Investigation of Forming Limit Curves of Various Sheet Materials Using Hydraulic Bulge Testing With Analytical, Experimental and FEA Techniques.

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ABSTRACT

In sheet hydroforming, variation in incoming sheet coil properties is a common problem for forming process, especially with materials for automotive applications. Even though incoming sheet coil may meet tensile test specifications, high rejection rate is often observed in production due to inconsistent material behavior. Thus there is a strong need for a discriminating method for testing incoming sheet material formability. The hydraulic sheet bulge test emulates biaxial deformation conditions commonly seen in production operations. This test is increasingly being applied by the European automotive industry, especially for obtaining reliable sheet material flow stress data that is essential for accurate process simulation. This paper presents determination of Forming Limit curves (FLCs) of materials Aluminium, Mild steel and Brass. Theoretical analysis is carried out by deriving governing equations for determining of Equivalent stress and Equivalent strain based on the bulging to be spherical and Tresca's yield criterion with the associated flow rule. For experimentation Circular Grid Analysis is used. Validation of Experimental results is carried out with explicit solver ANSYS LS-DYNA using inverse analysis method.

Keywords – Sheet hydroforming, Forming Limit Curve(FLC), Circular grid analysis, Tresca's yield criterion.

1. INTRODUCTION

In the automobile industry, there is an increase in demand for weight reduction, of automotive parts which becomes a driving factor in R&D work for both supplier industry and end users. Research is being carried out in the area of sheet hydroforming technology by many researchers. One of the most important objectives of hydroforming process is the production of the parts with a minimization of thickness, weight reduction and uniform thickness. A large number of studies have been carried out to optimize design and process variables in conventional sheet metal forming processes to enhance formability and to develop new materials and processes with improved formability[3]. Hydroforming processes have been developed to improve the material formability and the accuracy of the formed part and to reduce the number of forming steps. Limiting strain induced in material plays a vital role in Hydroforming. This Hydroforming is carried out with Hydraulic sheet bulge testing of sheet metal by two different ways i.e. stepwise and continuous [1].

2. Material Properties Influencing Formability

The properties of sheet metals vary considerably, depending on the base metal (steel, Aluminium, copper, and so on), alloying elements present, processing, heat treatment, gage, and level of cold work [7]. In selecting material for a particular application, a compromise usually must be made between the functional properties required in the part and the forming properties of the available materials. For optimal formability in a wide range of applications, the work material should:

- Distribute strain uniformly
- Reach high strain levels without necking or fracturing
- Withstand in-plane compressive stresses without wrinkling
- Withstand in-plane shear stresses without fracturing
- Retain part shape upon removal from the die
- Retain a smooth surface and resist surface damage

Some production processes can be successfully operated only when the forming properties of the work material are within a narrow range. More frequently, the process can be adjusted to accommodate shifts in work material properties from one range to another, although sometimes at the cost of lower production and higher material waste. Some processes can be successfully operated using work material that has a wide range of properties. In general, consistency in the forming properties of the work material is an important factor in producing a high output of dimensionally accurate parts.

3. Conventional sheet formability tests

Prior to 1960 sheet formability was determined by means of Fundamental (Intrinsic) tests and Simulative tests [13]. Fundamental Tests are insensitive to the thickness and surface condition and specific information, usually relates to only one type of forming operation. Simulative tests provide limited and specific information that is usually sensitive to thickness, surface condition, lubrication, geometry and type of tooling. Hydraulic bulge testing falls under Fundamental tests of bi-axial testing. Several techniques are used to obtain forming limit curve of the metallic materials such as tensile, compression, torsion, hydraulic bulge test etc [1]. These different tests do not replicate each other due to effects of stress state, yield criterion assumption, anisotropy, experimental inaccuracies, temperature etc. Hence, none of the test methods can be named as the best or optimal since each has its own specific field of application due to certain straining paths.

Among these techniques hydraulic bulge testing allows for an increased work hardening of sheet material by distinctive stretching operations and provides better shape accuracy for complex parts. Hence, by selecting proper material and the forming parameters for hydraulic sheet bulging study one can determine Forming Limit Curves (FLCs).

