Metal Forming Laboratory

Experiment No. 04: Hydraulic Bulge Test

- **Objective:** To find out the flow stress behavior of sheet metal under equi-biaxial stress condition.

- **Equipments Required:**

1. Hydraulic bulge test-rig
2. Sheet metal blank of diameter 120 mm.
3. Scriber
4. Micrometer (screwgauge)
5. Depth micrometer
6. Spherometer
7. Flexible scale

Fig. 1(b) Scriber

Fig. 1(a) Hydraulic bulge test-rig

Fig. 1(c) Depth micrometer

Fig. 1(d) Spherometer

[**Note:** Detailed information on **'Spherometer'** can be seen in *'Appendix 2'*.]

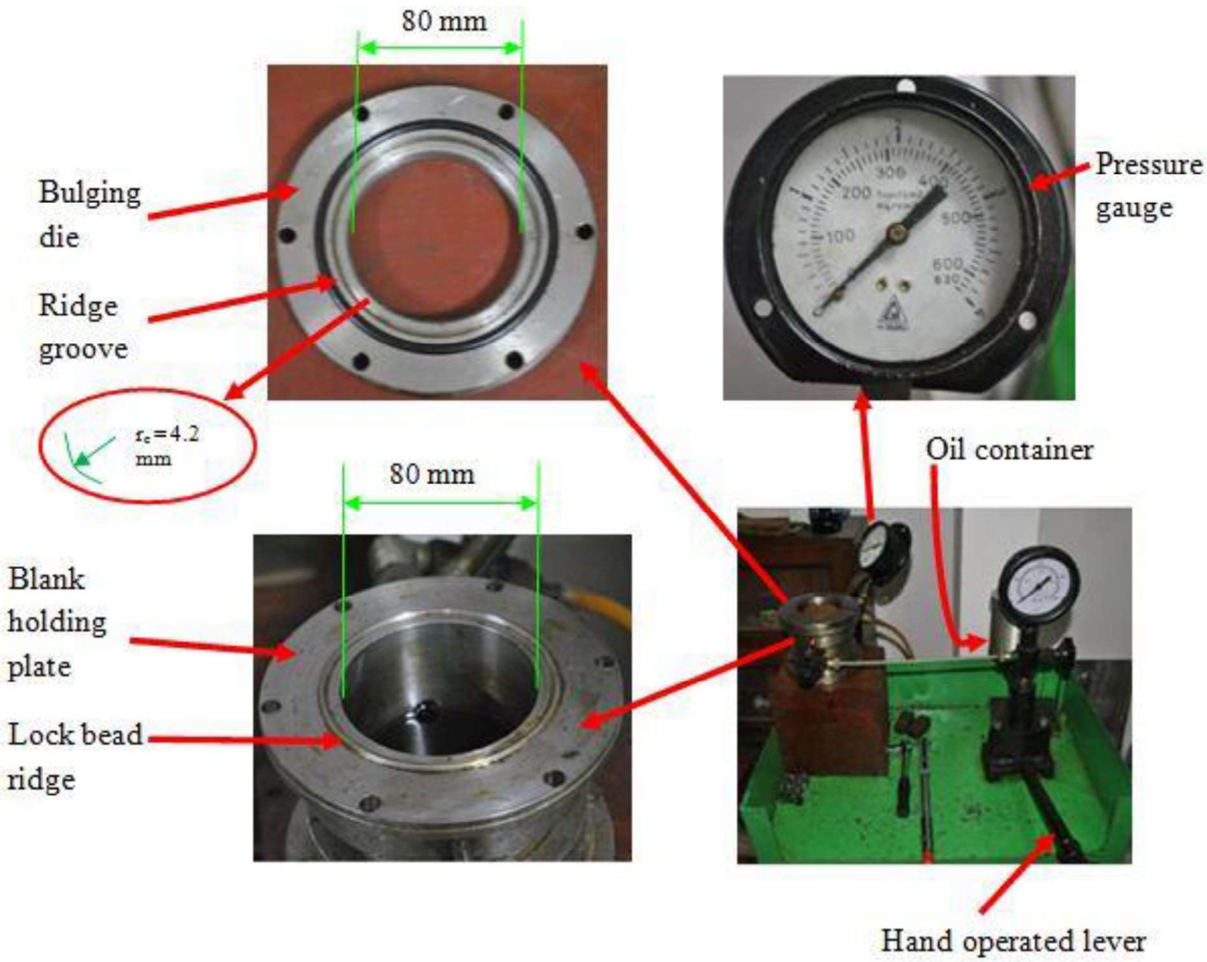


Fig.2.Various components of *'hydraulic bulge test-rig'*

- **Theory:** The stress-strain relationship of sheet metals are conventionally determined by tensile test, where the specimen is loaded uniaxially; but the range of stable uniform strain is restricted to approx 30% of the fracture value. Mostly the stress-strain states in actual sheet metal forming processes are biaxial but not uniaxial; so for finding out the biaxial stress-strain relationship of sheet metals '*Hydraulic bulge test*' is widely used, which gives flow curves for sheet metals with extended range of plastic strain up to 70% of fracture value. Another advantage of the process is that the deformation occurs isothermally [1].

