LPG cylinder is carried out by using ANSYS 14. Total hundred LPG cylinders are analyzed using ANSYS and following is the case study of one of the LPG cylinder.

A. Case study

Design Specifications: For analysis Two dimensional (2D) Axi-symmetric model of vessel is formed it is shown in Fig. 3, Also the dimensions used for analysis is shown in TABLE.I.

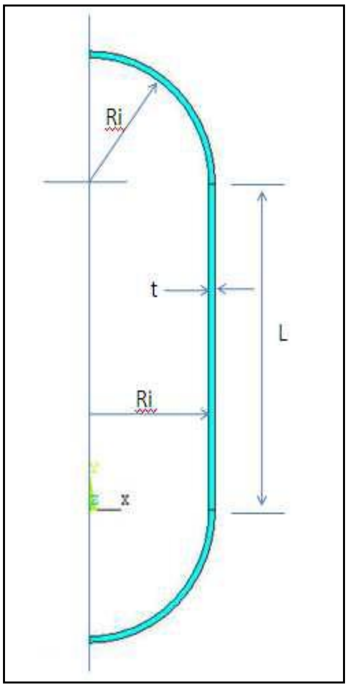

Fig.3. Two dimensional (2D) Axi-symmetric model of vessel

TABLE I. DIMENSIONS USED FOR ANALYSIS

Sr. No.	B.P. (Mpa)	D_i (mm)	t (mm)	D_o (mm)	L (mm)	σ_{ys} (Mpa)	σ_{uts} (Mpa)	e %
1	10.79 1	314.4	3.1	320.6	488	310	397	35

Where,

B.P. = Experimental burst pressure
D_i= Inner diameter of the cylinder
t=Thickness of the cylinder
D_o= Outer diameter of the cylinder
D_m= Mean diameter of the cylinder
L= Length outside to outside ends
σ_{ult}=Ultimate tensile strength
σ_{ys}= Yield strength
e%= Tensile strain (%)

B. Basic Assumptions

The main assumptions of the computational model developed in the current dissertation are:

a) Material is homogeneous and isotropic
b) Buckling as an Eigen value problem is not considered
c) Loading conditions are static

C. Material Properties

Stress strain curve for this material is shown in Fig. 4, .All material properties are taken at room temperature. Non linear material properties will be considered for inelastic analysis

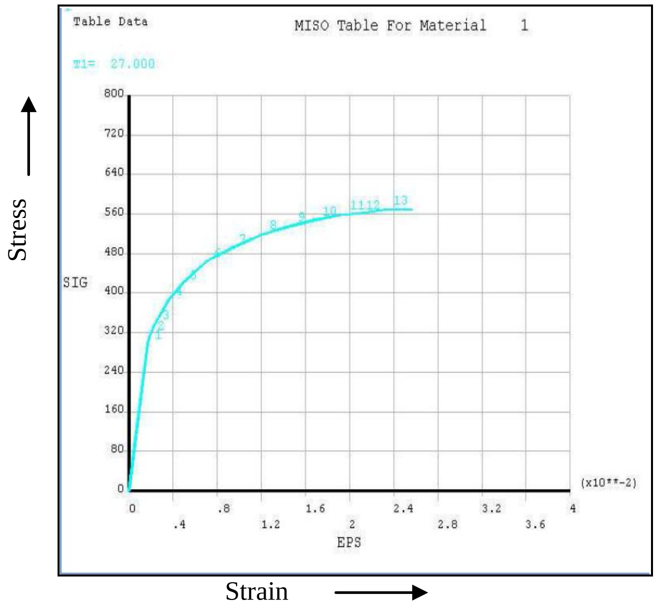

Fig.4. Stress strain curve used for analysis

D. FEA Model

Now we will estimate bursting pressure of cylinder (internally pressurized) by using Finite Element Analysis software ANSYS. Finite element model using plane 42 axisymmetric elements is shown in the Fig. 5, minimum three layers of element are kept in all sections of model. Also mesh grading was done to get higher mesh density in high stress region. Also precaution was taken to avoid error elements in meshing. Also mesh convergence was checked.

