C H A P T E R - III

EXPERIMENTAL STUDIES ON ROCK FRACTURE

3.0 General:

Owing to imperfactions, discontinuities and inherent flaws rock materials rupture when stress in the form of either tensile or shear exceeds certain value. Hence inorder to investigate the fracture in rocks, three classes of tests are generally conducted viz:

(I) Those in which the criterion of failure is nearly satisfied over a surface or a volume of the body. These include uniaxial and triaxial loading, the Brazilian test, and compression of a rectangular bar between line loads.

(II) Those involving uniform stresses in which the criterion for failure in the tensile region is only approached at a point. These include bending of beams and stressing of discs of moderate thickness.

(III) Those involving stress concentrations such as the disc with a small hole.

3.1 Direct methods:

The direct methods employed for tensile testing for rocks are essentially based on same principles as that for metals. It is essential that samples are mounted in tension grips without damaging the surface of the specimen. Abnormal stress concentrations would be produced if load is not parallel to the axis of specimen. The greatest difficulty in the direct test is gripping of the specimen. For easy gripping and uniform tensile stress distribution, specially prepared specimen are required. A number of direct methods are available notable among them are presented below:

3.1.1 Obert, Windes and Duvall method:

In Obert, Windes and Duvall (1946) method a cyllindrical specimen is held in place with a leadite compound cast around each end of the specimen forming a bearing surface. The grips do not touch the specimen but are in contact with the leadite cast. The alignment is achieved with the spherical seated joints at both ends of the specimen. There is a limitation in the method that leadite compound can not hold a specimen with tensile strength greater than 80 kg./cm^2 or 1200 psi. A large variation is also observed in the results (Fig 3.1).

3.1.2 Wuerker method:

Wurker (1955) used briquette shaped specimen. It is not possible to have true representation of the tensile strength value because of the stress concentrations of the curvature of the side of the specimen and the closeness of the grips. The ratio of maximum to the average stress at the plane of failure is about 1.75. The major difficulty is to prepare test sample (Fig 3.2).

3.1.3 Grosvenor method:

Grosvenor (1961) adopted a procedure similar to that of Obert etal. Instead of leadite compound sulphur conical plug was used. Cyllindrical specimens are tested by gripping in specially designed grips. The grips are designed

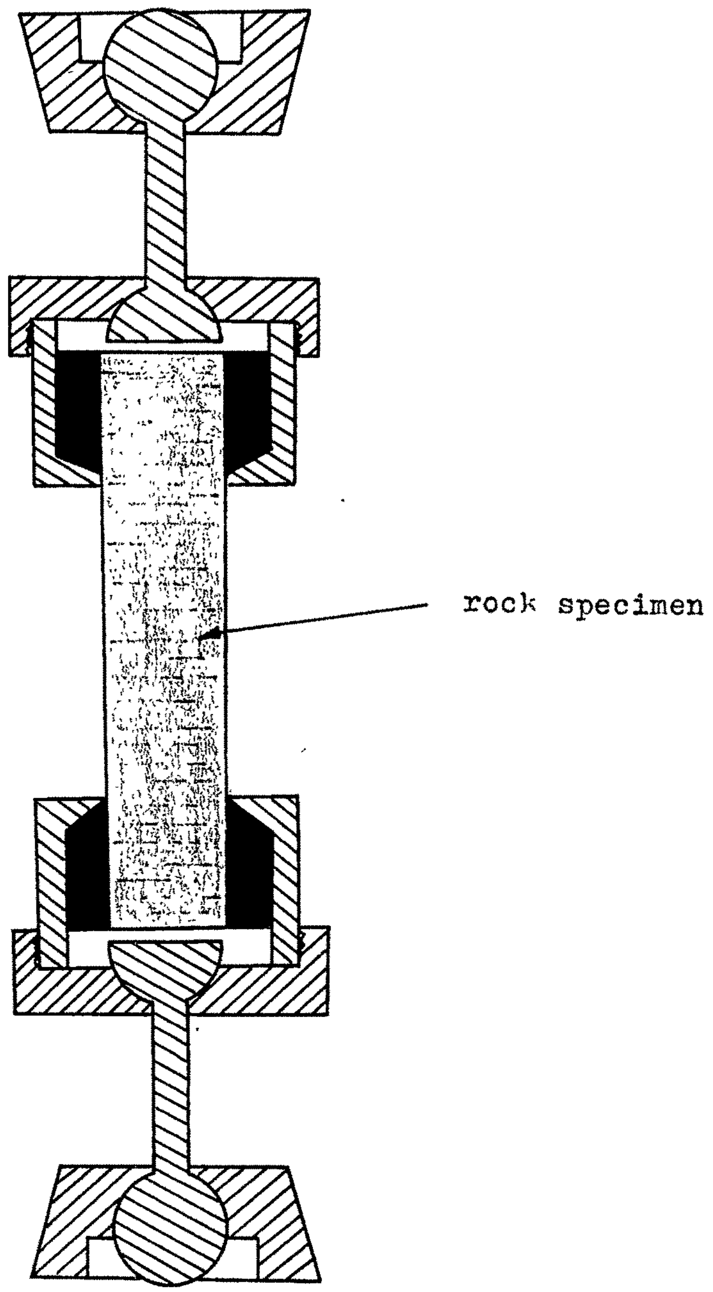


Fig. 3.1 Grips for tensile strength test
(after OBERT, WINDES and DUVALL, 1946)

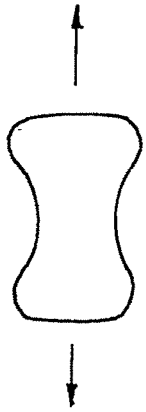


Fig. 3.2 Briquette tensile specimen
(after WUERKER, 1955.)

