CHAPTER - V

THEORETICAL AND EXPERIMENTAL DEVELOPMENT

5.0 General:

Theoretical developments to explain failure mechanism in rocks although, originated from classical theories of failure of materials, but it is the Griffith's theory of brittle fracture developed from experiments on glass forms the basis for the edifice of failure theories in rock. The manufacturing process of glass materials and natural process of rock formation specifically for igneous rocks may have certain similarities and therefore Griffith's concept as a base for rock materials is legitimate adoption. However to commence from atomic and subatomic levels as in glass materials as attempted by Griffith might be perhaps not possible for a rock material since sequence of formation are unknown. Therefore keeping the basic premise unaltered a theoretical development with experimental observation becomes the only approach to produce a rational and realiastic theory for understanding the failure mechanism in rocks. The present investigation proposes to develop a theoretical model primarily based on Griffith's theory keeping in view the subsequent developments attempted by various research workers in the filed of rock mechanics. To test the theoretical model it is proposed to conduct a series of experiments. One of the fundamental canon of an experiment is the fulfillment of the conditions formulating the theory. Amongst the experimental techniques available to investigate the failure in rock materials Brazil set up which to a fair degree satisfies the theoretical conditions of discs and rings subjected to diametral loading. Further the preparation of test specimen is simple and does not involve elaborate cumbersome procedures as required in other tests. The prime requirement of uniform distribution is also easily attainable by the use of properly designed grips.

5.1 Hypothesis:

Igneous rocks are the consequence of the process of cooling of magma. The process involves a change in pressure and temperature over a period of time. It is not possible to conceive nature of pressure - temperature cycle taking place during the process. Neverthless the conception that the nature of the stresses as hydrostatic is possible to accept. The process of differential thermal changes should produce stresses which can remain unrelieved and locked. Thus igneous rocks represent a mass with a pre-stress which when subjected to external loads triggers the mechanism of failure and manifests into the behaviour of rock materials leading to ultimate failure. The concept of 'locked stresses' has been acceptable by all research workers but it has not been possible to determine the value of pre-stress locked during the process of cooling magma. It is hypothesized that there is a clear manifestation of pre-stress in the nature of stress strain curve and it should be possible to determine that value which triggers the phenomenon of failure in rock materials.

5.2 Stress-strain characteristics:

5.2.1 Complete stress-strain behaviour

The rocks, in general, behave elastically in various forms until the first initiation of crack takes place in the material. The actual behaviour or the complete stress-strain curve of the rock can be described as below:

The stress-strain curve (Fig 5.1) can be divided in to following zones.

(a) Non linear zone

(b) Linear zone

(c) Pre-failure zone

(d) Fracture

(e) Post failure zone

(a) The zone OP is a non-linear zone, which is slightly convex upwards. The behaviour is very nearly elastic.

(b) The zone PQ is a linear zone, where stress is proportional to strain with in elastic limit and obey Hooke's law. This behaviour is called linearly elastic.

(c) The zone QR begins with decreasing slope of stress-strain curve up to zero with increasing stress. This is the region where irreversible changes are induced in the rock and loading unloading cycle at this portion of curve gives different paths in successive cycles leading to permanent set at zero stress. If the material is unloaded a curve AB is traced and then if reloaded a curve BC is traced which lies below the curve OPQR but meets before point R is reached.

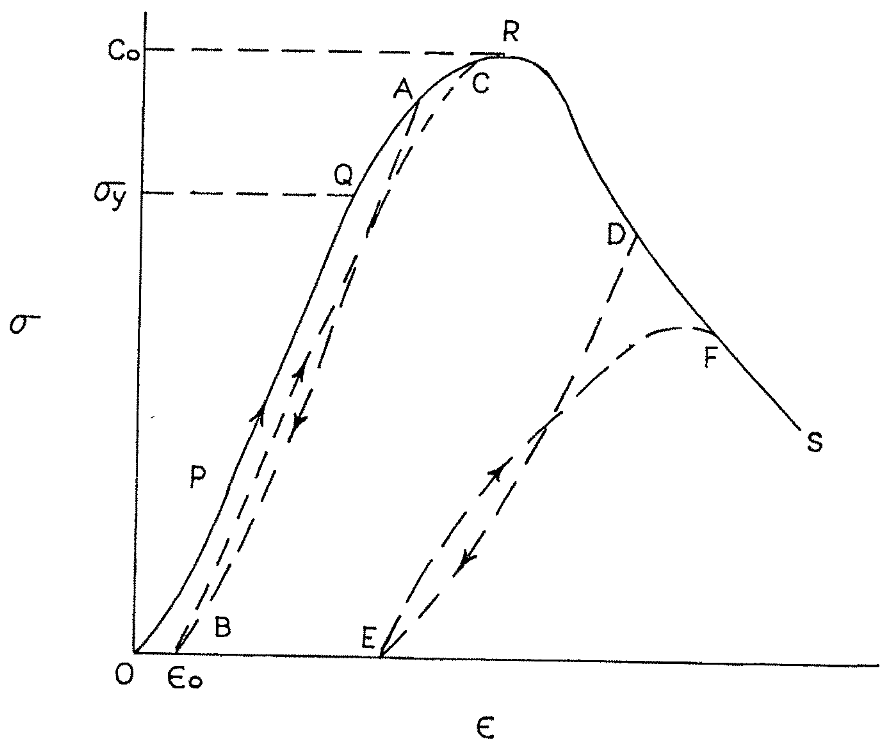

FIG. 5 1 THE COMPLETE STRESS-STRAIN CURVE FOR ROCK

(d) As the pre-failure zone is passed the failure is reached at a point R. The stress value corresponding to this point is called uniaxial compressive strength of the rock denoted as Co. The stress value two third of this value is the precise point of yield stress denoted as σ_y corrosponding to the point Q in stress-strain curve.

(e) The zone RS starts at the maximum of R in stress-strain curve giving a negative slope to the stress-strain curve. An unloading cycle DE give rise to large parmanent set and then if reloaded EF approaches at a stress lower then that corresponding to C. This zone is characteristic of brittle behaviour and a sudden breaking of the specimen is expected at R giving fracture of the specimen. The process of failure is a continuous and occurs progressively throughout the brittle region RS till the rock completely disintegrates.

5.2 Estimation of pre-stress:

The load displacement curve shows that initial portion is concave upwards signifying displacement to be increasing with the load. From this it may be implied that the locked stress or pre-load in the flaws and microcracks inherent in the rock is getting released. The estimation of pre-load or locked stress can be obtained from the geometrical characteristics of the curve. To accentuate the geometrical characteristics it is proposed to transfer the load displacement plot on natural scale to a plot on semilogarithmic scale. This plot produces a