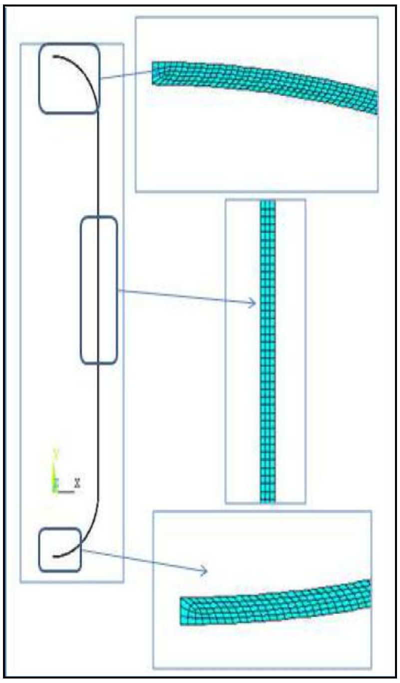

Fig .5 Axisymmetric Finite element model

E. Boundary conditions

Internal pressure is applied on internal surface of vessel as shown in Fig. 6; axisymmetric model was used for analysis. Pressure was increased from 0 MPa and effect of change in pressure on response of structure was observed.

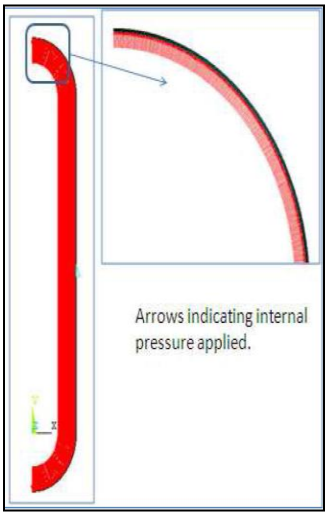

Fig.6. Boundary conditions applied to axisymmetric model

F. Element selection

Here for solving this problem we have selected axisymmetric plane 42 (element with 4 node) elements and solid 45 (element with 8 node) elements. Out of plane 42 is axisymmetric element and solid 45 is 3D element. After comparison of results of two elements it was observed that there is no remarkable change observed in results of two elements. Following Fig. 7 shows results of both elements, in which load verses deformation curve of two elements are coincident and hence any element can be used for this problem. It will be seen by another perspective that is by coming actual number of nodes used in both cases, for plane 42 element 1877 nodes are used and for solid 45 elements 24442 nodes. That means after increasing nodes number by approximately for using plane 42 elements is valid and plane 42 elements will be used to reduce computational time for all cases given below.