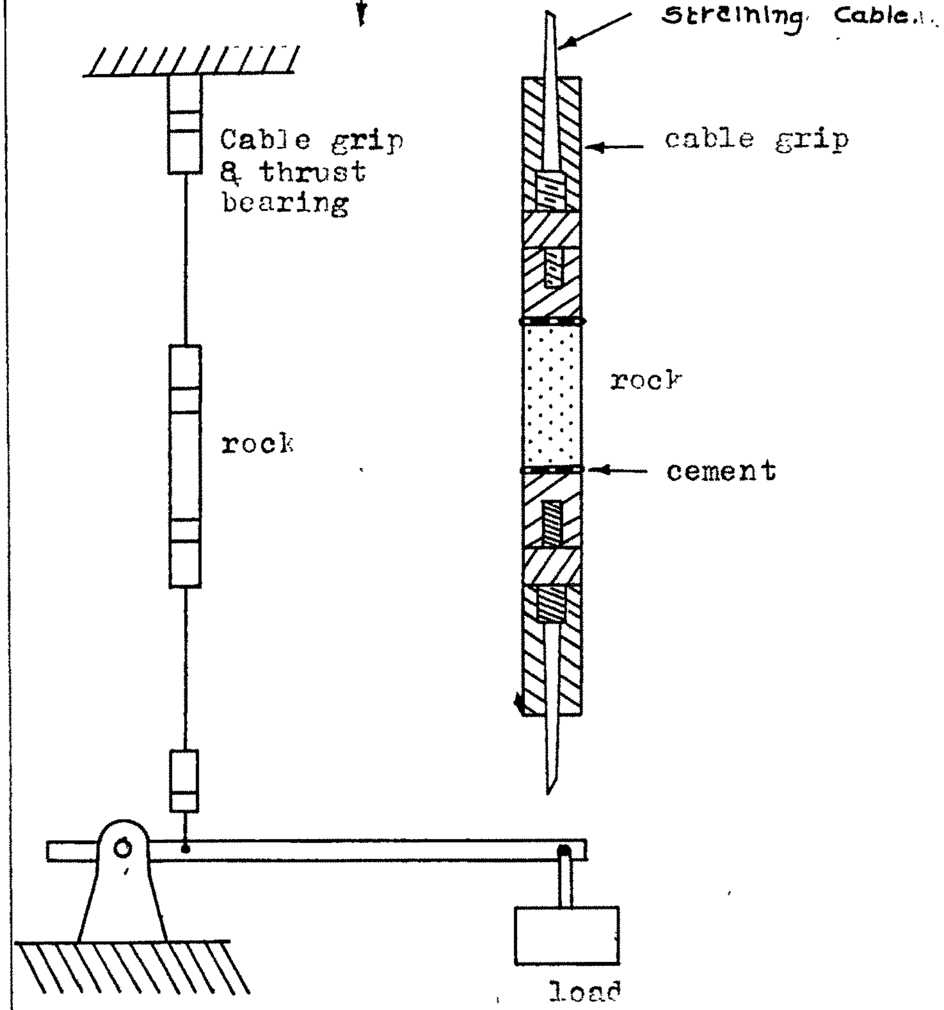


Fig. 3.3. Tensile test apparatus and gripping arrangement
(after FAIRHURST, 1961.)

to distribute the stress around the core when tightened. There is an arrangement to prevent bending and twising of the specimen. This method was not found to be suitable since failure often took place within the grip themselves due to stress concentrations and uneven tightening of grips.

3.1.4 Fairhurst method:

Fairhurst (1961) used cyllindrical specimen and epoxy based cements (Tensile strength equal to 3000 to 4000 psi. approximately). The specimen is glued to steel caps and loaded with the help of a flexible cable using a simple canteiever arrangement. In this method which is also called as plate and glue method, cyllindrical square or rectangular specimens can be used without any difficulty. The method gives consistent results and the preparation of specimen is simple. But the method is unsuitable for sound rocks as it is difficult to develop sufficient bond strength (Fig 3.3).

3.1.5 YU method:

YU (1963) also developed a procedure similar to that of Obert etal. He used a epoxy resin cast instead of the leadite cast. Failure was observed within the cast. He also investigated the plate and glue method using Devcon type plastic steel and found that this adhesive could be useful for rocks of tensile strength below 1000 psi.

3.1.6 N.M.E.R.I. method:

The rock mechanics division of National Mechanical Engineering Research Institute of South Africa used specimens of a shape similar to that used in testing of metals. Brace (1963) used such specimens except that the radius of curvature at point of reduction of diameter as 4" the specimen straight length (throat) as 1.0", the diameter as 0.5" and head diameter as 1.0". Heads were impregnated with epoxy resins (Fig 3.4).

3.1.7 Hawkes and Mellor's method:

Hawkes and Mellor (1970) have reported the use of aluminium collars designed to approximate the effect of rock fillets. A cyllindrical specimen 1" diameter and 4.75" long is cemented to chamfered aluminium collars. The collars are machined to allow a clearance of approximately 0.003" between rock and aluminium. They are slotted longitudinally to minimise radial and circumferential strain freedon and hoop stress. There is an unavoidable tendency for fracture to occur at the collar in this method (Fig 3.5).

3.1.8 U.S.Bureau of Mines method:

The fixture developed by U.S.Bureau of Mines essentially substitutes a spherical rod end bearing for chain or cable attached via a suitable platen to each end of the specimen. The platens which contain 0.25" dia are attached to the specimen ends by applying a small amount of the newly marketed Alphacynamide adhesive.

3.1.9 Mokhnachev and Gromova method:

Mokhnachev and Gromova (1970) prepared specimens with a height to diameter ration of 1.5 from blocks of limestone, sand stone, gabbro, diabase and mineralised siltstone. At the ends of the specimens they attached spherical yokes by means of which direct tension was applied.

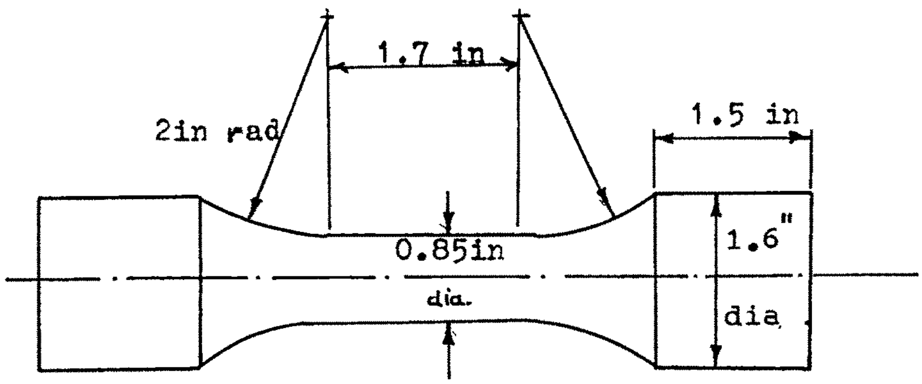


Fig. 3.4 Details of a tensile specimen used by N.M.E.R.I.
(after HOEK, 1964.)