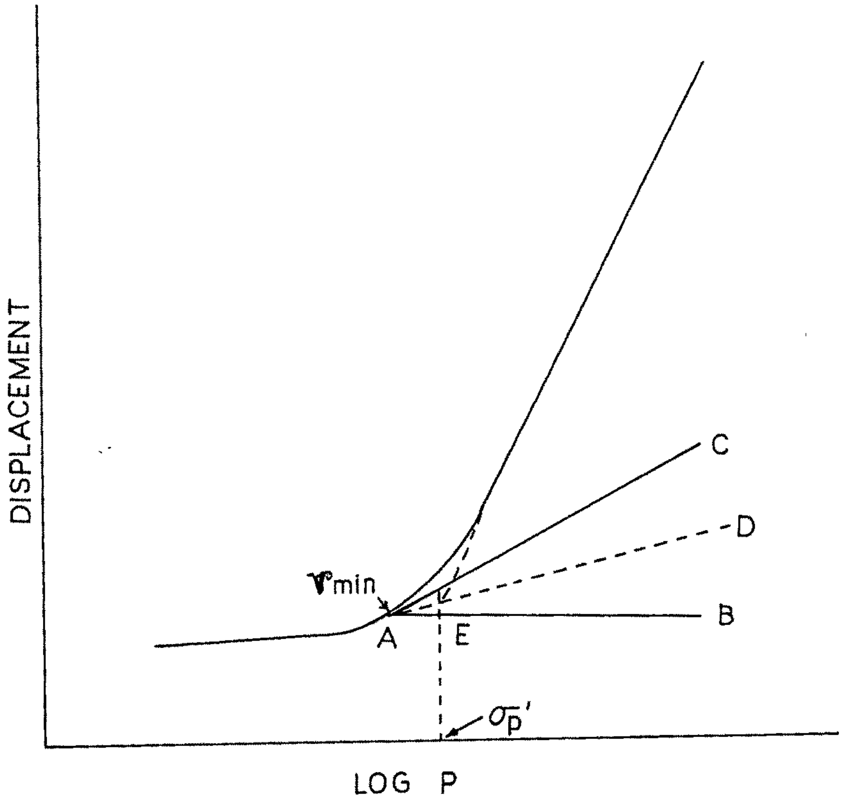

FIG. 5·1 ESTIMATION OF PRE-STRESS

characteristic hump exhibiting the departure from the virgin line indicative of previous stress history. From this geometrical characteristic it is possible to find out a value of pre-load by a well known geometrical construction. It consists in (a) selecting a point A at the point of maximum curvature or minimum radius on the curved portion, (b) setting a horizontal line AB and tangent to the curve AC and further (c) bisecting the angle BAC between the lines AB and AC to determine the point of intersection E with the virgin line. The load coordinate of E reads the value of pre-load.(Fig 5.2)

5.2.3 Constitutive relationship:

A constitutive law or relationship represents a mathematical model that explains the behaviour of a material. Constitutive relationship can permit reproduction of the observed response of a continuous medium. The establishment of constitutive relationship based on observations made at the microscopic level can impart physical significance in engineering. Following are the five essential steps for the development of a viable constitutive law.

(I) Mathematical formulation

(II) Identification of significant parameters

(III) Determination of parameters

(IV) Verification against experimental data

(V) Development of a relevent solution scheme incorporating constitutive relationship

5.2.3.1 Mathematical formulation:

Fig 5.3 portrays a typical observed stress-strain curve for a rock. Mathematically it represents a hyperbolic response curve signifying higher order constitutive relation. For uniaxial loading it can be expressed as

$$\sigma/\sigma_o = \text{Sinh}\,(\lambda \epsilon) \quad \ldots\ldots\ldots\ldots \quad 5.1$$

where $\sigma/\sigma_o = \dfrac{\text{Maximum external compressive stress}}{\text{Maximum internal pre-stress}}$

ϵ = Strain

and λ = A material constant

5.2.3.2 Identification of significant parameter:

It is postulated that the failure in the rock material is triggered when the stress ratio between external compressive stress and internal pre-stress σ/σ_o exceeds unity, whence

Sinh ($\lambda \epsilon$) = 1, the value of λ can then be found out from experimental curve from the strain value at $\sigma/\sigma_o = 1$. Article 5.2.2 explained the determination of σ_o . Further from test conditions in Brazil test on discs and rings $\sigma_{22} = \sigma_{33} = 0$ therefore there must be a specific ratio between strains in two directions.

5.2.3.3 Determination of the parameters:

The value of pre-stress can be found out through a geometrical construction and also possibly from theoretical analysis. The value of λ can be determined from strain value corresponding to the unit stress ratio. The strain ratios can be determined from independent tests.

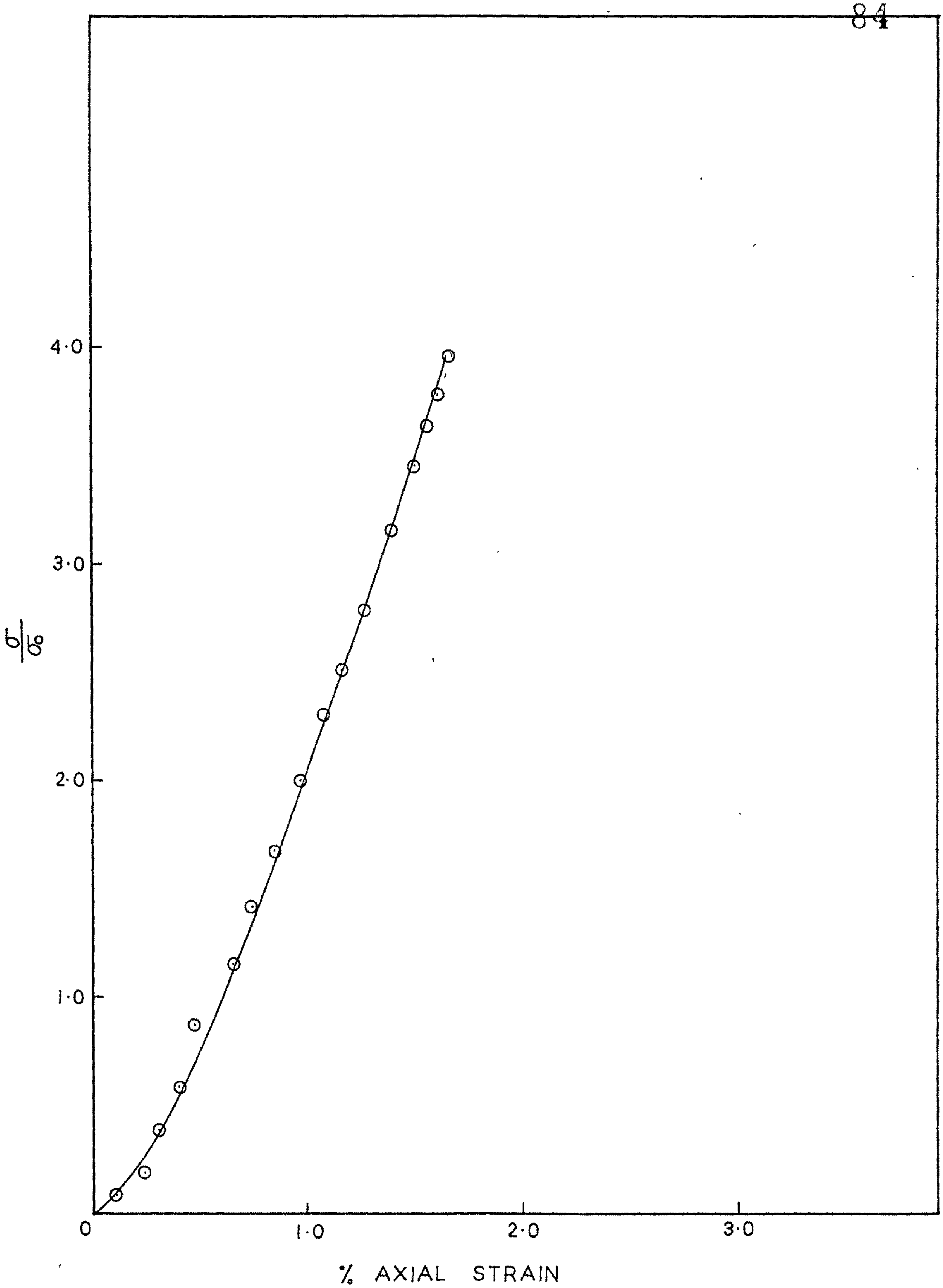

FIG. 5·3 $\frac{\sigma}{\sigma_o}$ Vs % STRAIN

5.2.3.4 Verification against experimental data:

It is proposed to compare the experimental observations in Brazil test on disc and rings in the next chapter with the proposed mathematical relation.

5.2.3.5 Development of a relevent solution scheme incorporating constitutive relationship:

Currently employed techniques for solutions of boundary value problems in the field of rockmechanics, are finite difference, finite element and boundary integral methods besides the classical elastic solution techniques. All these techniques call for a constitutive relationship which can be expressible in incremental forms and also possible to subject to inversion processes. The developed constitutive relationship should be able to fulfil these requirements since its relationship formulation is mathematically simple.