- **Methodology:** In '*Hydraulic bulge test'* a thin metallic sheet is clamped at its periphery between circular die ring & blank holder and then uniform hydraulic pressure is applied at one side of the sheet; as shown in the figure 3. The edge of the dome is prevented from slipping by a lock bead placed in the die ring. It consists of a 'ridge' with small radii on one side and a 'matching groove' on the other. The constant parameter for die set is the die corner radius r_c; as it affects the bulged sheet`s shape & size. Initial thickness of sheet metal t_0 is another constant. As pressure is introduced, the metal starts to bulge to a hemispherical dome shape. Instantaneous variables of this bulging are the dome height h_d, pressure P, dome apex thickness t and bulge or dome radius R_d. In order to obtain the flow curve, these values should be measured at different stages of bulging, and then should be converted into strain and stress values. These values should then be plotted as a flow curve.

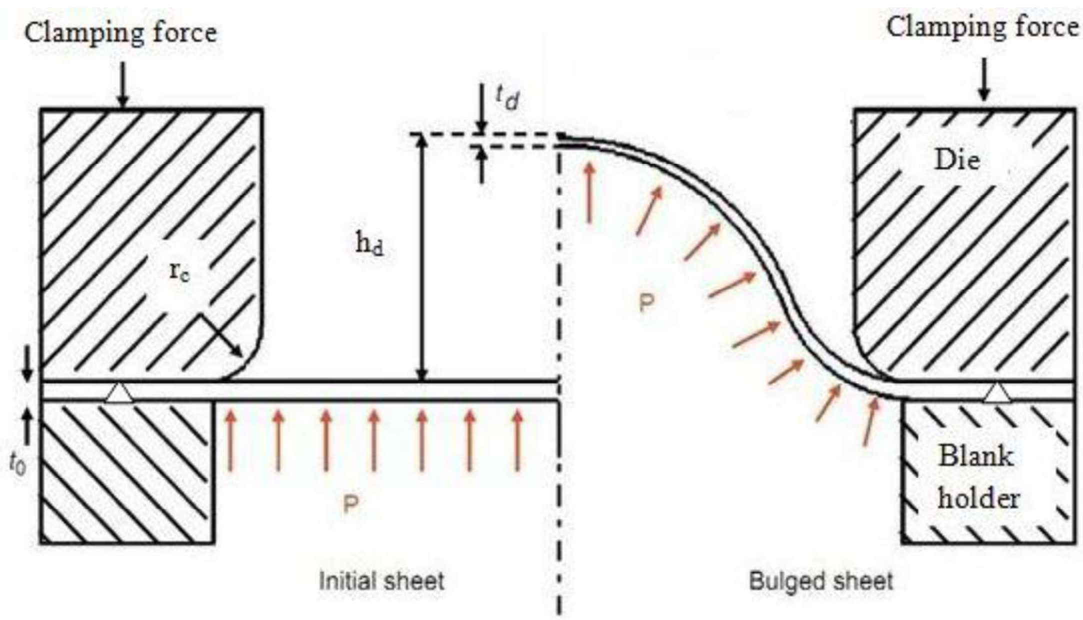


Fig.3. Geometry of '*Bulge test*': Initial (left) and Instantaneous (right)

Since the bulge diameter is greater than 10 times of the sheet thickness, so the effect of bending of the sheet can be neglected & the bulged sheets can be treated as a *'membrane'* in which the stresses are tangential to the middle surface of the wall & uniformly distributed across its thickness [2]. Such stresses are called *membrane* stresses and can easily be calculated by applying *membrane* theory neglecting bending stresses as:

$$\frac{\sigma_c}{R_c} + \frac{\sigma_r}{R_r} = \frac{P}{t_d} \tag{1}$$

[Note: Derivation of equation (1) can be seen in '*Appendix 1*'.]