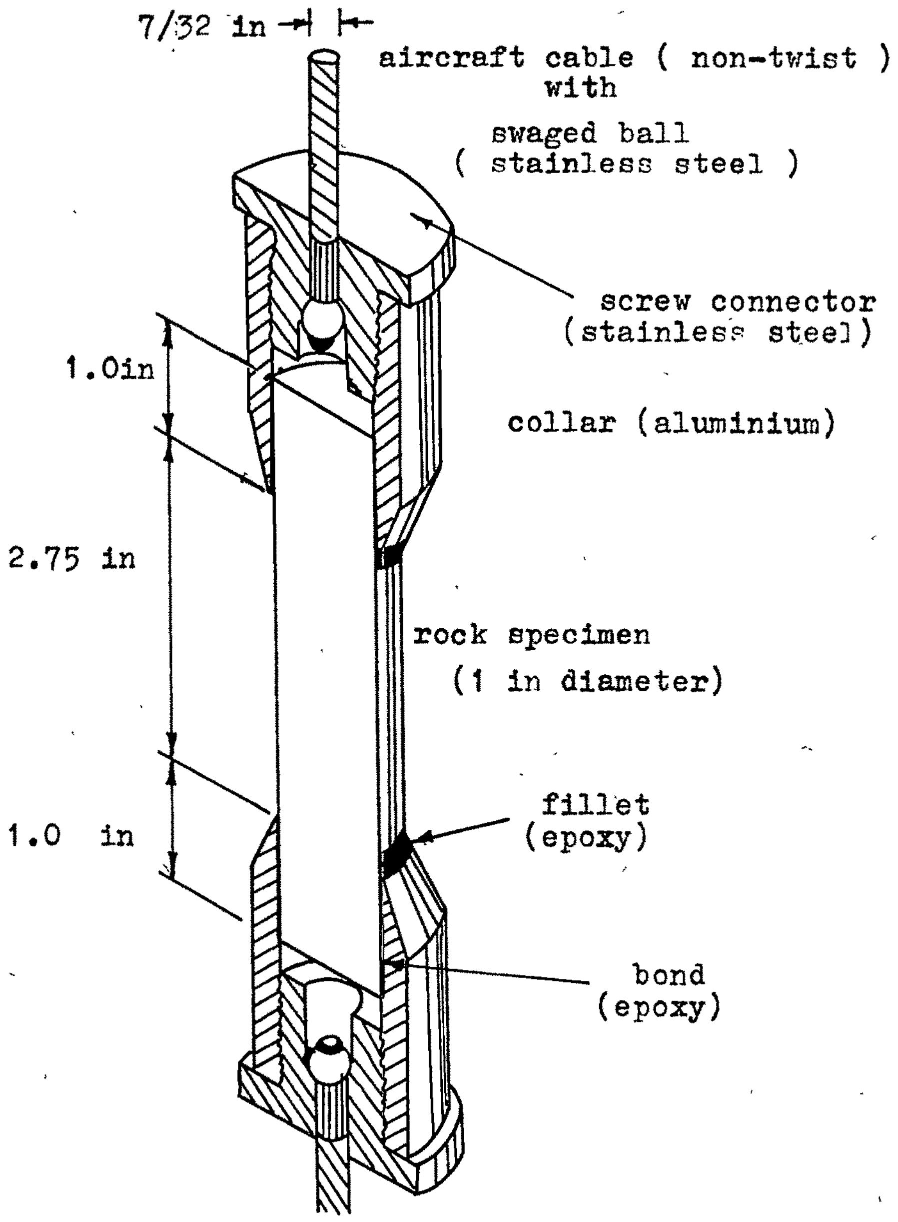


Fig 3.5 Chamfered collar method for uniaxial tensile test (after HAWKES and MELLOR, 1970).

3.1.10 Testing of specimens of irregular shape:

The testing of irregular shaped specimens reduce the labour many times in preparation of specimens. The specimen is embedded in cement between two metal dies leaving a narrow transverse slit-between the dies. The dies are pulled in a unversal testing machine until the failure of the specimen carbon and white papers are pressed against the specimen to obtain the outline of rupture surface. The rupture surface area is measured through planimeter. The possible disadvantage in this method is the existance of a bending moment owing to eccentric loads on specimen which consequently lower the strength. The method is limited to rocks whose strength is less than that of a cement. It also involves a time delay for setting of the cement (Fig 3.6).

3.2 Indirect methods:

A number of indirect methods have been developed for tensile strength measurement in rocks because of the difficulty of uniform stress distribution and gripping of the specimens in direct tests. The notable methods among those are presented below:

3.2.1 Bending of prismatic and cyllindrical specimens:

If a beam is strained in bending, tensile, compressive and shear stresses set up in the specimen or a portion of the specimen is placed in pure bending only tensile stresses are developed on convex side of the beam and compressive stresses on concave side of the beam. The maximum tensile stress at the extreme most fibre at failure can be

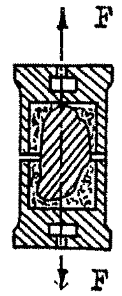


Fig. 3.6. Direct tensile test on irregularly shaped sp cimen (after PROTODYAKONOV, 1961.)

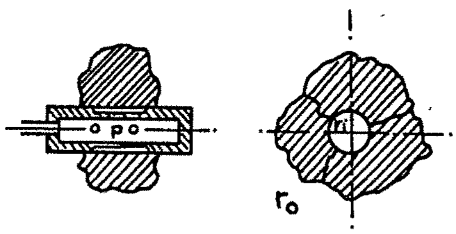


Fig 3.7 Hydraulic extension of irregular ring (after PROTODYAKONOV, 1961.)

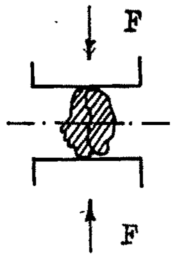


Fig 3.8 Compression of irregular specimen (after PROTODYAKONOV, 1961).

taken as the tensile strength (It is also termed as modulus of rupture) and is expressed as:

$$\sigma_t = -\frac{Mb\ C}{I} \quad . \quad . \quad . \quad . \quad . \qquad 3.1\ A$$

where C is the distance from the neutral axis. The equation is valid under following assumption viz:

(I) Original transverse plane of the beam at the locations of the moment calculation remains strictly as a plane and normal to all longitudinal fibres before and after bending.

(II) Material is homogeneous and elastic following Hooke's law.

(III) Bending occurs in the plane of symmetry of beam.

(IV) The stress strain behaviour is same both in tension and compression and neutral axis is located at the middle of the beam.