5.3 Failure criteria:

5.3.1 Griffith's theory:

The Coulomb - Navier and Mohr's theories of failure are dealing with the mechanism of fracture and yield in terms of appearance of tensile and shear fracture surfaces at macroscopic level precluding the mechanism at microscopic level. Griffith (1921) hypothesized that fracture is caused due to stress concentrations at the tips of minute 'Griffith Cracks' which are supposed to pervade the material causing the crack to propagate and ultimately contribute to macroscopic failure. The fracture is initiated when the maximum stress near the tip of the most favourably oriented crack reaches a value characteristic of the material, Inglis (1913) determined the maximum stress for a thin elastic strip of unit thickness containing an elliptical hole oriented with its long axis perpendicular to the applied tensile stress

$$\sigma_{max} = 2\ \sigma_p \sqrt{\frac{C}{\rho}} \quad . \quad . \quad . \quad . \qquad 5.2$$

where σ_p is the applied meanstress 2C = length of the crack ρ = radius of curvature at the apex. Griffith sought the configuration which minimised the total free energy of the system, the crack would then be in a state of equillibrium and thus on the verge of extension. Griffith computed the difference of energy W_e in the strip with and without hole.

$$W_e = \pi C^2\ \sigma_p^3 / E \quad . \quad . \quad . \quad . \qquad 5.3$$

The surface energy resulting from the formation of the crack is $W_s = 4\ C\ T$ 5.4

Where T is the surface tension. Hence the elliptical hole has decreased the totalenergy by

$$W = W_e - W_s = \pi\ C^2 \sigma_p{}^2\ /E - 4\ C\ T \quad . \quad . \qquad 5.5$$

Instability will result and the crack will propagate if $\partial w/\partial c = 0$ i.e. if the total energy becomes the maximum hence.

$$\sigma_p = \sqrt{2\ E\ T\ /\pi C} = To \quad . \quad . \quad . \qquad 5.6$$

where To is the tensile strength of the material. The criterion for fracture will be

$$(\sigma_1 - \sigma_3)^2 = -\ 8\ To\ (\sigma_1 + \sigma_3) \quad . \quad . \qquad 5.7$$

such that randomly distributed and oriented cracks occur

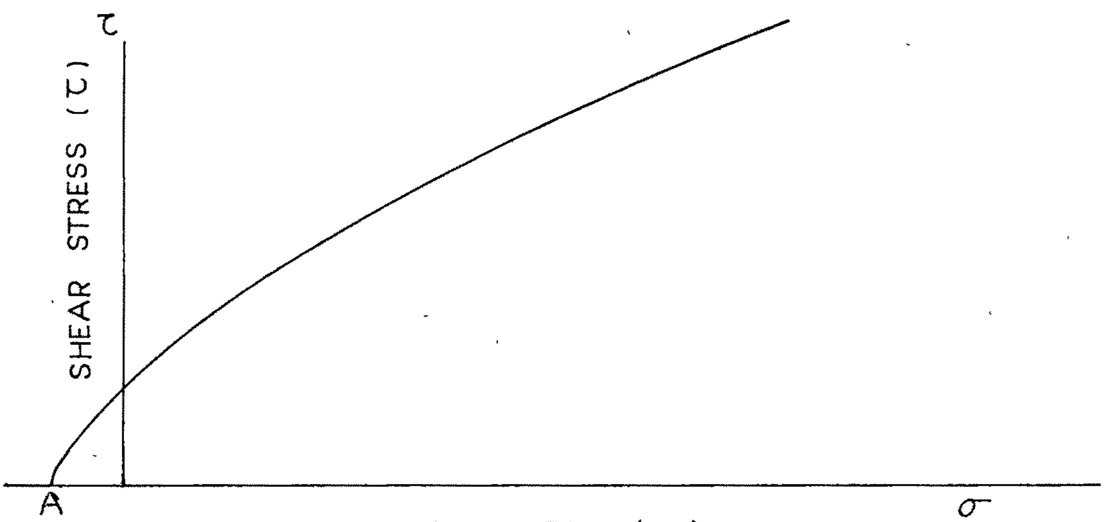

FIG. 5·4 NORMAL STRESS (σ)

throughout the body in two dimensional case at an angle

$\cos 2\theta = \frac{1}{2}(\sigma_1 - \sigma_3)/(\sigma_1 + \sigma_3)$

similarly if $\sigma_1 > \sigma_3$ and $3\sigma_1 + \sigma_3 > 0$

the fracture will occur when $\sigma_1 = -To$ when $\theta = 0$

$$\tau^2 = 4\,To\,(\sigma + To) \qquad . \qquad . \qquad . \qquad 5.8$$

which is a parabola passing through A (Fig 5.4).

5.3.2 Empirical strength criterion:

The experimental data for intact rock and rock discontinuities generally show that the relationships between major and minor principal stresses and between normal and shear stresses at failure are non-linear. Hoek and Brown (1980) developed empirical strength criterion using non-linear failure envelope as predicted by classical Griffith criterion. The empirical relationship between the principal stress at failure is written as

$$\sigma_1/C_o = \sigma_3/C_o + \sqrt{m\,\sigma_3/C_o + S} \qquad . \qquad . \qquad 5.9$$

in which m and s are constants that depend on the properties of rock and on the extent to which it had been broken before being subjected to the principal stresses. The equation may be rewritten in the form as

$$\sigma_{1n} = \sigma_{3n} + \sqrt{m\;\sigma_{3n} + S} \qquad . \qquad . \qquad . \qquad 5.10$$

in which σ_{1n} and σ_{3n} are the principal stresses normalized with respect to

$C_o(\sigma_{1n} = \sigma_1/C_o,\ \sigma_{3n} = \sigma_3/C_o)$

by putting $\sigma_3 = 0$ in equation 5.9 the uniaxial compressive strength of the rock is obtained as

$$\sigma_{cn} = \sqrt{S\ C_o^2} \qquad . \qquad . \qquad . \qquad . \qquad 5.11$$

For intact rock material S = 1.0 and σ_{cn} = Co as required. For previously broken rock $S < 1$ and the compressive strength at zero confining pressure is given by equation 5.11. For a completely granulated specimen or a rock aggrigate S = 0. The uniaxial tensile strength of a specimen if found by putting $\sigma_1 = 0$ in equation 5.9 and solving the resulting equation for $\sigma_3 = T_o$ to obtain

$$T_o = C_o/2\ (m - \sqrt{m^2 + 4\ S}\ ) \qquad . \qquad . \qquad . \qquad 5.12$$

When S = 0, T_o = 0 as would be expected for completely broken material. For intact rock material with S = 1.0, and $m >> 1$, $m = C_o/T_o$. However because of the difficulty involved in adopting the uniaxial tensile strength as a fundamental rock property it is prefereable to treat 'm' simply as an empirical curve fitting parameter. The value of 'm' will decrease as the degree of prior fracturing of a specimen increases. For a general non-linear failure criterion the relation between normal and shear stress is written as:

$$\sigma = \sigma_3 + \frac{\tau_m^2}{\tau_m + mC_o/8} \qquad . \qquad . \qquad . \qquad 5.13$$

$$\text{and} \quad \tau = (\sigma - \sigma_3\ )\ \sqrt{1 + m\ C_o/4\,\tau_m} \qquad . \qquad 5.14$$

$$\text{in which} \quad \tau_m = \tfrac{1}{2}(\sigma_1 - \sigma_3) \qquad . \qquad . \qquad . \qquad 5.15$$

From it can be seen that the normalized values of τ and $\sigma_n = \sigma\ /\ C_o$ and $\tau_n = \tau/C_o$ which further , may be related by an equation of the form.

$$\tau_n = A\,(\sigma_n - \sigma_{tn})^B \quad . \quad . \quad . \quad . \qquad 5.16$$

in which σ_{tn} is the normalized tensile strength of the rock given by

$$\sigma_{tn} = \tfrac{1}{2}\,(m - \sqrt{m^2 + 4\,S}\ ) \quad . \quad . \quad . \qquad 5.17$$

and A and B are constants depending upon the value of 'm'.