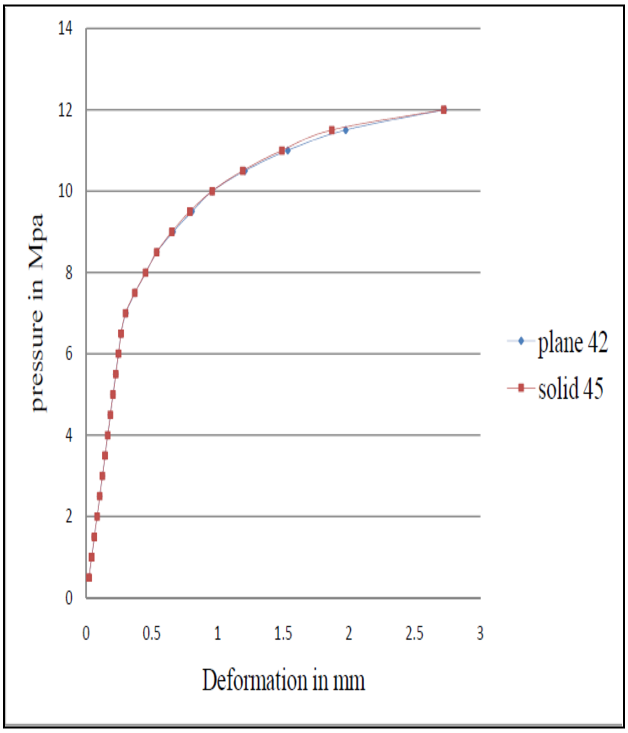

Fig.7. Load verses deformation curve by using different elements

G. Mesh sensitivity analysis

After deciding element type next question arises how much fine mesh is necessary. To find out answer of this question number of trials have taken by changing number of elements keeping load and other details constant, and results are plotted as deformation verses number of nodes as shown in Fig. 8, and stress verses number of nodes as shown in Fig 9, in both cases number of nodes were increased from 1000 to 6000 nodes (i.e. six times increase in node) but stress is increased from 232.69 MPa to 232.79 MPa as shown in Fig. 9, which is far less as compared to increase in number of nodes. Also trend of graph from 2000 nodes to 6000 nodes is horizontal and hence any number of nodes above 2000 nodes can be used for this problem. But on safer side care was taken for generating nodes higher than 6000 for each model followed here after and hence this approximation is also valid one.

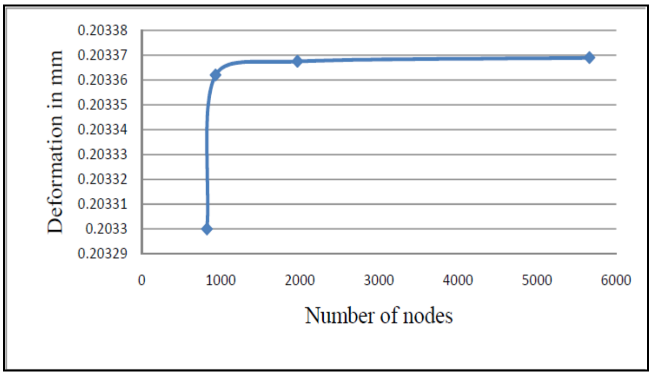

Fig.8. Graph of deformation in mm verses node number

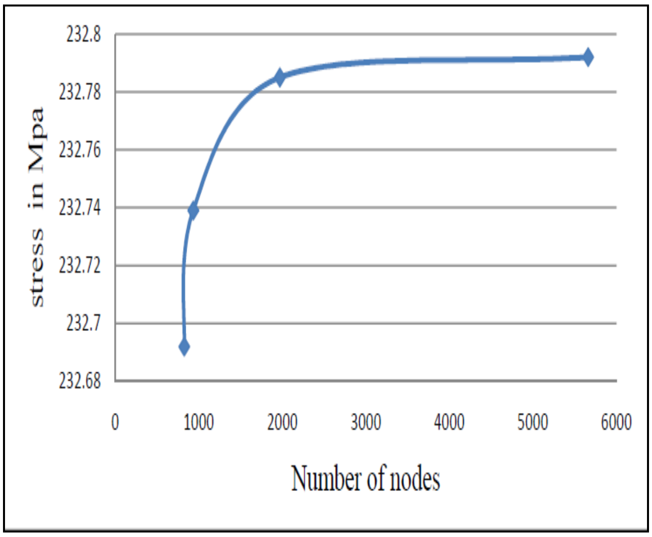

Fig.9. Graph of stress verses node number

Deformation is increased from 0.2033 to 0.20337 mm as shown in Fig. 8, which means deformation increases by 0.00007 mm by increasing nodes from 1000 to 6000. As model contains elements with more than 6000 nodes in each model hence approximation is valid for this case also.

H. FEA Results

In this section the FEA results are drawn and deformation values are calculated**.** The deformation of LPG cylinder is calculated from 0 MPa to limiting pressure. At 0.5 MPa pressure the deformation obtained is 0.023774 mm. Following Fig. 10 shows the deformation of LPG cylinder at 0.5 MPa. Red colour in Fig. 10 indicates maximum deformation of vessel. There is less radial deformation observed at ends due to heads. Cylinder deforms more at middle due to internal pressure. Similarly the pressure is applied to cylinder in step by step manner. For this cylinder limiting pressure is 12.6 MPa. At 12.6 MPa deformation is maximum and the value is 3.8556 mm. Fig. 11, shows the deformation of LPG cylinder at 12.6 MPa. This values 12.6 MPa is the theoretical maximum value of burst pressure vessel.