For rocks assumption four is not valid hence it will give erroneous results. To evercome this difficulty Duckworth developed an equation for rectangular beam taking in to consideration the difference in Young's Modulus value in tension and compression.

$$\sigma_t = -3M_b\ (E_1 + E_2)\ /\ b_g\ t_g^2 \quad . \quad . \qquad 3.1\ B$$

where b_g and t_g are the width and the thickness of the gauge section respectively. (Fig 3.9)

3.2.2 Bending of discs:

A simply supported or a clamped plate when loaded at centre, causes the tensile stresses to set up at bottom surface. The maximum tensile stress developed in the

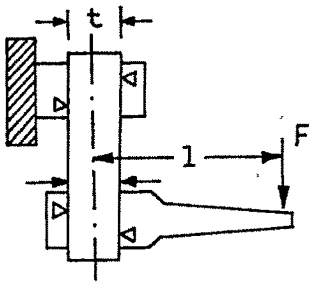


FIG. 3·9 Bending of prisms in vertical position by the application of couples (after PROTODYAKONOV,1961)

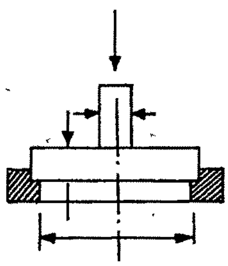


FIG. 3·10 Bending of a disc (after PROTODYAKONOV, 1961) plate is (Seely and Smith 1952).

$$\sigma_t = \frac{3(1+\nu)P}{2\pi t_d^2} \quad \frac{1}{(1+\nu)} + \text{Log}_e \frac{r_d}{r_p} - \frac{(1-\nu)}{(1+\nu)} \frac{r_p^2}{4 r_d^2} \quad . \quad . \quad 3.2$$

The equation is valid under following assumptions:

(I) The deflection of the plate is relatively small (4t) otherwise direct tensile stresses in addition to the bending stresses will contribute substantially to the failure of the plate.

(II) The material is ideally elastic.

(III) The plate remains flat i.e. it remains straight and normal to the deflected middle surface after the plate is loaded.

For rocks 1st. assumption usually holds good and 3rd. assumption can be made valid by carefully preparing specimen. The 2nd.assumption is rarely true and that is why yield may occur which causes readjustment of stresses. The bending tests usually give higher values than direct tests but still it is used to determine the strength of rocks.
(Fig 3.10 and 3.11)

3.2.3 <u>Compression of irregular specimen:</u>

In this method rock pieces are selected whose volume does not differ more than a factor of 2. The specimens are placed between platens of a compressive testing machine after blunting their sharp edges and crushed. The specimens normally rupture along a plane connecting the points of loading. The failure is assumed to be due to uniform tension applied accross their surface (Fig 3.8).

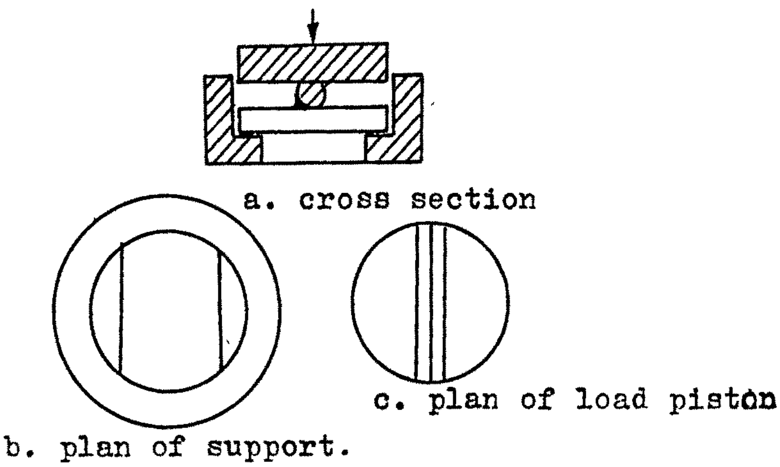


Fig 3.11 Bending of a disc
(after MAZANTI and SOWERS, 1965.)

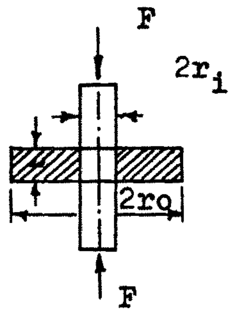


Fig 3.12 Extension of a ring
(after PROTODYAKONOV, 1961.)

3.2.4 Hydraulic extension method:

If a thick walled ring or cylinder is subjected to an internal hydrostatic pressure the stresses developed can be given(Seely and Smith 1952).

$$\sigma_\theta = - P_1 \frac{r^2}{r_o^2 - r_i^2} \left\{ \frac{r_o^2}{r^2} + 1 \right\} \quad . \quad . \quad 3.3.A$$

$$\sigma_r = - P_1 \frac{r^2}{r_o^2 - r_i^2} \left\{ \frac{r_o^2}{r^2} - 1 \right\} \quad . \quad . \quad 3.3\ B$$

Failure of the ring or cylinder occurs due to tengential tensile stress and its value is maximum at the inner surface (Fig 3.12). It is given as:

3.2.5 Hydraulic extension of irregular rings:

A specimen is prepared by drilling a central hole in irregular shaped specimen. A perforated tube within a rubber casing is inserted in the hole. Oil is injected in to the tube to apply a uniform pressure (p) inside the specimen. The inner radius and outer radius are measured after the sample has broken. The tensile stress at failure is obtained assuming that a crack first appears on the inner radius of the specimen and gradually develops untile it reaches the centre of the thickness of the specimen. The equation is derived from Lame's theory of thick walled cylinders taking in to account the appearing of first crack (Fig 3.7).

3.2.6 Centrifugal tension:

Tensile strength can also be obtained from centrifugal tensile test rig Bernaix (1969). The maximum rotational speed of their machines is 12000 rpm such that tensile stress upto 1450 psi. can be measured.

3.2.7 Diametral compression of cylinders:

Jaeger (1967) tested cylinder of 2" diameter and 1" length under diametral compression by applying 4 equal line loads. It is observed that for ω = 45° the tensile strength is very nearly equal to Brazilian tensile strength. For greater value of (ω) there exists substantial tensile stress at failure but are less than Brazilian tensile strength (Fig 3.13).