Where σ_c and σ_r are the principle stresses on the sheet surface along the circumferential & radial directions, R_c and R_r are the corresponding radii of the curved surface, P is the hydraulic pressure, and t_d is the thickness of bulged sheet. For axisymmetric case of the hydraulic bulge test, $\sigma_c = \sigma_r$ and radius of the bulged dome is $R_d = R_c = R_r$.

So,

$$\sigma_c = \sigma_r = \frac{PR_d}{2t_d} \tag{2}$$

In '*hydraulic bulge test'* initially both internal & outer sheet surfaces remain at atmospheric pressure. But once hydraulic pressure is applied the internal sheet surface experiences pressure P. Therefore the average stress σ_n in the sheet metal normal to the sheet surface will be:

$$\sigma_n = \frac{1}{2}(-P + 0)$$

$$\sigma_n = \frac{1}{2}(-P) \tag{3}$$

Now the effective stress $\bar{\sigma}$ can be calculated using *'Von Mises'* Plastic flow criterion as [1]:

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{[(\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 + 6(\tau^2{}_{xy} + \tau^2{}_{yz} + \tau^2{}_{zx})]}$$

Substituting $\sigma_{xx} = \sigma_c$, $\sigma_{yy} = \sigma_r$, $\sigma_{zz} = \sigma_n$, $\tau_{xy} = \tau_{yz} = \tau_{zx} = 0$; and then simplifying the equation we get:

$$\bar{\sigma} = \frac{P}{2}\left(\frac{R_d}{t_d} + 1\right) \tag{4}$$

Similarly the strain normal to the sheet surface can be calculated using '*Volume constancy'* condition as:

$$\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz} = 0$$
$$\varepsilon_{xx} + \varepsilon_{yy} = -\varepsilon_{zz}$$

Substituting $\varepsilon_{xx} = \varepsilon_c$, $\varepsilon_{yy} = \varepsilon_r$ & $\varepsilon_{zz} = \varepsilon_t$ in the above equation we get;

$$\varepsilon_c + \varepsilon_r + \varepsilon_t = 0$$

$$\varepsilon_c + \varepsilon_r = -\varepsilon_t \tag{5}$$

Now similar to the effective stress; effective strain can also be calculated as:

$$\bar{\varepsilon} = -\varepsilon_t = -\ln\left(\frac{t_d}{t_0}\right) \tag{6}$$

- ## Experimental Procedure:

1. Mark a circle of 60 mm diameter exactly at the centre of the sheet blank & then divide its circumference into four equal quarters.
2. Measure the sheet thickness at three different places using 'screwgauge micrometer'. Take the average and note it on the observation table.
3. Keep the sheet on blank holder plate & put the die over the sheet such that the marked circle of the sheet should be exactly at the centre. Tight the complete setup by nuts & bolts using 'adjustable torque wrench', so that every bolts must be tightened by same torque.
4. Take the initial height of the sheet exactly at the centre of the marked circle using 'depth micrometer', assuming the die top surface as a reference.
5. Apply hydraulic pressure using 'hand operated lever' attached with the machine, shown in figure 1.
6. Simultaneously look at the 'pressure gauge', once the indicator comes to first division of the inner circular scale of pressure gauge (i.e. hydraulic pressure inside the sheet blank reaches to10 kgf/cm^2); stop applying more hydraulic pressure.
7. Again take the height of bulged shape using 'depth micrometer' assuming die top surface as a reference. Measure arc length of any one quarter along circumference of the marked circle,

using ‘flexible scale’. Also take the reading of ‘spherometer’.

8. Start applying hydraulic pressure till the pointer of pressure gauge reaches to next division. Take all the readings & repeat the process till bursting of the sheet or the shape of the dome becomes perfectly hemispherical.

- ## Observation Tables:

Initial thickness of the sheet blank t_0 =
[{Main scale reading + (Circular scale reading × Least count of micrometer)} – (± Zero error)]

Table No - 01.

Sr. No.	Main scale reading	Circular scale reading	Total value
1.			mm
2.			mm
3.			mm
Average value of initial thickness of the sheet blank t_0 =			mm

Table No - 02.