5.3.3 Extension of classical Griffith brittle fracture criterion for rocks under pre-stress:

It is postulated that when the ratio of applied stress to prestress locked in the rock exceeds unity fracture is triggered in pre-existing flaws randomly distributed throughout the material as per Griffith classical mechanism. The Griffith criterion is a parabola on Mohr plot (σ, τ) (Cartesian co-ordinates)

$$\tau^2 = 4\,T_o\,(\,\sigma + T_o) \quad . \quad . \quad . \qquad 5.18$$

where τ is the shear stress across the plane of failure at the point of failure, σ is the stress normal to the plane of failure at the point of failure. The fracture process consists of deformation of submicroscopic pre-existing cracks traversing from state of tensile stress to state of compressive stresses leading to ultimate shear failure in rocks. The failure envelope on a Mohr plot is a parabola consisting of three circles of failure stresses (Fig 5.5). As these circles have their centres on the x-axis and are touching each other the parabola is also symmetrical about x-axis. The general equation of the parabola is of the

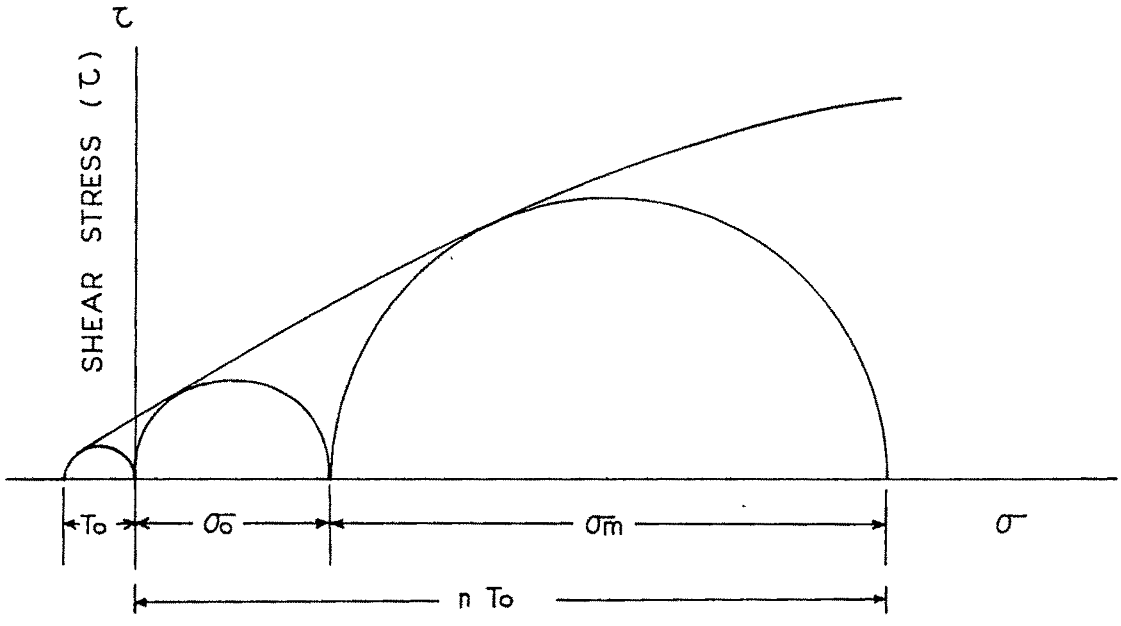

FIG. 5·5 NORMAL STRESS (σ)

form

$$\tau^2 = 4\psi(\sigma + T_o) \quad . \quad . \quad . \quad . \quad . \qquad 5.19$$

where ($-T_o$, 0) represents its vertex and 2ψ is radius of curvature at the vertex. Considering the radius of the pre-stress circle as $\frac{\sigma_o}{2}$ and the radius of the next circle as $\frac{\sigma_m}{2}$ the equations of these circles are

$$(\sigma - \sigma_o/2)^2 + \tau^2 = (\sigma_o/2)^2 \quad . \quad . \qquad 5.20$$

and

$$\{\sigma-(\sigma_o+\sigma_m/2)\}^2 + \tau^2 = (\sigma_m/2)^2 \quad . \quad . \qquad 5.21$$

Eliminating τ from equations 5.19, 5.20 and from equations 5.19, 5.21 we get

$$\sigma^2 + 2\,\sigma\,(2\psi - \sigma_o/2) + 4\ \ T_o = 0 \quad . \quad . \qquad 5.22$$

and

$$\sigma^2 + 2\,\sigma(2\psi - \sigma_o - \sigma_m/2) + 4\ \ (\sigma_o/2)^2 + (\sigma_o/2.\ \sigma_m/2) + \ T_o \quad . \qquad 5.23$$

For the point of tangency the roots of equation 5.22 and 5.23 must be equal therefore we have

$$4\psi\, T_o = (2\psi - \sigma_o/2)^2 \quad . \quad . \quad . \quad . \qquad 5.24$$

and

$$4\psi\, T_o = (2\psi - \sigma_o - \sigma_m/2)^2 - 4\ \ (\sigma_o/2)^2 + (\sigma_o/2.\sigma_m/2) \quad . \qquad 5.25$$

From equation 5.24 and 5.25 after simplifying we get

$$4\psi = (\sigma_m - \sigma_o)/2 \quad . \quad . \quad . \quad . \qquad 5.26$$

The maximum compressive stress is

$$C_o = \sigma_m + \sigma_o = nT_o \quad . \quad . \quad . \quad . \qquad 5.27$$

Then

$$\tau^2 = (nT_o/2 - \sigma_o)\ (\ \sigma + T_o\ ) \quad . \quad . \qquad 5.28$$

if $\sigma_o = 0$ and $n = 8$ the equation degenerates in to Griffith equation as

$$\tau^2 = 4\ T_o\ (\ \sigma + T_o\ ) \quad . \quad . \quad . \quad . \qquad 5.29$$

5.4 Stress distribution:

5.4.1 Stress distribution in discs:

A stress solution for a disc or cylinder compressed normally by a line load along diametrally opposite generators was obtained by Hertz (1883) and then later on by Michell (1903). Hondros (1959) analysed the stress distribution in a thin disc assuming material as homogeneous, isotropic and lineraly elastic loaded by uniform pressure radially applied over a short strip of the circumference at each end of the diameter. Since the Brazilian test is only valid when primary fracture starts from the centre spreading along the loading diameter the stress distribution along that diameter is of greater interest. The stress component normal to the loading diameter yy' (σ_θ) and the stress component along the loading diameter yy' (σ_r) are given by the expressions.

$$\sigma_\theta = - \frac{F}{\pi r_o t \alpha} \left[\frac{\left\{1-(r/r_o)^2\right\} \operatorname{Sin} 2\alpha}{1 - 2\,(r/r_o)^2 \operatorname{Cos} 2\alpha + (r/r_o)^4} - \tan^{-1} \left\{ \frac{1+(r/r_o)^2}{1-(r/r_o)^2} \right\} \tan\alpha \right] \quad . \quad . \quad . \quad 5.30$$

$$\sigma_r = + \frac{F}{\pi r_o t \alpha} \left[\frac{\left\{1-(r/r_o)^2\right\} \operatorname{Sin} 2\alpha}{1 - 2(r/r_o)^2 \operatorname{Cos} 2\alpha + (r/r_o)^4} + \tan^{-1} \left\{ \frac{1+(r/r_o)^2}{1-(r/r_o)^2} \right\} \tan\alpha \right] \quad . \quad . \quad . \quad 5.31$$