3.2.8 Point load method:

Reichmuth (1962) compressed cylinders between two point contacts. He suggested that for specimen of 0.5" to 1.2" diameter satisfactory tensile strength values are obtained using the equation (Fig 3.14).

$$\sigma_t = 0.6\ F/D^2 \qquad . \quad . \quad . \quad . \quad . \qquad 3.4$$

3.2.9 Diametral compression of shperes:

The spheres when subjected to concentrated loads at opposite ends shows an extension failure in a plane or planes passing through the loaded diameter. The stress distribution in sphere compressed diametrally was determined by Hiramatsu and Oka (1966). The tensile strength has been obtained from the following equation (Fig 3.15). (Art.3.3.2.7)

3.2.10 Compression of square plates along diameter:

When a square plate is compressed on opposite ends between a pair of symmetrically placed flattend

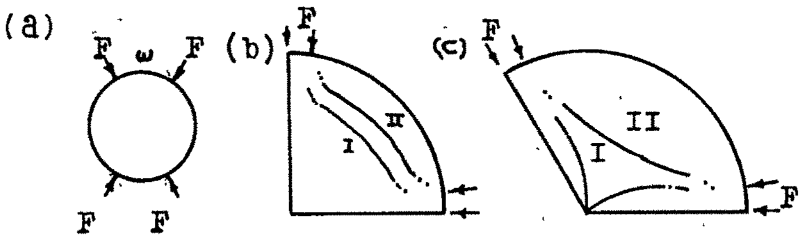


FIG. 3·13 (a) Cylinder compressed in two diametral planes inclined at ω;

(b) ω = 90. Curve I, limit of tensile field; Curve II, locus of maximum tensile stress ;

(c) w = 60° Curve I, limit of tensile field : Curve II , locus of maximum tensile strees

(after JAEGER, 1967.)

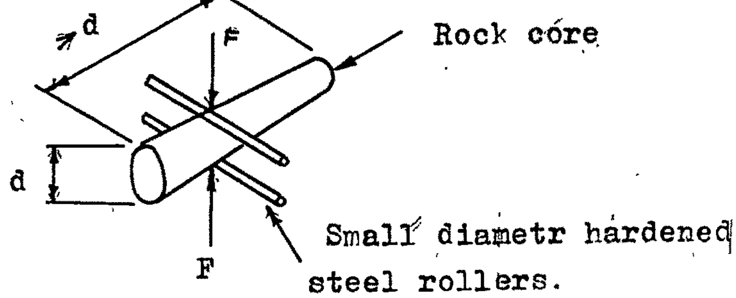


FIG. 3·14 Point loading method for cylinders (after REICHMUTH, 1962.)

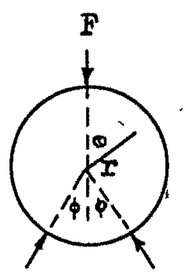


FIG. 3·15 cylinder compressed by three line loads;

indenters, the tensile stress develop in its central region. Berenbaum and Brodie (1959) determined stress distribution along the two central axis from photo elastic analysis (Fig 3.16).

3.2.11 Diametral compression of discs:

The diametral compression of disc also called as Brazilian test originated from South Africa. This test was proposed by Carneiro and independently by Akazawa. The test makes use of circular solid disc which is compressed to failure across a diameter. Hondros (1959) and Shook (1962) analysed the stress distribution in a thin disc loaded by uniform pressure radially applied over a short strip of the circumference at each end of the diameter. Following assumptions have been made for analysis (Fig 3.17).

(I) Material is homogeneous.

(II) Material is isotropic.

(III) Material is linearly elastic.

The tensile strength.is obtained by the expression given below:

$$\sigma_t = 2F/\pi D t_d \qquad . \quad . \quad . \quad . \quad . \qquad 3.5$$

3.2.12 Diametral compression of rings:

The Brazilian test done on circular rock samples with co-axial hole driven through it is termed as ring test. The test has been developed to avoid the existence of biaxial stress field in Brazilian test. Ripperger and Davids (1947) Timoshenko and Goodier (1951) analysed for indirect tensile testing of brittle materials assuming material to be homogeneous, isotropic and linearly elastic.

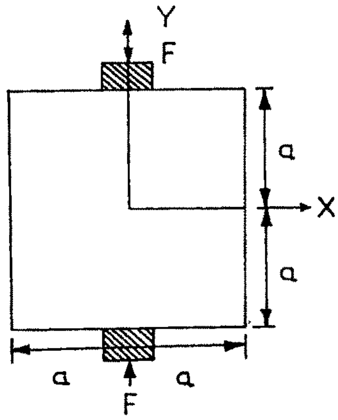
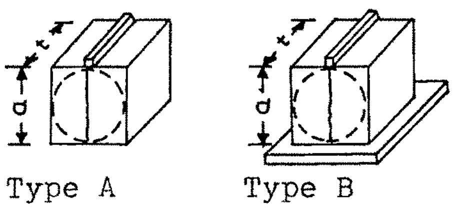


FIG. 3·16 A Compression of square plate along a diameter (after SUNDARA RAJA IYENGAR AND CHANDRASHEKHAR 1962).



Splitting tests for square specimens.

FIG. 3·16 B Test arrangement for type A and type B square specimens (after DAVIES and STAGG, 1970)

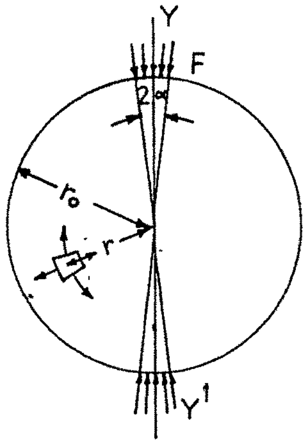
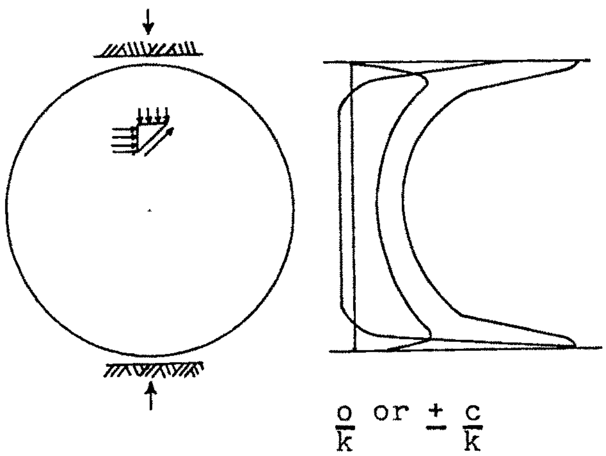
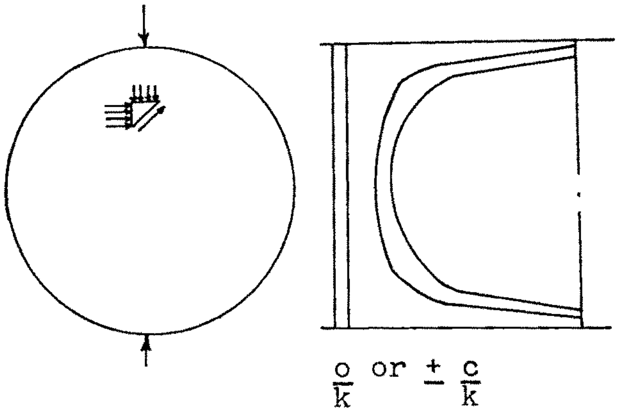


FIG. 3·17 A The Brazilian test, showing notation used.