3.1 Significance

- Hydraulic bulge testing is more appropriate for sheet metal forming operations as deformation mode is bi-axial rather than uniaxial. Also it provides flow curves for the materials with extended range of plastic strain levels up to 70% before bursting occurs.
- It is helpful to generate the FLCs which will be reliable sense of reference input to the explicit solver like LS-DYNA. These obtained FLCs are used as load curve input for such solvers for analysis.
- FLCs also serve the best for identifying the exact zone for forming operations without getting affected with localized necking and other possible defects while forming.
- Hydraulic bulge testing would be helpful to calculate the Strain hardening coefficient- 'n' (i.e. Work hardening coefficient) of the material, to determine the ability of the material to be formed.
- A simple and versatile approach.
- A controlled pressure distribution over part surface during forming can be used to "control" the sheet thickness and postpone localized necking.
- The use of only single form surface tooling, which saves time and expense in the manufacture of tooling. Absence of rigid tool contact on one surface also reduces surface friction and thus surface defects, resulting in a good surface finish.

3.2 Materials used for testing

Sheet materials used are Aluminium(Alloy4450-IS617-1994), Mild Steel 40C8(I.S.1570-1979revised), Brass (Commercial Yellow Brass).

3.3 Geometry of the bulge

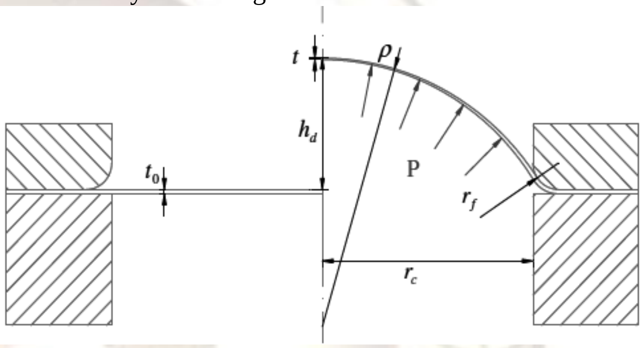

Figure 1. Typical geometry of bulge test

Typical geometry of hydraulic bulge test is shown in Fig.1; in this sheet metal is clamped between two dies as shown [1]. It consists of die cavity radius (r_c), upper die fillet radius (r_f), initial thickness of sheet metal (t_0). As pressure applied, metal will start to bulge to hemispherical dome shape. In order to obtain the flow curve, instantaneous variables such as dome height (h_d), pressure (P), dome apex thickness (t) and bulge radius (ρ) values should be measured at different stages of bulging, and then converted into strain and stress values. These values then plotted as a forming limit curve.

4. Background of research

The first significant attempt to solve the problem of the hydrostatic bulging of circular diaphragms appears to have been made by Gleyzal, who obtained a numerical solution for small strains based on the total-strain theory of plasticity [2]. Hill developed a more general solution for small strains based on the Mises theory, but his method of successive approximation is only valid for sufficiently work-hardened materials. Of greater practical interest is a special solution obtained by Hill on the assumption that the particles at each stage move normally to the momentary profile of the bulge. This solution is valid for strains of any magnitude and provides a useful estimate of the polar strain at instability for materials having arbitrary strain hardening properties. Ross and Prager used Tresca's yield criterion and the associated flow rule to derive a simple solution of the problem with the assumption that the thickness of the bulge is uniform at each stage.

Experimental results show that a central part of the bulge is very nearly spherical and the spherical region increases with the bulge height. Since no membrane solution is expected to be sufficiently accurate near the clamped edge, it is reasonable to assume the bulge to be entirely spherical when large strains are considered [4]. In the present paper, a solution is therefore developed by assuming the bulge to be spherical and employing Tresca's yield criterion and the associated flow rule.

5. Plan of Instrumentation and test setup

In hydraulic bulge test the biaxial stretch forming of the sheet metal is done by fluid pressure. The test specimen (blank) of 225mm diameter and 1.2mm thickness is clamped between two die rings. The upper and lower dies have diameter of 340 mm and the hydraulic pressure is applied from the bottom of the lower die ring with stepped opening of 70mm diameter. For sheet bulging, conical opening of 140mm diameter is provided at the center of the upper die. The fluid pressure is applied with the help of pump and motor (power pack) as it was already available with Mechanical dept. R.I.T. From Fig.2 the pump discharge is connected to the system pressure relief valve, so as to control the pressure, so that the initial pressure is applied accurately. The outlet of system pressure relief valve is connected to 4/3 Direction control valve, such that the rated pressure at all places remains same. The fluid then passes from flow control valve to the lower die opening through narrow channel. The pressure gauge on power pack indicates the pressure applied. The drain valve and pipe is connected to adapter from where the oil flows back to the reservoir (oil tank). Obtained bulge test specimen is shown in fig.3