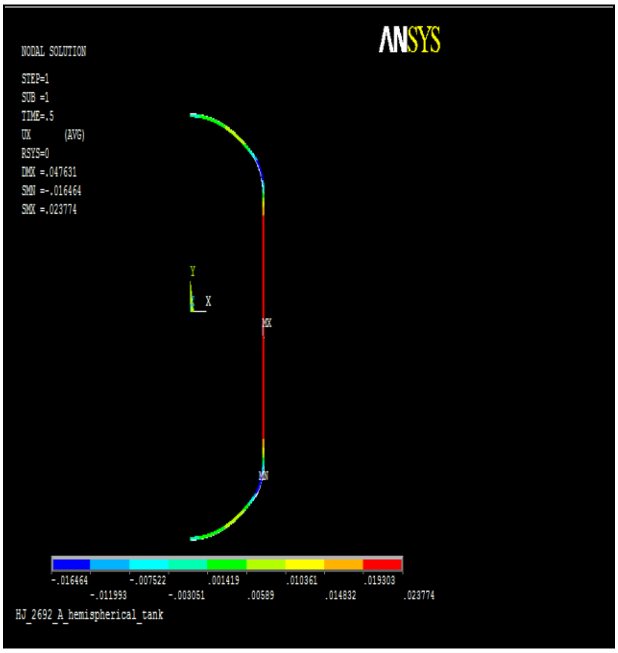

Fig.10. Deformation of LPG cylinder at 0.5 Mpa

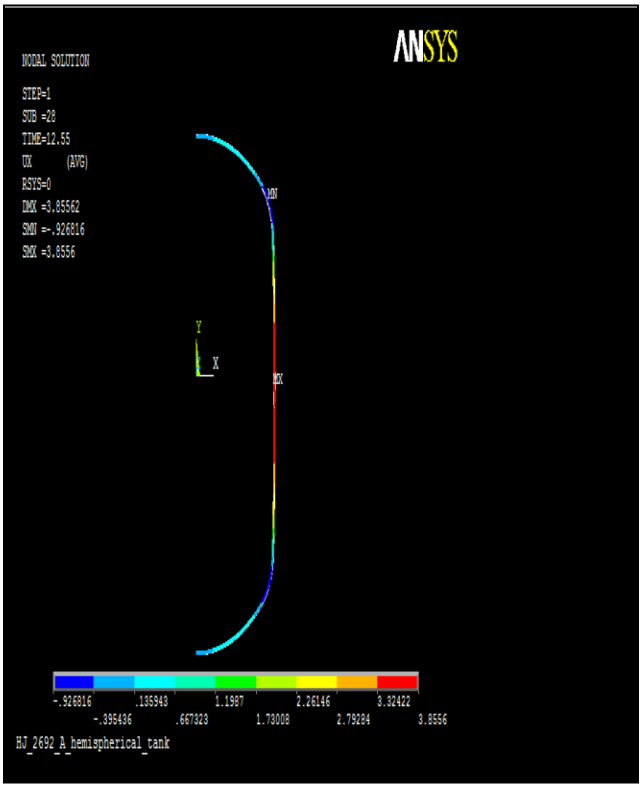

Fig.11. Deformation of LPG cylinder at 12.6 MPa

Following TABLE II summarize the values of deformation at each pressure applied to LPG cylinder starting from 0 MPa up to limiting pressure 12.6 MPa. Also values of 2D that is twice slope are calculated and tabulated in the following table. By using this data we plotted load –deformation curve and twice slope line. Then the intersection of this twice slope line with load-deformation curve gives some value and that value is the burst pressure by TESC.