FIG. 3·17 B Loading configuration and stress distribution across the loaded diameter for Brazilian test (after SHOOK,1963)



Stress distribution across loaded diameter for a cylinder compressed between two flat plates.



Stress distribution across loaded diameter for a cyliner compressed between two line loads.

The tensile strength is obtained through following equation:
(Fig 3.18 A & B)

$$\sigma_t = \frac{2F}{\pi D t_d} \left(6 + 38q^2 \right) \quad . \quad . \quad . \quad 3.6$$

3.3 Experimental studies:

Many experimental studies have been carried by research workers during tensile testing of rock. These studies not only involve various aspects for understanding mechanical behaviour and failure phenomenon but also include the development of testing methods in rocks. The notable studies during principal tests are presented below:

3.3.1 Experimental studies on disc and ring tests:

Diametral compression of rock discs and rings has strong practical appeal and alternative to the uniaxial tensile tests which are difficult to perform to acceptable standard due to difficulty in specimen prepartions and gripping techniques. The experimental study includes the aspects viz:

3.3.1.1 Specimen geometry:

3.3.1.1.1 Berenbaum and Brodie (1959 b) as well as YU (1963) found that if the ratio between the thickness of the disc and the diameter increases the tensile strength decreases. Dube and Sing(1969) also reported similar results.

3.3.1.1.2 Protodyakanov (1961) used cylinders with a high length to diameter ratio. The cylinders are subjected to compression by placing them in the press platens. Failure takes place due to the penetration of the prisms of the

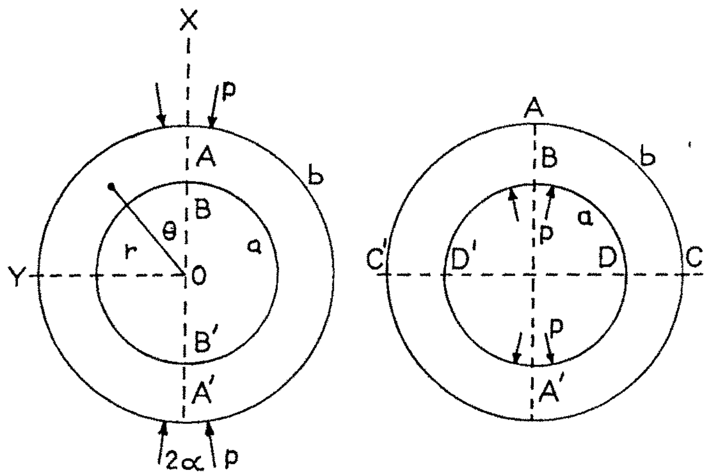


FIG. 3·18 A

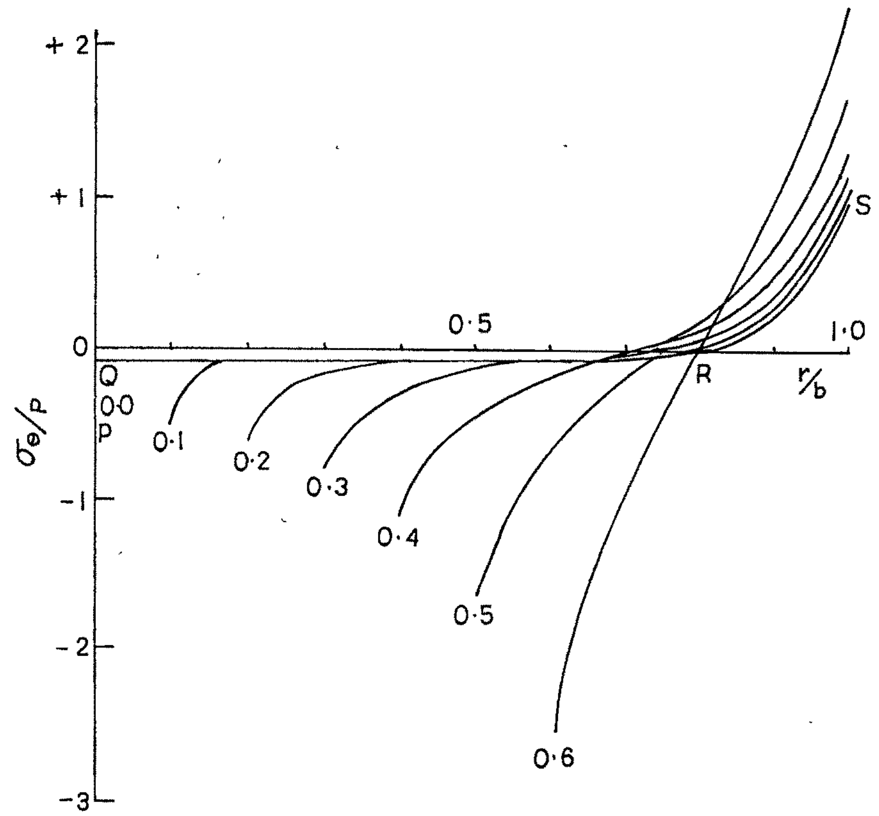


FIG. 3·18 B THE VARIATION OF TANGENTIAL STRESS σ_θ OVER THE LOADED DIMETER AB OF FIG. 3·18 A NUMBERS ON THE CURVES ARE VALUES OF THE RATIO $q = a/b$

deformed rock at the places of contact.

3.3.1.1.3 Bernaix (1969) reported the results of Habib and Voulie on the effect of diameter on the calculated tensile strength.

3.3.1.1.4 Mellor and Hawkes (1971) investigated the influence of specimen diameter over the practically feasible range of sizes 1"to 3"in on the Brazilian test results. The results show that the size effect for typical rocks is significant for diameters up to 1"in and less but they suggest that measured strength may tend to a steady value for diameters above about 3". Mellor and Hawkes further suggested, taking in account the theoritical considerations and experimental findings, that Nx core size 2.125" diameter should be taken as minimum acceptable size for Brazilian tests on typical rock materials. They also concluded that thickness equal to radius of disc should be taken as the minimum acceptable thickness for Brazilian specimens.