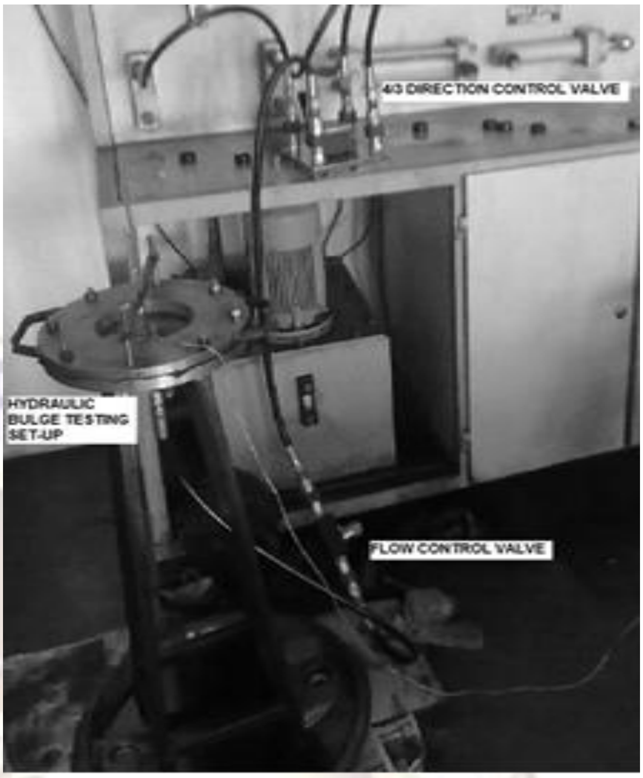

Figure 2.Actual set-up

6. Performance Testing

Before going for actual testing and to ensure the repeatability of the results, three plates for each material are used. Both the processes are employed continuous and step wise bulging method. For first specimen continuous bulging is used to mark the upper limit of the pressure. Later, stepwise bulging is used in steps of 4-8-12-16Kg/cm^2. One of the M.S. specimens is shown in figure. For each pressure, change in diameter of concentric circle is measured and it is expressed in terms of equivalent strain and equivalent strain. FLC's obtained for Aluminium, M.S and Brass are shown in figure below. (Refer fig. 4,5,6)