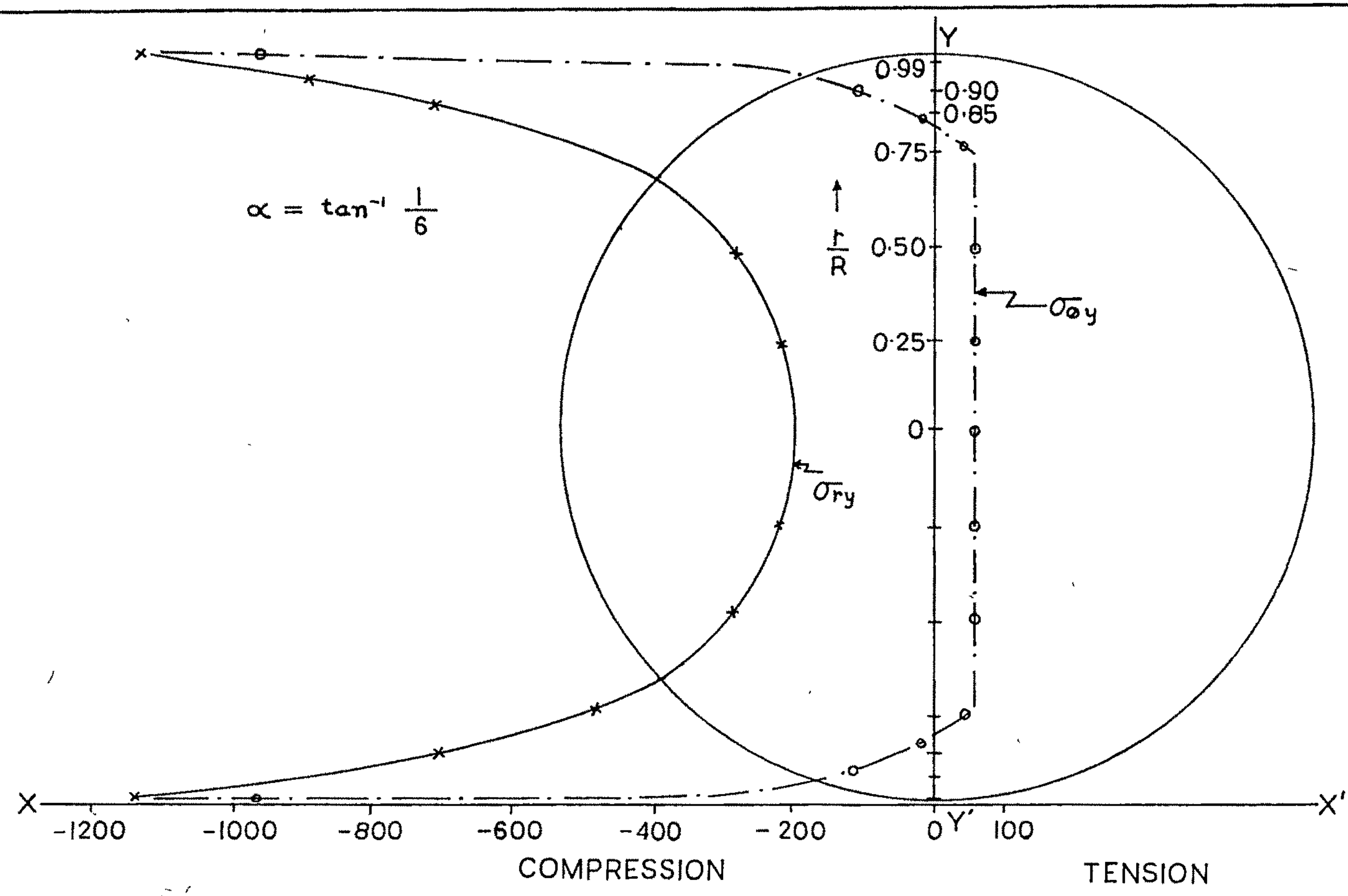

FIG. 5·6 STRESSES ALOG LINE OF LOADING YY' IN BRAZILIAN TEST FOR STRIP ANGLE $\alpha = \tan^{-1}\frac{1}{6}$

where σ_θ = Stress component normal to the loading diameter

σ_r = Stress component along the loading diameter

F = Applied force

r_o = Radius of the disc

t = Thickness of the disc

2α = Angular distance over which F is assumed to be distributed radially

and

r = Distance from the centre of the disc

The maximum tensile stress at the centre in a disc loaded diametrally by uniform pressure radially applied over a short strip of the circumference.

$$\sigma_t = -\frac{F}{\pi r_o t}\left(\text{Sin } 2\alpha/\alpha - 1\right) \quad . \quad . \quad 5.32$$

$$\approx -\frac{F}{\pi r_o t} \quad . \quad . \quad . \quad . \quad . \quad 5.32\ A$$

5.4.2 Stress distribution in rings:

Kirsch (1898) analysed the stress distribution around a circular hole in a disc loaded diametrally. The work was followed by Nelson and Filon (1924), Ripperger and Davids (1947), Timoshenko and Goodier (1951), Leeman (1956), Jaeger and Hoskin (1966) and Nevel (1969). The required general stress solution in polar co-ordinates (r , 0) with symmetry about the line

$\theta = 0\ ,\ \pi$ is

$$\sigma_r = 2(A_o/r_o^2) + (B_o/r_o^2)\,(r/r_o)^{-2}$$

$$+\sum \Big[A(2-n)\,(1+n)\,(r/r_o)^{n} + B_n\,(1-n)\,(r/r_o)^{n-2}$$

$$- C_n\,(1+n)\,(r/r_o)^{-n-2} + D\,(2+n)\,(1-n)\,(r/r_o)^{-n}\Big]\,\frac{\cos(n\theta)}{r_o^2} \quad 5.33$$

$$\sigma_\theta = 2\,(A_o/r_o^2) - (B_o/r_o^2)\,(r/r_o)^{-2} + \frac{C_o}{r_o^2}\;3+2\log(r/r_o)$$

$$+\sum \Big[A(2-n)\,(1+n)\,(r/r_o)^{n} - B_n\,(1-n)\,(r/r_o)^{n-2}$$

$$+ \quad C_n\,(1+n)\,(r/r_o)^{-n-2} + D\,(2-n)\,(1-n)\,(r/r_o)^{-n}\Big]\,\frac{\cos(n\theta)}{r_o^2} \quad 5.34$$

. . 5.34

where Ao, Bo, A,B,C,D, ro are constants and 'n' is a positive integer. The values of constants are given as

$$A_o = -\frac{Pr_o}{2\ (1-a^2)}, \qquad B_o = \frac{Pr_o\ a^2}{(1-a^2)}$$

$$A = \frac{Pr_o}{\pi R}\ \frac{\sin n\alpha}{n\alpha}\left[a^{2n} - \frac{1+n\ a^{2n-2}}{1+n}\right]$$

$$B = \frac{Pr_o}{\pi R}\ \frac{\sin n\alpha}{n\alpha}\left[a^{2n} - \frac{1-n\ a^{2n+2}}{1-n}\right]$$

$$C = \frac{Pr_o}{\pi R}\ \frac{\sin n\alpha}{n\alpha}\left[a^{2n} - \frac{a^{4n}+n\ a^{2n+2}}{1+n}\right]$$

$$D = \frac{Pr_o}{\pi R}\ \frac{\sin n\alpha}{n\alpha}\left[a^{2n} - \frac{a^{4n}-n\ a^{2n-2}}{1-n}\right]$$

$$R = (1-a^{2n})^2 - n^2\ a^{2n-2}\ (1-a^2)^2$$

a = r_1/r_o

r_1 = Inner radius

r_o = Outer radius

2α = Angle of distributed load at centre

r = Distance at which stress is to be determined

P = Applied force per unit thickness of the ring.

The maximum tensile stress at the intersection of the loading diameter with the hole is expresses as

$$\sigma_t = \frac{2F}{\pi Dt} (6 + 38q^2) \quad . \quad . \quad . \quad . \quad 5.35$$

5.4.3 Critical stress ratio of compressive and tensile stress:

Maximum tensile stress as obtained by theoretical solutions in disc and ring specimens greatly differ in value. The diametral tensile strength in Brazil test is more near to the uniaxial tensile stress value. The maximum tensile stress in disc and ring can also be estimated using the failure criterion which has been developed in previous section 5.3.3 incorporating the pre-stress values. The failure equation is

$$\tau^2 = (n\,To/2 - \sigma_o) (\sigma + To) \quad . \quad . \quad . \quad 5.28$$

comparing with Griffith criterion

$$\tau^2 = 4\,To (\sigma + To) \quad . \quad . \quad . \quad . \quad 5.18$$

and eliminating τ we get

$$(n\,To/2 - \sigma_o) = 4\,To$$

and

$$To = (n\ To/2 - \sigma_o)/4 = (C_o/2 - \sigma_o)/4 \quad . \quad . \quad . \quad 5.36$$

where the 'Co' is the maximum compressive stress and 'n' is the Griffith ratio. The value of To can be obtained by substituting the value of Co. It has been shown that the value of critical ratio (n) between maximum compressive stress and maximum tensile stress is 8 if σ_o is zero.