3.3.1.2 Strength and deformation characteristics:

3.3.1.2.1 Addinall & Hackett (1964) studied the effect of platen conditions on the tensile strengths of rock - like materials. The effects of platen hardness upon the apparent tensile strength were recorded from the solid disc Brazilian test. They have shown that the use of cushion materials between the specimen and the platens of the testing machine has a pronounced effect on the tensile strength values obtained. The conclusive results show that to obtain the most consistent results, hard high modulus platens are required. They also concluded that :

(I) The softer the cushion material, the higher the tensile strength.

(II) The softer the cushion materials, the greater is the range of values obtained.

(III) The softer the cushion material, the longer is the area of contact caused by the loading platens.

(IV) All discs except those tested between rubber platens fractured in the usual way.

(V) The softer the cushion material, the less symmetrical is the fractured pattern.

(VI) The lowest value for the tensile strength corresponds to the use of steel platens alone. Photoelastically this system give a stress distribution in the disc most closely resembling the theoretical distribution for line contact.

3.3.1.2.2 D.W. Hobbs (1964) studied the variation of the tensile strength with lamination orientation. He discussed the results of tensile strength obtained by using the technique of diametral compression of a disc with central hole. He concluded as follows:

(I) The tensile strength of rock is generally greatest when the applied tensile stress is at 0° to the laminations and smallest at 90° to the laminations.

(II) The maximum variation in tensile strength with lamination orientation is shown by the lightly laminated siltstone and is about 3.5 : 1.

(III) It is suggested that a relationship exists between the tensile and compressive strengths of massive and laminated rocks.

(IV) The magnitude of the variation of the compressive and tensile strength with lamination orientation for blocks of the same rock type is not necessarily constant.

3.3.1.2.2.1 Hobbs also studied that eccentrically placed holes can either increase or decrease the fracture load. The fracture load increases with eccentricity when the hole centre lies on a diameter perpendicular to the line of load and decreases with eccentricity when hole centre lies on the line of load.

3.3.1.2.3 Berenbaum and Brodie (1959) prepared and tested coal specimen for tensile strength by Brazilian test at various orientations of the planes of weakness. On each set of discs measurements are recorded at five different angles to the planes perpendicular to the faces of the set, these angles were 0°, 25°, 45°, 65° and 90°. The discs used had a mean thickness 0.31 inch. The mean diameter was 1.00 inch. In general it is observed that the strength is greatest at 0° and lowest at 90° to the bedding planes.

3.3.1.2.4 Holdsworth and Werblow (1960) have studied the failure using an electronic microsecond counter and high speed photography in Pennant sand stone rings. It was found that breakage of the line closest to the hole along the diameter started the counter and the counter was subsequently stopped when the other graphite line was broken.

Thus the direction of the travel of the crack from the internal to the external diameter was established. It was estimated that the speed of the travel of the crack is approximately 23,000 inch/sec. The cracking mechanism was observed to be completed in less than 300 microseconds.

3.3.1.2.5 Price and Knill (1966) studied the variation in tensile strength with rate of loading for dolerite and metamorphosed lime stone of thickness equal to 1" and 2.1" and diameter of 2.4" with 0.35" central hole. There was observed increase in computed strength with increase in rate of loading.

3.3.1.2.6 Brown and Trollope (1967) exhibited photographs of fracture surface showing the central origin and propagation path of the crack in a plaster specimen and observed a cheuron pattern. But in rocks this pattern is rarely observed.

3.3.1.2.7 Willard and McWilliams (1969) developed microstructural techniques to investigate relations between rock fabric and mechanical properties. The defect frequency orientation is compared with the tensile strength of Barre granite from Brazilian test. The tensile strength was calculated from each of these line angles. The frequency of defects tends to be inversely proportional to strength suggesting that the direction of weakest tensile strength is approximately normal to the direction of most defects.

3.3.1.2.8 Dube and Singh compressed specimen to failure along lines which were inclined at different angles to the bedding planes. The results indicate that the strength of the specimen is greatest when the applied load acts 80° to the bedding planes and it decreases as the angle of inclination increases. It is lowest when the direction of the bedding plane is parallel to the direction of the applied load. The ratio between the lowest and the highest strength was 0.66 and 0.76 for 30mm and 54mm diameter disc respectively.

3.3.1.2.9 Hooper (1971) reported that failure always initiates at the loading points in the case of glass. The cracking of brittle materials, he observed, is influenced by the local microfracturing and the contact conditions.

3.3.1.2.10 Barron (1971) has evaluated the effect of orientation of the bedding planes on the tensile strength of siltstone and the failure using ring test. All specimens failed directly across the loading diameter. Hobbs reported similar results.

3.3.1.2.11 Hudson (1969) studied the effect of geometry on tensile strength. All rings of Gypsum Plaster with and without limestone inclusions were tested at a loading rate of 0.002"/min. for the large hole sizes and 0.005"/min. for the small hole sizes. All specimens failed in approximately 1 minute and loading rate effects were kept to a minimum.

3.3.1.2.11.1 According to Hudson, the tensile strength within the ring test varies between two constant values. One is the true tensile strength in this situation for large hole sizes when the elastic calculations adequately represent the physical situation. The other is a totally fictitious tensile strength for small hole sizes which have no effect on failure. Tensile strength varation within the ring test is thus explained by the gradual breakdown of elasticity theory as the hole size is reduced. Tensile strength variation between the ring test and Brazilian test, however, remains a paradox. Author has shown that this variation is not caused by ignoring the compressive stress component in the Brazilian biaxial stress field.

3.3.1.2.12 Bortz and Lund (1961) and Addinal and Hackett observed the tensile strength variation. They tested a range of fine grained material at q = 0.292, 0.500, 0.708 and found that there was a little variation in the values of tensile strength at q = 0.2. The tensile strength rises sharply below q = 0.2 until it reaches a constant value approximately double the large hole value. The point at which the tensile strength becomes constant represents the critical hole size below which the hole has no influence. The hole size q = 0.022 was subcritical for plaster with limestone inclusions and in a few cases the cracks bypassed the hole.

3.3.1.2.13 According to Moller and Hawkes (1971), the object of a diametral compression test is to measure the force required to form the primary diametral crack in the specimen so that tensile strength can be calculated. In most laboratories this force is read directly from the dial of a universal testing machine, but the authors found that the peak force measured in this way is sometimes too large. To avoid errors of this kind the authors supplemented the dial read out system with chart records of load as a function of displacement, and also attempted to release the load at the first indication of failure.

3.3.1.3 Environment:

3.3.1.3.1 Dube and Singh (1972) studied the effect of humidity on tensile strength of five different types of sandstones. Their results show a decrease in the strength ranging from 11 to 48% under fully saturated atmosphere.