Length between two legs of spherometer (a_l) = 40mm

Diameter of circle marked on the sheet = 60mm

Initial depth micrometer reading (H_0) = _______ mm

Sr. No.	P (kgf/cm^2)	Depth micrometer reading H_i (mm)	Dome height $h_d = H_0$ - H_i (mm)	Quarter circumference C/4 (mm)	Spherometer reading h' (mm)	Radius of bulged dome $R_d = \frac{{a_l}^2}{6h'} + \frac{h'}{2}$
01.	00					
02.	10					
03.	20					
04.	30					
05.	40					
06.	50					
07.	60					
08.	70					

Table No - 03.

Sr. No.	h_d	R_d	ε_r	C/4	ε_c	$\varepsilon_t = -\varepsilon_r - \varepsilon_c$	t_d	$\sigma_c = \sigma_r = \frac{PR_d}{2t_d}$	$\bar{\sigma} = \frac{P}{2}\left(\frac{R_d}{t_d} + 1\right)$	$\bar{\varepsilon} = -\varepsilon_t = -\ln\left(\frac{t_d}{t_0}\right)$
01.										
02.										
03.										
04.										
05.										
06.										
07.										
08.										

- **Calculations:**

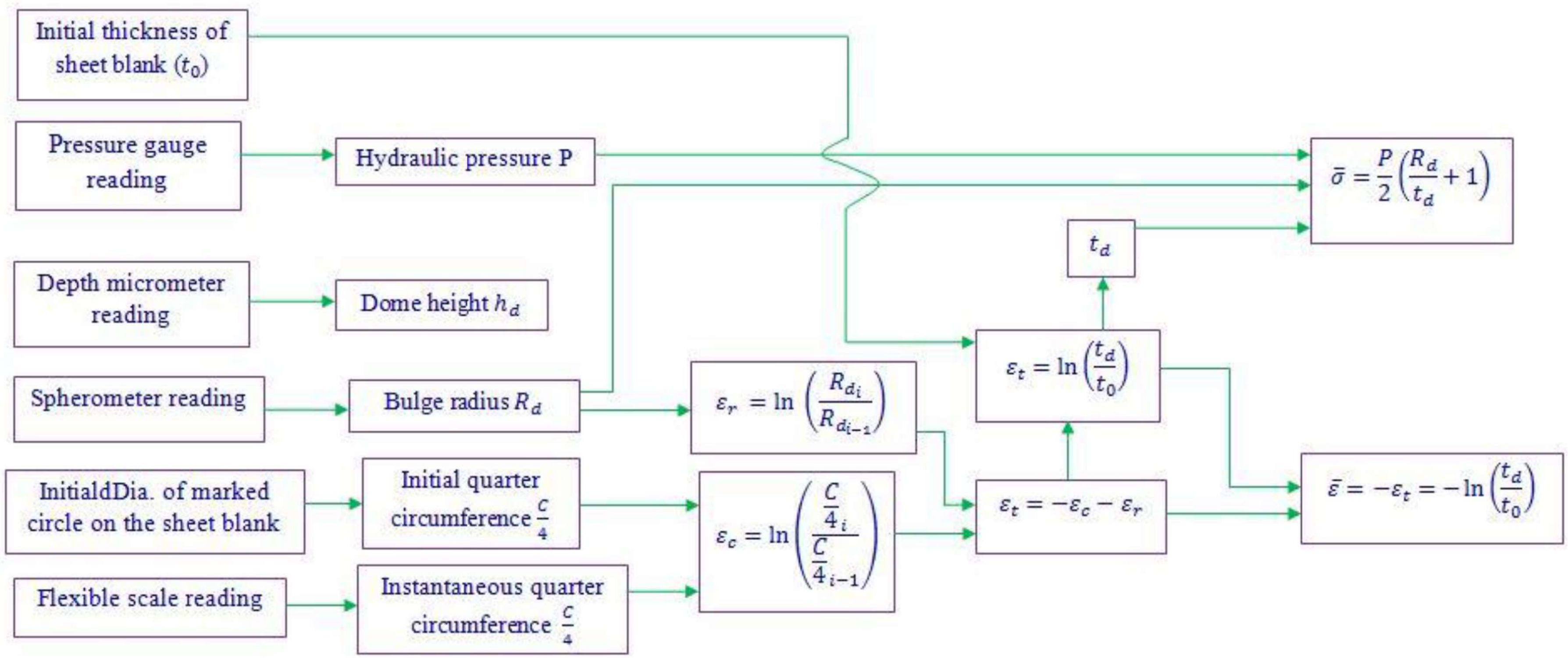
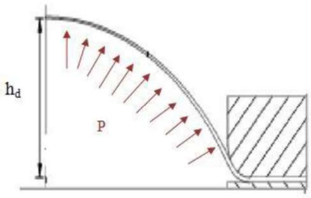