5.5 Experimental development:

5.5.1 Grip design and development:

5.5.1.1 Theoretical requirements:

If disc and ring tests are to be valid the applied load must be confined to a narrow strip so as to approximate a uniform line load and the contact stresses must not be so high that they cause premature cracking. Simple theory for discs and rings assume line loading at the boundary although true line loading which would imply infinite contact stresses can never be realised in practice. The width of the contact area when a flat platen and a cylindrical sample are pressed together can be found from elastic theory (Timoshenko and Goodier 1951).

$$2b = 4 \; \frac{FR}{t}\left[\left(\frac{1-\nu^2}{E_p} + \frac{1-\nu^2}{E_s}\right)\right]^{\frac{1}{2}} \quad . \quad . \quad 5.37$$

$$\text{or} \quad b/r = 2\ (F/\ Rt)^{\frac{1}{2}}\left[\left(\frac{1-\nu^2}{E_p} + \frac{1-\nu^2}{E_s}\right)\right]^{\frac{1}{2}} \quad . \quad . \quad 5.37\text{ A}$$

where 2b is the width of the contact strip F is applied load r is sample radius, t is sample thickness and the subscripts p and s refer to platen and specimen respectively.

Hence assuming rock to be linearly elastic the contact width between a steel platen and a specimen of rock can be calculated. The analysis of stress for the elastic half space loaded over a rectangular strip of finite length also shows that platen cracking of some kind will occur in a Brazil test when there is a direct contact between rock and platen. Reduction of contact stresses are therefore clearly necessary. There are two ways to reduce contact stresses, the first is to increase contact area, the second is to alter the distribution of stress so as to reduce stress concentrations. In order to reduce stresses solely by increasing contact area it would be ne essary to increase the contact width by atleast a factor of five from R/15 to R/3, but there is a possibility that this might alter the stress conditions in the critical test zone of the specimen. However the photoelastic observations and theoretical solutions suggest that stress distribution in the critical zones of disc and annuli are virtually unaffected distribution of boundary loads over contact arc upto 15°.

5.5.1.2 Previ s devices:

.e problem of how to achieve the stress distribution in practice has been the subject of many research investigators. Jaeger and Hoskin (1966) and others adopted a practice to groove the platen so as to make direct contact over an arc of the specimen periphery. A testing jig developed consist of reversible platens grooved on one side to the radius of the specimen so as give initial contact over 10°. Under the load the edges of the platen grooves catch the rock specimen and promote platen cracking. Mellor & Hawkes (1971) designed curved platens or pair of jaws the contact surface of which are circular arc of radius larger than the specimen radius. The jaw radius has been chosen so as to get a contact arc of approximately 10° ($2\alpha = R/6$). While it greatly improved the contact conditions the contact stresses could not be decreased sufficiently to permit direct steel rock contact. Further the device lacked in making a provision for displacement measurement and adequate provision for centering.

5.5.1.3 Present device:

Keeping in view the attempts to ensure the uniform load distribution a modified grip design is developed and produced for present investigation.

5.5.1.3.1 Contact area measurement:

In earlier attempts there is no mention of measurement of contact area. Therefore during the present investigation the following attempts were made for the measurement of contact area. First it was tried with wet chalk but contacts were very crude owing to the swelling of wet chalk and therefore correct contact area determination could not be accomplished. Second attempt consisted with butter paper inserted between jig and specimen. The pressing folds of the butter paper measured and the contact area determined. The butter paper being sensitive the pressing folds produced error in contact area determination. Third attempt involved the use of white paint spread at the surface of the grip. The rock disc when pressed under the jigs produced an imprint of contact area. A slight variation in the contact area at top and bottom noticed. Fourth attempt consisted in wraping the rock disc with butter paper and pressed with the jig where the whiter paint thoroughly spread. The measurement of the contact arc showed no appreciable difference at both top and bottom. The average value corrosponds to contact angle of 10° subtended at the centre of the disc or ring.

5.5.1.3.2 Grip dimension:

The steel loading jaws designed and developed in the department for the use with disc-shaped rock samples consisted of diametrically opposed surfaces over an arc of contact of approximately 10°. The critical dimensions of the grip are the radius of curvature of the jaws, the clearance and length of the guide pins coupling the two curved jaws and the width of the jaws. The dimensions of the grip are radius of jaws = 1.5 times the specimen thickness. Width of the jaws equal to 1.1 times specimen thickness. The upper jaw contains a spherical seating conveniently formed by a half ball bearing. The developed grip incorporates essential facilities of self centering of disc and provision for measurement of displacement while test is in progress. The design of grip varies with the thickness and size of the specimens

(Fig 5.7, Fig 5.8, Fig 5.9 and Fig 5.10)

5.5.2 Test specimen:

5.5.2.1 Specimen diamensions:

5.5.2.1.1 Specimen thickenss

Since theoretically the controlling stresses are plane stress conditions there is no explicit constraint on specimen thickness. The disc is favoured over the cylinder because of economy and also because of non-availability of perfectly stright rock cores for cyliner specimens. Theoretically the minimum thickness of a ring or a disc shall be approximately 10 times of grain diameter of rock structure. The thickness can also be fixed with the concept of critically stressed volume which is comparable with that of uniaxial tests. The ideal requirement is

	$t > 5/R^2$		in Brazil tests
and	$t > 130/R^2$		in Ring tests
where	t	=	specimen thickness in mm
and	R	=	out side radius of disc/Annulus in mm

In accordance with the above requirement in the present investigation the thickness of the specimen has been approximately kept equal to radius of the specimen.

5.5.2.1.2 Specimen diameter:

Specimen diameter must necessarly be such that the sample test material within the critically stressed volume of the specimen. The smaller linear