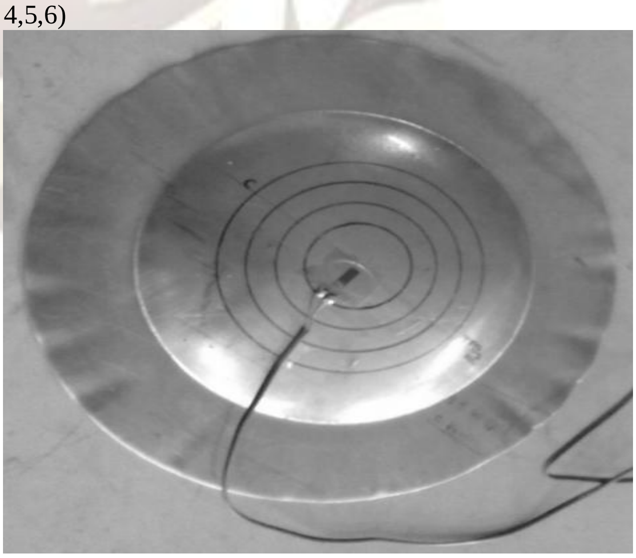

Figure 3 Bulged test specimen

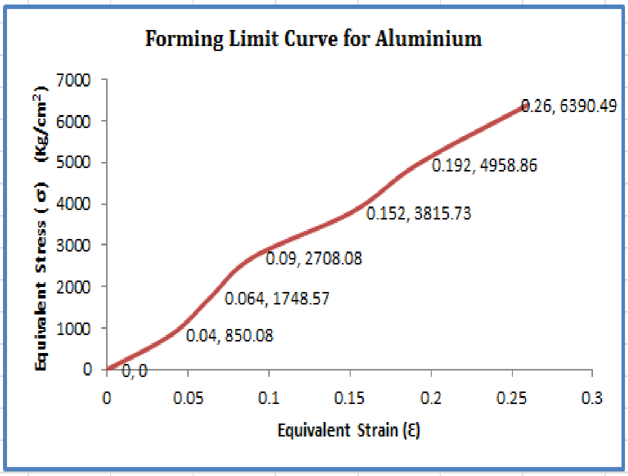

Figure 4. FLC for Aluminium

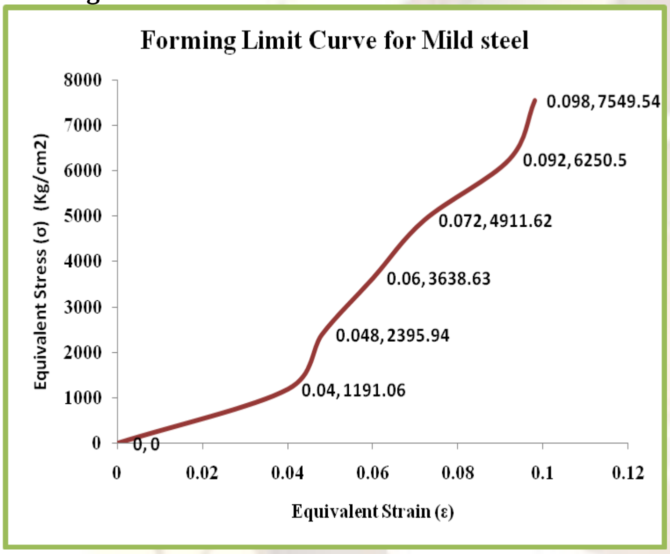

Figure 5. FLC for Mild steel

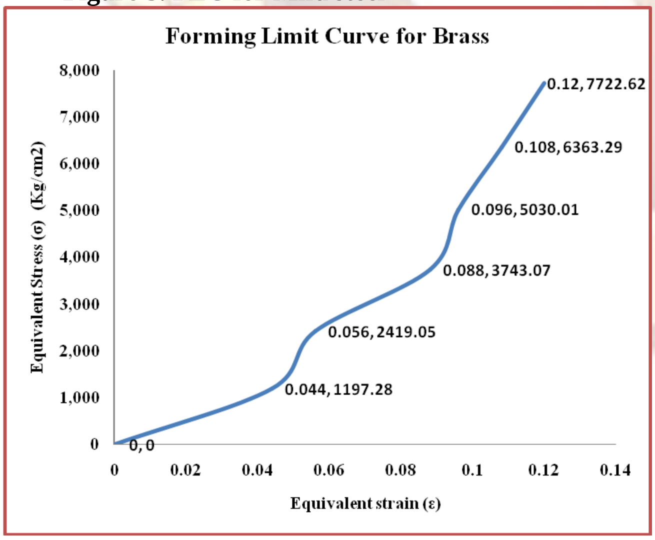

Figure 6. FLC for Brass

7. Numerical Investigation and Verification of Semi-Analytically Obtained Results by ANSYS LS DYNA Software

The forming limit curve is a graphical representation of the relationship between equivalent stress and equivalent strain, derived from measuring the load applied on the sample, i.e. elongation, compression, or distortion [5]. The slope of forming limit curve beyond the point of Elasticity, at any point is called the tangent modulus; the slope of the elastic (linear) portion of the curve is a property used to characterize materials and is known as the Young's modulus. The nature of the curve varies from material to material.

7.1 Inverse analysis methodology – Application to room temperature [10]

The block diagram below shows, the schematic of the proposed inverse analysis methodology. In order to determine flow stress data using a measured geometry (of the deforming bulge), some observable geometric quantities (e.g. bulge height and bulge apex thickness) must be identified, based on their sensitivity of the material properties. Refer free body diagram of set-up form fig.7.

For room temperature bulge testing, the bulge height and bulge apex thickness was selected as the geometric quantity for comparison. Here behavior of the material is assumed to be Bi-linear. Each kind of material inherently consists of two modulus Elasticity modulus- describing elastic behavior and Tangent modulus-describing plastic behavior.

From literature reviewed, Tangent Modulus value was selected as per material used and the analysis carried out [6]. Different checkpoints were used in order to verify the trend of analysis with obtained semi-analytical results. If the assumed values were found to be irrelevant then, with proper changes in assumption of Tangent Modulus values from available existing literature was done. And again analysis is being done till the convergence criterion of analysis is achieved. For such kind of nonlinear analysis ±11% variations in the results is agreeable as per international norms.