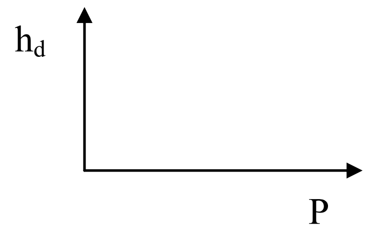
Fig.4. Steps to be followed for calculation of 'Effective stress' & 'Effective strain'

- ## Results:

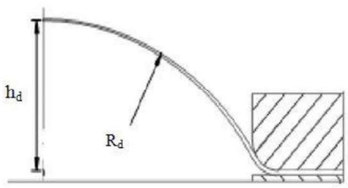
Plot a graph for following variations & give a proper justification for each variation.

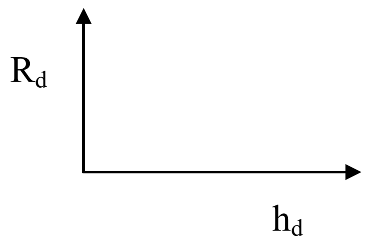
1. Variation of ‘Dome height’ with ‘Hydraulic pressure’



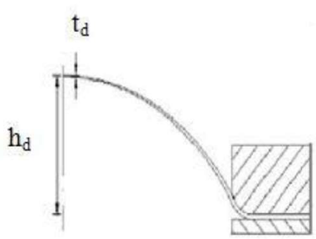


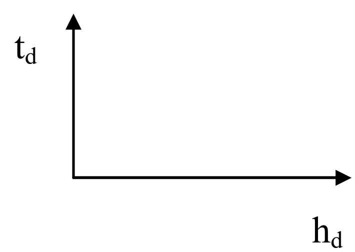
2. Variation of ‘Dome bulge radius’ with ‘Dome height’





3. Variation of ‘Dome apex thickness’ with ‘Dome height’

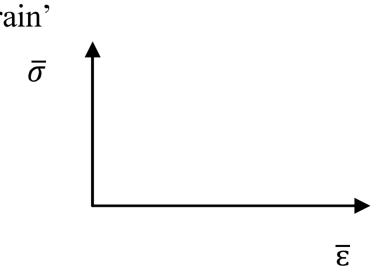




4. Variation of ‘Effective stress’ with ‘Effective strain’

Effective stress $\bar{\sigma} = \frac{P}{2}\left(\frac{R_d}{t_d} + 1\right)$

Effective strain $\bar{\varepsilon} = -\varepsilon_t = -\ln\left(\frac{t_d}{t_0}\right)$



- **Discussion on Defects:** The *‘Hydraulic bulge test’* would be defect less, if the sheet metal has smooth surfaces, has constant thickness throughout the surface area and does not have any sharp scratch mark on the surface; because these factors cause the defects. But mostly sheet metals are non isotropic in nature, which causes *‘Earing’* defect. So to avoid this defect *‘ridge impression’* & *‘matching groove’* were made on the lock bead & die respectively. One more defect which generally appears on the bulged sheet blank at the flank region is *'Wrinkling'*. It occurs due to insufficient clamping force. For avoiding this defect, all the bolts should be tightened by same sufficient torque using 'adjustable torque wrench'.

Fig.5. Defective bulged sheets

Fig.6. Successfully bulged sheet

- **Conclusions:** Based on the conducted test following conclusions can be made:

1. The bulged dome shape has been found very near to hemisphere.
2. Due to equi-biaxial stress state the maximum achievable strain before necking/bursting was much larger.

- **Precautions:** Since the measured thickness and bulge radius values are used as parameters to calculate flow stress curve in the test, so measurement & calculation accuracy of these parameters directly affect the accuracy of the curve. Therefore the operator must follow few precautions as:

1. Before clamping the sheet blank, place it on the blank holder plate such that the marked circle on the sheet blank must be concentric with the bulging die internal periphery.
2. For clamping the sheet blank, all the bolts bust be tightened by the same torque; in order to achieve uniform strain during bulging.
3. Manually applied hydraulic pressure should be such that the strain rate has to be constant during bulging.