TABLE II VALUES OF DEFORMATION AND TWICE SLOPE (2D) FOR LPG CYLINDER UPTO LIMITING PRESSURE

Sr. No.	Pressure	Deformation	2D (Twice Slope)
1	0.00	0	0
2	0.50	0.023774	0.047548
3	1.00	0.047534	0.095068
4	1.50	0.071282	0.1426067
5	2.00	0.094981	0.1901407
6	2.50	0.118704	0.2376747
7	3.00	0.142415	0.2852087
8	3.50	0.166115	0.3327427
9	4.00	0.189804	0.3802767
10	4.50	0.213522	0.4278107
11	5.00	0.237184	0.4753447
12	5.50	0.26085	0.5228787
13	6.00	0.285103	0.5704127
14	6.50	0.316297	0.6179467
15	7.00	0.366255	0.6654807
16	7.50	0.428218	0.7130147
17	8.00	0.495118	0.7605487
18	8.50	0.565001	0.8080827
19	9.00	0.657153	0.8556167
20	9.50	0.771075	0.9031507
21	10.00	0.921299	0.9506847
22	10.50	1.11252	0.9982187
23	11.00	1.40398	1.0457527
24	11.50	1.75152	1.0932867
25	12.00	2.3001	1.1408207
26	12.50	3.31434	1.1883547
27	12.60	3.8556	1.2358887

Above TABLE II summarize the values of deformation at each pressure applied to LPG cylinder starting from 0 MPa up to limiting pressure 12.6 MPa. Also values of 2D that is twice slope are calculated and tabulated in the above TABLE II. By using this data we plot load–deformation curve and twice slope line. Then the intersection of this twice slope line with load-deformation curve gives some value and that value is the burst pressure by TESC.

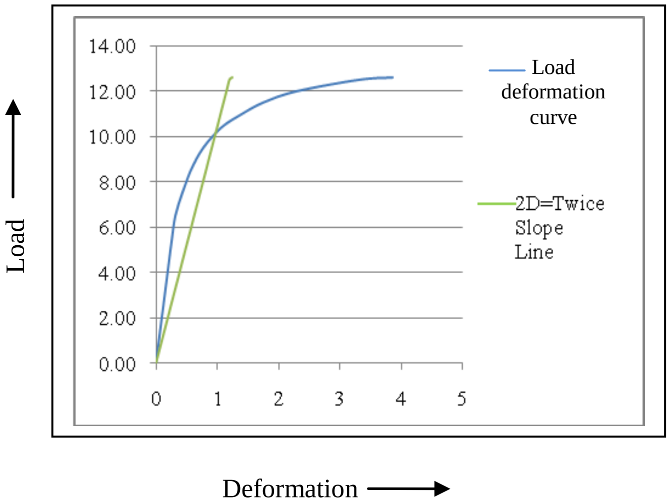

Fig.12. Load verses deformation curve with twice elastic slope method

In above Fig. 12, the intersection of this twice slope line with load-deformation curve gives value of 10.3 MPa. Likewise for remaining ninety nine LPG cylinders we applied same procedure and Values of Burst pressure by DBA-DR are calculated. Following TABLE III shows the results of Burst pressure of hundred LPG cylinders by DBA-DR method.

TABLE III VALUES OF BURST PRESSURE OF HUNDRED LPG CYLINDER BY DBA-DR

Sr. No.	BP(MPa)	t (mm)	DBA-DR
1	10.791	3.1	10.5
2	10.2024	3.62	10.1
3	10.3986	3.53	10.2
4	10.3005	3.51	10.31
5	10.3005	3.05	10.1
6	10.0062	3.65	10
7	10.5948	3.6	11
8	10.3005	3.53	10.2
9	10.3986	3.55	10.4
10	10.3986	3.45	10.38
11	9.81	3.51	9.9
12	9.81	2.9	9.8
13	10.3005	3.53	10.2
14	10.3986	3.32	10.72
15	10.3005	3.62	10.4
16	10.3986	2.98	9.9
17	10.3005	3.51	10.2
18	10.3005	2.97	9.9
19	10.5948	3.6	10.45
20	10.3005	3.42	10.92
21	10.791	3.08	10.3
22	10.791	3.06	10.2
23	10.791	3.45	10.6
24	10.791	3.5	10.65
25	10.6929	3.66	10.5