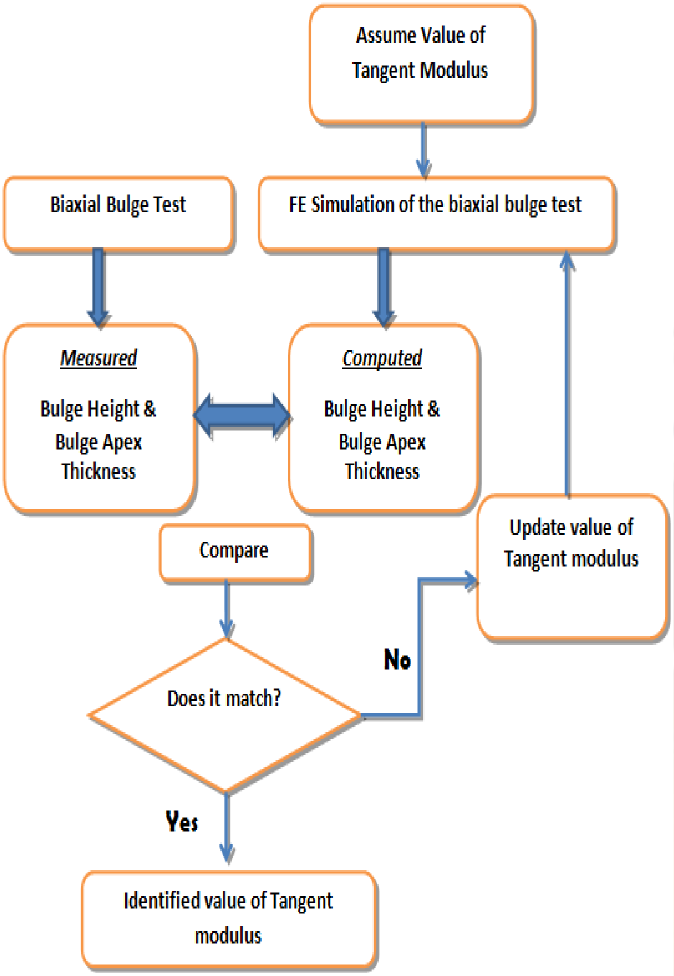

Figure 6. Inverse analysis methodology to determine Forming Limit Curve using the bulge geometry evolution from the biaxial bulge test [10].

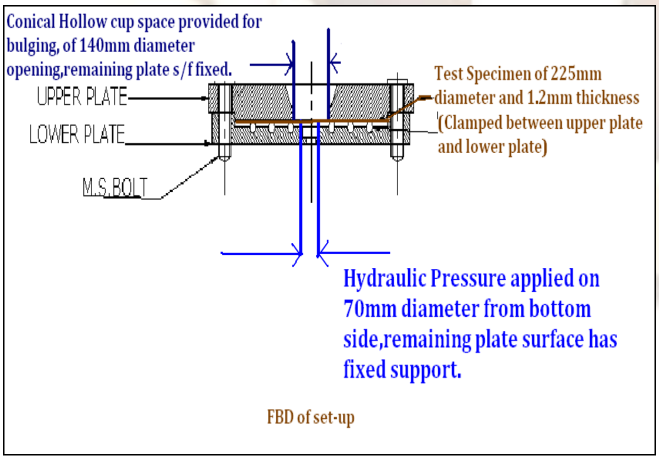

Figure 7. FBD of set-up

The behavior of the sheet metal during bulging was found to be nonlinear and hence, for FEM Explicit dynamic analysis was used [8, 9, 11]. This is nothing but explicit solver used extensively for nonlinear analysis. Here, bulge height and bulge apex thickness were used as a parameters of comparison with Semi-analytical findings.

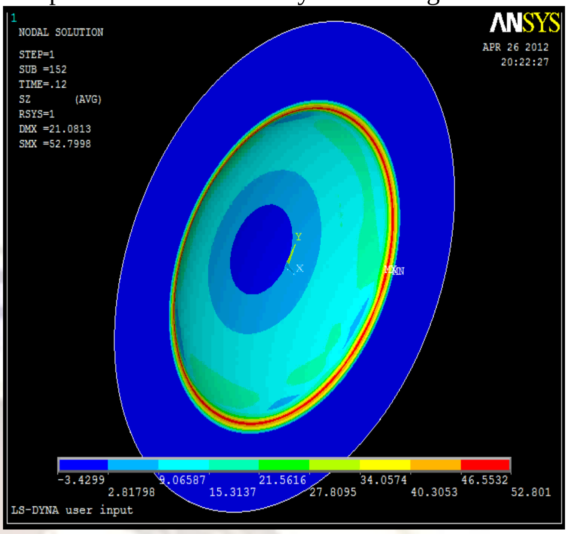

Figure 8. LS-DYNA Contour plot

8. Comparison of Semi-analytical and LS-DYNA analysis results

Bulge height and bulge apex thickness are the parameters of comparative assessment of semi-analytical and LS-DYNA analysis results. As in LS-DYNA there in no provision for determination of Equivalent stress and strain directly, so bulge height and bulge apex thickness are considered as checkpoints for verification of results obtained from semi-analytical method.