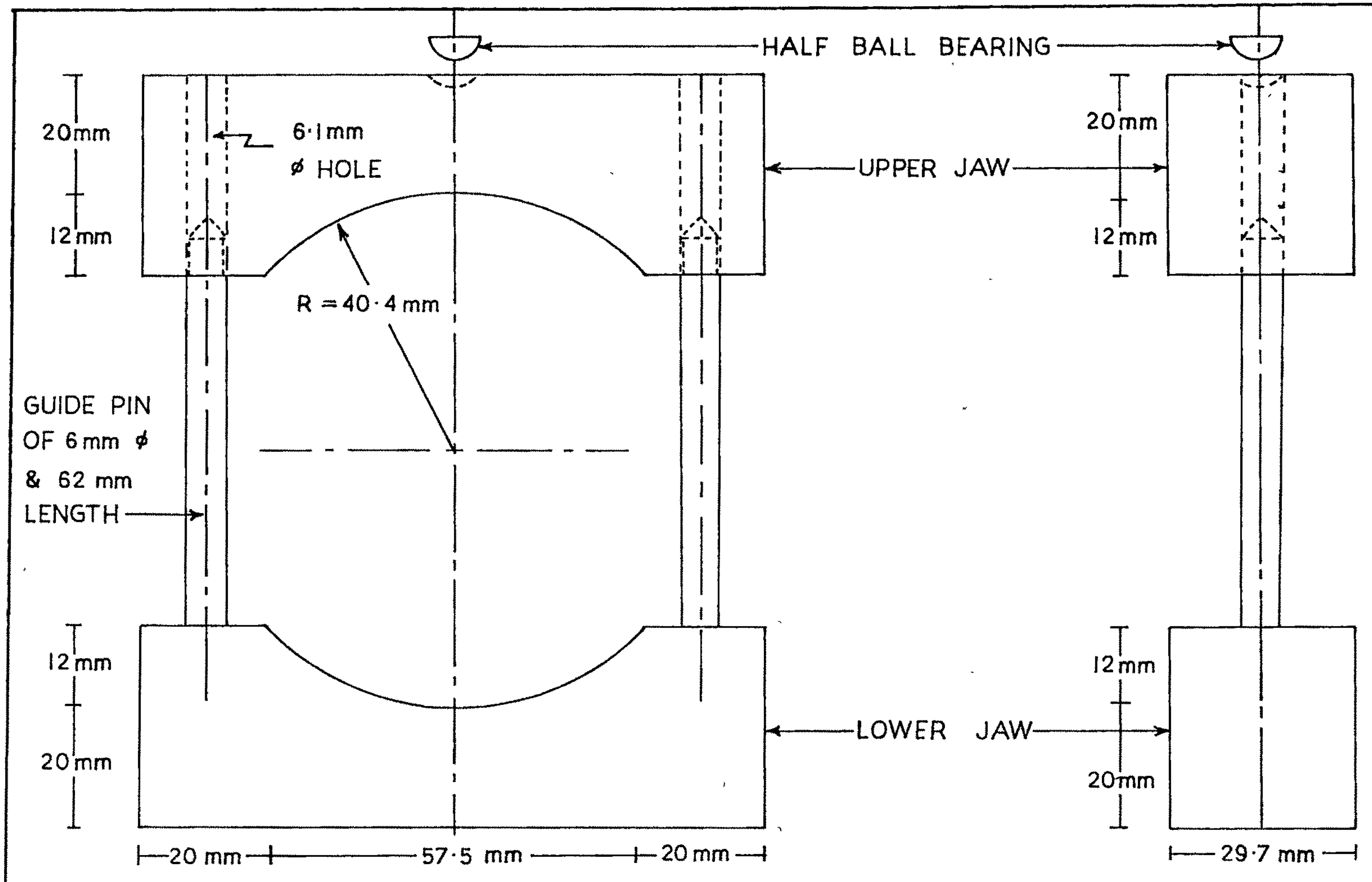

FIG. 5·7 BRAZILIAN TEST GRIP FOR Nx SAMPLE

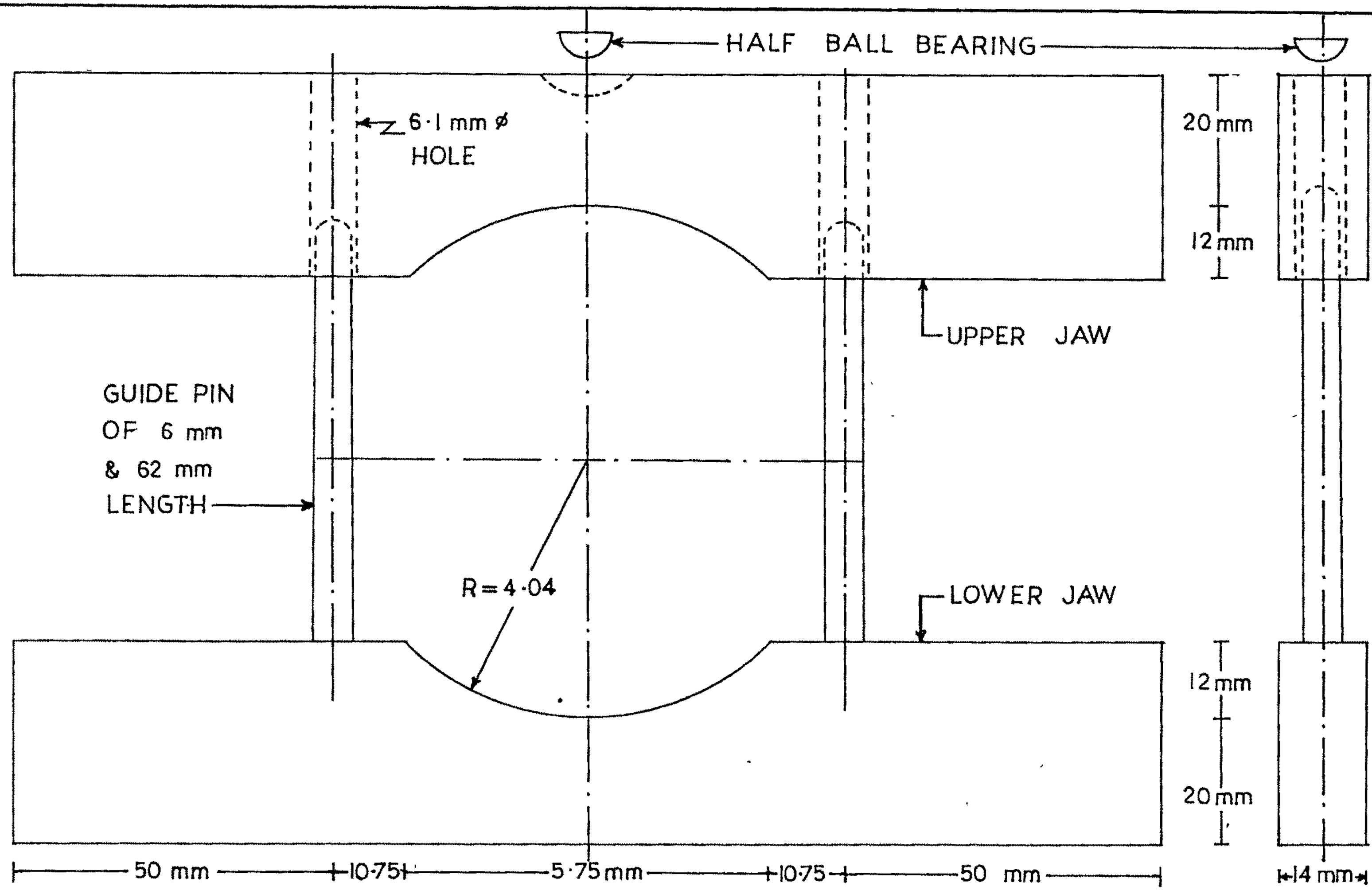

FIG. 5·8 BRAZILIAN TEST GRIP FOR Nx SAMPLE (½" TH)