- **Applications:** '*Hydraulic bulge test'* is widely used for determining:

1. Flow stress or behavior at plastic stage of sheet metals.
2. *'Work hardening'* behavior of sheet metals.
3. *'Planner & Normal anisotropy'* of sheet metals; etc.

- ## References:

[1]. Johnson W., Mellor P. B., "Engineering Plasticity", 'Van Nostrand Reinhold Company Ltd.', 1st ed., p. 103, (1973)

[2]. Timoshenko, S. P., Young, D. H., "Elements of Strength of Materials", 'East-West Press Private Limited', 5th ed., p. 51, (1968)

- ## Questions:

1. What is 'Plane stress' & 'Plane strain'?
2. What is 'Principal stress' & 'Principal strain'?
3. What is 'Strain rate'?

Appendix 1

- **Stresses in a ‘*membrane*’:**

To calculate ‘Circumferential stress’ & ‘Radial stress’ in a *membrane*, let us refer to fig. A-1.

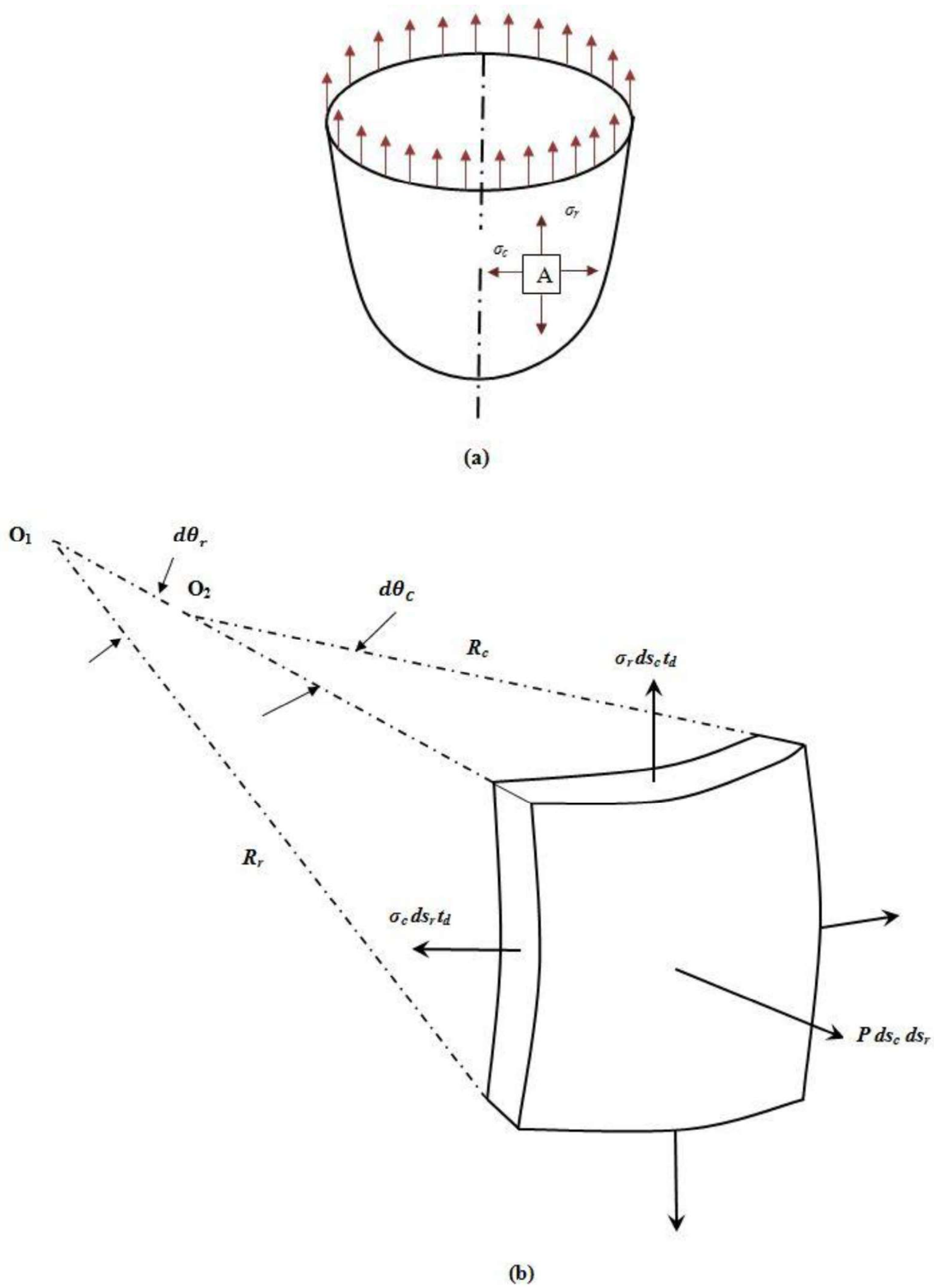


Fig. A-1. Stress state at an instant in finite small area of a *membrane.* [2]

Now, consider the following notations:

P = pressure inside the thin wall shell.

σ_c = tensile stress in circumferential direction or hoop stress.

σ_r = tensile stress in radial direction or meridional stress.

t_d = average thickness of shell wall.

R_c = radius of curvature perpendicular to meridian at 'A'.

R_r = radius of curvature of meridian at 'A'.

$d\theta_c$ = angle substended by arc normal to meridian at 'A'.

$d\theta_r$ = angle substended by meridian arc of element.

$ds_c = R_c d\theta_c$ = dimension of element in circumferential direction.

$ds_r = R_r d\theta_r$ = dimension of element in meridional direction.

Then the stress resultant acting on the edges of the element are $\sigma_c\, ds_r\, t$ and $\sigma_r\, ds_c\, t$ as shown in the fig. A-1. The two stress resultants in the circumferential direction have a resultant in the direction of the normal to the element equal to