26	10.6929	3.65	10.45
Sr. No.	**BP(MPa)**	**t (mm)**	**DBA-DR**
27	10.791	3.2	10.6
28	10.791	3.45	10.62
29	10.791	3.35	10.8
30	10.791	3.65	10.7
31	10.5948	3.6	10.5
32	10.5948	3.65	10.6
33	10.791	3.3	10.8
34	10.791	3.62	10.5
35	10.791	3.49	10.7
36	10.791	3.52	10.6
37	10.791	3.62	10.5
38	10.791	3.57	10.7
39	10.3986	3.6	10.4
40	10.3986	3.51	10.3
41	10.6929	3.4	10.9
42	10.6929	3.5	10.6
43	10.791	3.58	10.7
44	10.791	3.5	10.7
45	10.5948	3.67	10.5
46	10.5948	3.45	10.4
47	10.5948	3.46	10.5
48	10.5948	3.49	10.6
49	10.791	3.45	10.4
50	10.791	3.4	10.9
51	10.9872	3.58	10.9
52	10.9872	3.51	10.8
53	9.81	3.04	10
54	9.81	2.95	9.8
55	10.791	3.58	10.65
56	10.791	3.35	10.8
57	10.791	3.52	10.6
58	10.791	3.46	10.7
59	10.791	3.49	10.6
60	10.791	3.45	10.7
61	11.1834	3.49	11.4
62	11.1834	3.45	11
63	11.2815	3.42	11
64	11.2815	3.48	11.3
65	11.1834	3.47	11.2
66	11.1834	3.46	11.2
67	10.791	3.49	10.8
68	10.791	3.55	10.8
69	11.2815	3.46	11.3
70	11.2815	3.42	11.2
71	10.9872	3.21	10.6
72	10.9872	3.3	10.9

73	11.2815	3.22	11.3
Sr.No.	**BP(MPa)**	**t (mm)**	**DBA-DR**
74	11.2815	3.22	11.3
75	11.2815	3.28	11
76	11.2815	3.39	11.3
77	10.9872	3.55	11.2
78	10.9872	3.48	11
79	11.2815	3.49	11.3
80	11.2815	3.46	11.2
81	11.2815	3.48	11.3
82	11.2815	3.52	11.4
83	11.2815	3.65	11.5
84	11.2815	3.55	11.3
85	11.2815	3.6	11.3
86	11.2815	3.62	11.4
87	11.2815	3.53	11.3
88	11.2815	3.6	11.3
89	11.2815	3.47	11.2
90	11.2815	3.65	11.3
91	11.1834	3.5	11.2
92	11.1834	3.48	11.2
93	10.791	3.65	10.7
94	10.791	3.5	10.6
95	10.6929	3.63	10.6
96	10.6929	3.55	10.7
97	10.5948	3.62	10.6
98	10.5948	3.6	10.6
99	10.2024	3.45	10.2
100	10.3986	3.52	10.4

VI. STATISTICAL ANALYSIS OF FEA RESULTS AND EXPERIMENTAL RESULTS

Mean Error (ME) is the important statistical error parameter used for the statistical analysis of FEA results and experimental results. Mean Error is the relative error on average. The formula to calculate the Mean Error is,

$$\text{Mean error (ME)} = \Sigma\, [(P^{cal}/P^{exp}-1)/N]$$

Where P^{cal} denotes the calculated prediction of burst pressure using the different burst pressure prediction models, P^{exp} is the experimental test data of burst pressure, N is the total number of tests in a burst database considered in a statistical analysis. For a best predictive model, the prediction should match a large population of experimental samples, with a mean error approaching to zero.

Then the results of hundred cylinders by DBA-DR method that is FEA results are compared with experimental results of Burst Pressure and mean error is calculated and the mean error obtained is -0.5741%

VII. CONCLUSION

The current study is dealing with the Burst Pressure prediction by using Design By Analysis approach with the help of ANSYS software. The FEA results showed the good agreement with the experimental results.

As we discussed Design by experimentation have certain disadvantages like inaccurate results, high cost, and requirement of large number of experimental results and risk to life while carrying out experiments. The disadvantages of DBF approach is that formulae change with load, size, shape and some other factors. Also it is unable to account nonlinearity. The disadvantages of Design by experimentation and Design by formulae are overcome in this approach. So the Design by analysis is also the effective method to estimate the Burst Pressure of LPG cylinder.

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