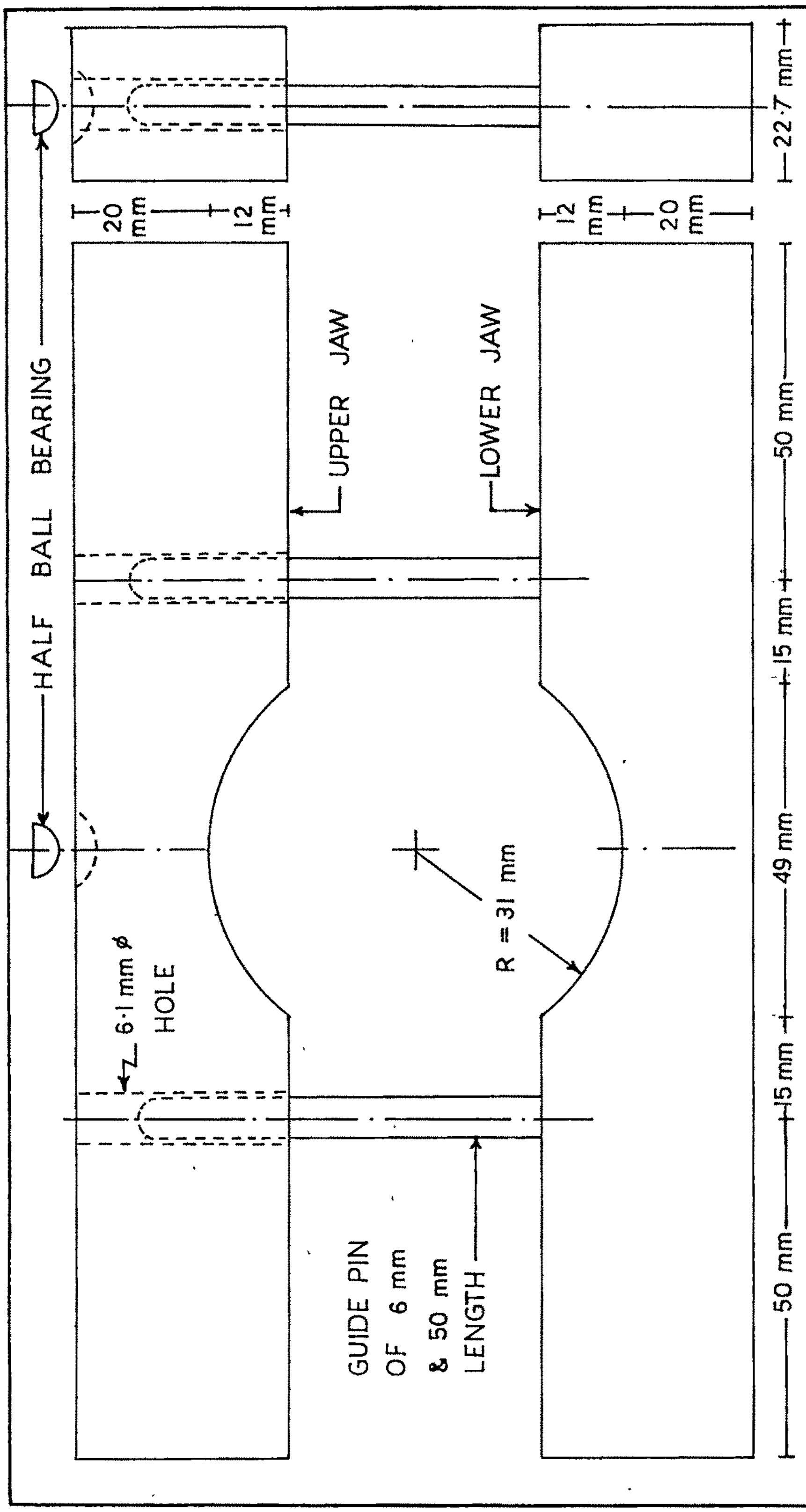

FIG. 5·9 BRAZILIAN TEST GRIP FOR Ax SAMPLE

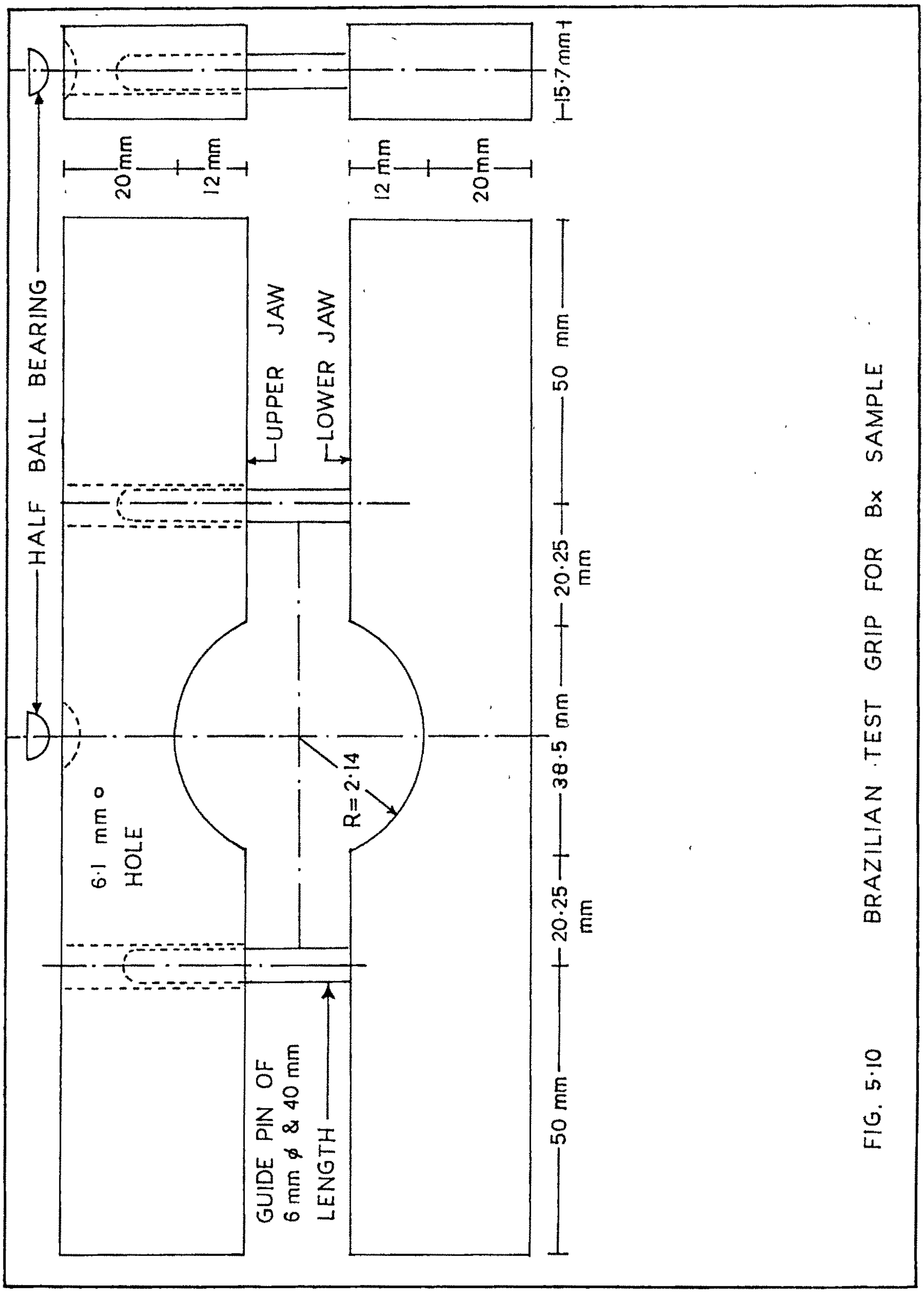

FIG. 5·10 BRAZILIAN TEST GRIP FOR Bx SAMPLE dimension of this critically stressed volume equals to 10 grain diameter of the rock. For ring test the minimum requirement suggested is R = 100 d where d is the grain diameter. Taking in to account theretical consideration, experimental findings and practical limitations 2.125 inch diameter has been taken as the minimum acceptable size for Brazil and Ring tests for the present investigation.

5.5.2.1.3 Tolerances of specimen dimension:

The cylindrical surface should be free from obivious tool marks and any bumps or waves across the thickness should not exceed 0.001 inch in height. End faces should be flat within 0.01 inch and if possible square and parallel to within 0.25°. Profilometer is generally employed to check the tolerance value.

5.5.2.2 Specimen preparations:

Samples have been collected from Navagam Dam site (Gujarat State) in the form of cores obtained through diamond drilling. The procured core samples of Basalt rock has been sliced in laboratory by a stone cutting machine using diamond saw and continuous water flow to check the thermal variation. The holes have been then drilled through discs and ring samples prepared subsequently subjecting to finishing and polishing. Finishing of the specimen ends to certain standard before testing is important because the ridges and hollows at the specimens ends form points of stress concentration and cause failure at a relatively low load. Stronger rocks like basalt are more sensitive to roughness than weaker rocks. Rock specimens finished on laths, a surface grinder and a lapping machine for exact dimensions with grinding on carborandum emary block. The finishing is particularly very important when strain gauges are to be used for strain measurements.

5.5.3 Test setup:

5.5.3.1 Equipment:

A 5 ton loading frame has been used for the test set up. The machine is consisting of five pairs of driver and driven wheels and six lever combinations giving 30 different speeds. The speed of the machine is ranging from 1.9 x 10-5 to 2.4 x 10-1 inch/min.

5.5.3.2 Measurements:

The test specimen in the form of Nx size discs and rings measured for its size and thickness prior to testing. The thickness is measured at the points of contacts of specimen and jigs and at two other points perpendicular to the loading diameter with the help of vernier callipers of least count equal to 0.001 cm.The load measured with proving ring of capacity equal to 5 tonnes. The dial gauge of proving ring calibrated giving a least count of 7.22 kg/div. The displacement of the sample measured with the help of dial gauge having least count equal to 0.0005. For measuring the average displacement of the specimen two dial gauges installed on the upper jaw of the specimen jig. A steel flat having width equal to grip is mounted on the grip and on each side of the grip one dial gauge is fitted.

5.6 Concluding remarks:

A theoretical model developed from first principles has been put forward with a clear scheme for experimental verification. The next chapter presents the analysis of the experimental results obtained from Brazil test on discs and rings of two varieties of basalt from the same region.