$$\sigma_r\ ds_c\ t_d\ d\theta_r = \frac{\sigma_r ds_r ds_c t_d}{R_r}$$

In the same manner, the stress resultants in the meridional direction have a normal resultant equal to

$$\sigma_c\ ds_r\ t_d\ d\theta_c = \frac{\sigma_c ds_c ds_r t_d}{R_c}$$

The sum of these normal forces is in equilibrium with the normal pressure force on the inside surface of the element; thus

$$\frac{\sigma_c ds_c ds_r t_d}{R_c} + \frac{\sigma_r ds_r ds_c t_d}{R_r} = P\ ds_c\ ds_r$$

From which,

$$\frac{\sigma_c}{R_c} + \frac{\sigma_r}{R_r} = \frac{P}{t_d}$$

- **Spherometer:**

- **Principle:**

Spherometer is an instrument based on the principle of micrometer screw. It is used for measuring radii of curvature of spherical surfaces accurately up to 0.01mm.

- **Construction:**

A spherometer consists of a triangular metallic frame F supported on three fixed legs whose tips from the vertices of an equilateral triangle. A vertical nut N is fixed at the centre of the triangular frame in which a uniformly cut screw S can be moved with the help of knob K having circular metallic disc D attached slightly below it. On the circumference of the circular disc D, circular scale is engaged dividing the circumference into 100 equal divisions. The lower end N of the screw S is made pointed on lowering it at the level of three legs, it touches at its centroid. On moving the screw clockwise or anticlockwise, the edge of the circular disc moves across a flat vertical metallic linear scale called main scale or pitch scale. The main scale has divisions marked in millimetres or half millimetres with zero at its centre.