8.1 Verification of results for Aluminium material

Table 9.1Results comparison between Semi-analytical and LS-DYNA method for Aluminium

Comparison of Results by Semi-analytical and LS-DYNA method for Aluminium							
Sr. No	Pressure (Kg/Cm2)	Semi-analytically determined **Bulge Height(mm)**	**Bulge height** obtained from LS-DYNA(mm)	% Error	Semi-analytically determined **Bulge apex thickness(mm)**	**Bulge apex thickness** obtained from LS-DYNA(mm)	% Error
1	4	5.8	5.3	8.62	1.1153	1.19831	6.93
2	8	9	8.68	3.56	1.1126	1.19312	6.75
3	12	13	12.17	6.38	1.1097	1.18344	6.23
4	16	17.5	14.65	16.29	1.031	1.16817	11.74
5	20	19.4	17.14	11.65	0.99	1.18274	16.30
6	24	22.52	21.08	6.39	0.909	1.12869	19.46
			Average % error=	8.82		Average % error=	11.23

8.2 Verification of results for Mild Steel material

Table 9.2Results comparison between Semi-analytical and LS-DYNA method for Mild Steel

Comparison of Results by Semi-analytical and LS-DYNA method for Mild Steel							
Sr. No	Pressure (Kg/Cm2)	Semi-analytically determined Bulge Height(mm)	Bulge height obtained from LS-DYNA(mm)	% Error	Semi-analytically determined Bulge apex thickness(mm)	Bulge apex thickness obtained from LS-DYNA(mm)	% Error
1	4	4.15	3.83	7.71	0.826	0.859804	3.93
2	8	6.12	5.5537	9.25	0.82	0.858908	4.53
3	12	8.45	7.883	6.71	0.81	0.85699	5.48
4	16	11.09	10.1252	8.70	0.8	0.853749	6.30
5	20	13.25	11.883	10.32	0.784	0.84993	7.76
6	24	16.3	14.4742	11.20	0.781	0.841392	7.18
			Average % error=	8.98		Average % error=	5.86

8.2 Verification of results for Brass material

Table 9.3 Results comparison between Semi-analytical and LS-DYNA method for Brass

Comparison of Results by Semi-analytical and LS-DYNA method for Commercial Yellow Brass							
Sr. No	Pressure (Kg/Cm2)	Semi-analytically determined Bulge Height(mm)	Bulge height obtained from LS-DYNA(mm)	% Error	Semi-analytically determined Bulge apex thickness(mm)	Bulge apex thickness obtained from LS-DYNA(mm)	% Error
1	4	5.34	4.82227	9.70	0.823	0.858605	4.15
2	8	8.88	7.2692	18.14	0.8132	0.856255	5.03
3	12	11.66	9.4608	18.86	0.7876	0.855521	7.94
4	16	14.12	11.8432	16.12	0.7873	0.852368	7.63
5	20	16.56	13.9942	15.49	0.772	0.847211	8.88
6	24	18.3	17.6061	3.79	0.7628	0.835673	8.72
			Average % error=	13.68		Average % error=	7.06

Conclusion

The Main conclusions drawn from are as under-

1. Results obtained by semi-analytical method for all sheet materials (Aluminium, Brass and M.S.) are found to be fairly close with LS-DYNA results.
2. Similarly, for all test sheet materials i.e. bulge height and bulge apex thickness at pole are closely agree with LS-DYNA results.
3. As test pressure goes on increasing, the bulge apex thickness goes on decreasing.

Scope for Future work

Based on the problems encountered during testing of the equipment, the modification can be taken up as future work-

1. Yet there has been numerous approaches followed for Hydraulic bulge testing but similar to Universal testing machine standardization of this test is not done.
2. This test could be effectively used for light weight composite materials such as Aluminium metal matrix composites.

So, the above recommendations could be considered as a part of further study in future.

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