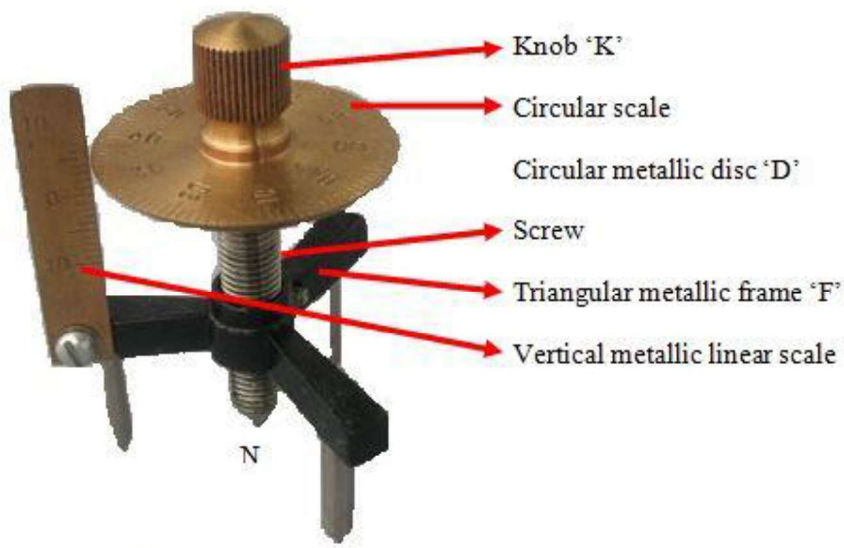


Fig.A-2.1. Spherometer

'Pitch' is perpendicular distance between any two consecutive threads provided that the threads on the screw are evenly spaced or it is the linear distance traversed by the screw in one complete rotation of its head, i.e.,

$$Pitch\ (P) = \frac{\text{Distance moved by the plane of the disc along the verticle scale}}{\text{Number of complete rotations given to the circular scale}}$$

'Least count' is the least measurement that can be measured accurately by the spherometer, i.e.,

$$Least\ count\ (LC) = \frac{\text{Pitch}\ (P)}{\text{Total number of divisions on the circular scale}\ (n)}$$

- **Zero error:**

After placing spherometer on a plane surface, if three fixed legs and the central screw are at the same level, i.e., touching the plane surface and the zero mark on the disc is in line with the zero mark on the main scale, then the instrument posses no zero error. Otherwise the instrument posses zero error. It may be of two types:

1. **Positive zero error:**

If the zero mark on the circular scale lies a little above the zero mark on the main scale (vertical scale), the zero error is positive. To determine the magnitude of this error, let the Nth division of circular scale lying in line with any graduation on the vertical scale is multiplied by the least count, i.e.,

$$\text{Positive zero error} = N \times LC.$$

2. **Negative zero error:**

If the zero mark on the circular scale lies a little below the zero mark on the main scale, the zero error is negative. To determine the magnitude of the negative zero error, read the division of the circular scale coinciding with the edge of the main scale (or pitch scale). Let it be N'. Then the

$$\text{Negative zero error} = -(n - N') \times LC.$$

- **Working:**

When a spherometer is placed on a spherical surface (a part of large sphere) such that, tips of three fixed legs are touching it. The tip of the screw S will be a little higher from the bulged out portion of the convex surface which is related to the radius of the curvature of the surface (radius of the large sphere whose part is the spherical surface).

From the geometry of fig. A-2.2. shows that

$$AO \times OB = QO \times OF$$

$$\Rightarrow r \times r = h' \times (2R - h')$$

$$\Rightarrow r^2 = 2h'R - h'^2$$

$$\Rightarrow R = \frac{r^2}{2h'} + \frac{h'}{2}$$

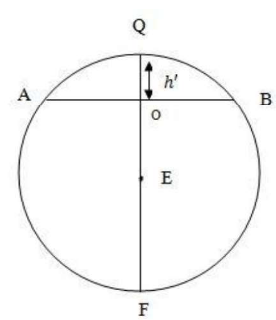


Fig.A-2.2. Measurement of radius of curvature of a convex surface using spherometer

If 'a_l' is the length between two tips of a spherometer, then $\frac{BD}{BO} = \cos 30°$

$$\Rightarrow \frac{a_l}{2} = \frac{r\sqrt{3}}{2}$$

$$\Rightarrow r = \frac{a_l}{\sqrt{3}}$$

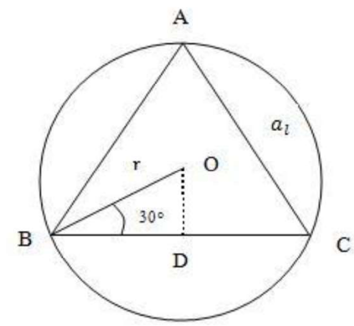


Fig.A-2.3. Section of the sphere cut by the plane containing tips *A*, *B*, & *C* of three legs

Hence, radius of curvature,

$$\Rightarrow R = \frac{\left(\frac{a_l}{\sqrt{3}}\right)^2}{2h'} + \frac{h'}{2}$$

$$\Rightarrow R = \frac{{a_l}^2}{6h'} + \frac{h'}{2}$$