3.3.1.3.2 Dube and Singh (1972) observed increases in strength with increases in the percentage of matrix (matrix is essentially the cementing material) in sand-stones. The authors also observed the decrease in strength with increase in porosity in sand-stones.

3.3.1.3.3 Merriam, Rieke Iii and Kim (1970) found the tensile strengths of a variety of granite rocks to be inversely proportional to quartz content. They altributed this relationship to textural differences as suggested by highquartz rocks composed of equidimensional grains showing little crystal intergrowth, or interlocking, whereas lowquartz rocks consists of inter-locking laths and prisms.

3.3.1.3.4 Vutukuri (1972) determined the effect of

$ALCL_3$ solutions on the tensile strength of quartzite. He observed reduction in strength (compared to water) upto about 11%.

3.3.1.4 Effect of stress volume:

3.3.1.4.1 Statistical theory by Weibull (1939) suggest that some departure from the uniaxial strength value might be expected to be caused by the stress gradient in the ring and by the relatively small volume of the ring specimen which is subjected to the peak stress, even if the test were otherwise to behave exactly according to simple theory. These two effects can be discussed together, since there is an implicit relationship between critically stressed volume and stress gradient at the critical point.

3.3.1.4.2 Addinall and Hackett (1964) plotted computed strength against stress gradient for their experimental data, and found no simple relationship. There can however, be little doubt about the reality of 'volume effects'.

3.3.1.4.3 Lundborg (1967) investigated the dependence of tensile strength by Brazilian test on volume of the material in the case of granite cylinders of the same length and diameter 2cm, 3cm, 4cm and 6cm.

3.3.1.4.4 For values of q in the ring test below 0.1 the volume of the specimen stressed to within 10% of the tensile peak stress is so small that it is virtually insignificant, i.e. it has no more effect than a naturally occuring pore or crack. We would therefore expect a disc with a very small hole to act largely as a solid disc, as is borne out by experimental data

3.3.1.5 Loading rate and elastic response:

There are at least three broad principles to be considered in choosing loading rates for ring and disc tests.

3.3.1.5.1 Strength is calculated from test results on the assumption that the discs or rings are linearly elastic, so loading rates must be fast enough to evoke elastic response from the specimens.

3.3.1.5.2 Most rocks fail by time-dependent development of internal microcracks and, in general, apparent strength increases as loading rate increases or test duration decreases.

3.3.1.5.3 There are practical limitations on loading rates. Typical testing machines become unreliable at their highest speeds (head speed 2 inches/min.); due largely to inertial effects in the load measuring and dial readout systems. At very low loading rates (head speed = 0.001 inch./min. approx.; loading rate = 400 lbf/min. approx.) test durations become inordinately long i.e. 15 minutes or more.

3.3.1.5.4 On the basis of test experience with a wide range of material and five different testing machines, Mellor & Hawkes (1971) have opined that for common rocks and typical machines, head speeds above 1.5 inches/min.are too high unless oscilloscope readout is provided, while nominal head speeds much below 0.1 inch/min. may result in excessive test durations. With simple equipment, reproducibility tends to be best at the lowest speeds, but there are no great problems in this respect upto a nominal head speed of about 0.5 inch/min.

3.3.1.5.5 Observation by Stowe and Ainsworth (1968) and Green and Perkins (1968)show that the quasi-elastic response of rocks becomes more nearly linear as loading rate or strain rate increases.

3.3.1.5.6 At low loading rates, non-linearity of the stress-strain characteristic is pronounced, particularly at high stresses, since there is sufficient time for flaw and internal cracking to exhibit their effects. Thus, the actual peak stresses at the critical points of disc and ring specimens will be lower than those predicted by linear elastic theory; and test results calculated from elastic theory will tend to exaggerate the strength of the rock.

3.3.1.5.7 For most rock at normal environmental temperatures, a marked transition from viscous to elastic predominance is likely to occur at strain rates very much smaller than those imposed by typical testing machines, but nevertheless the general point remains valid, and loading rates should be sufficiently fast to suppress creep effects.

3.3.1.6 Contact stresses:

3.3.1.6.1 Elastic theory from Timoshenko and Goodier (1951) deals with the width of the contact area when a flat platen and a cylindrical area are pressed together. The simple theory for discs and rings assumes line loading at the boundary, although true line loading, which would imply uniform contact stresses can never be realised in practice. If Brazil 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, but contact stresses must not be so high that they cause premature cracking. Reduction of contact stresses is necessary at least in the Brazil test, and the figures already arrived at, suggest that reduction should be by a factor of 5.

3.3.1.6.2 Photoelastic observations by Colback (1966) suggest that stress distribution in the critical zones of discs and annuli is virtually unaffected by distribution of boundary loads over contact arcs upto 15°. Hence the possibility that the stress conditions in the critical test zone of the sample is altered in order to reduce the contact stresses solely by increasing contact area may not arise. Therefore it would be necessary to increase contact width by atleast a factor of 5 from R/15 to R/3. Further the contact stresses can also be reduced by altering the distribution of stress so as to reduce stress concentrations.

3.3.1.6.3 Hondros's (1959) solutions indicate that the simple Brazil formula for principal tensile stress at the center of the sample is in error by less than 2% for contact arcs upto 15° wide, while studies by Jaeger and Hoskins (1966) indicate that the ring stress concentration factors for line loads differ from those for loads distributed over 15° arcs only by some 2% for typical values or q.

3.3.1.6.4 Jaeger and Hoskins (1966) and Mellor and Hawkes (1971) concluded from the evidences that 15°, i.e. $2\alpha = R/4$ is an acceptable upper limit for contact width.

3.3.1.7 Crack propagation and failure phenomenon:

3.3.1.7.1 Fairhurst (1964) analysed the Brazilian test on the basis of Griffith's criterion and showed that failure is in conformity with Griffith's criterion. He also suggested a parameter 'stress severity' defined as the ration of theoretical load at failure of the specimens at the most highly stressed point to the load required to cause failure. This can be calculated as a function of position along the loading diameter. His conclusions are as follows:

(I) The lower values of tensile strength is obtained when loading is applied over small strip angles. This dependence of tensile strength on strip angle decreases as the compression-tension ratio increases.

(II) A greater region is critically stressed with larger strip anlge ($\alpha = \tan^{-1} 1/6$) in order to assure fracture initiation near the centre of a homogeneous specimens it is necessary to spread the applied load over an appreciable arc of contact (20° or more). They further suggest that with a narrow contact strip ($\alpha = 5°$) there will be a pronounced tendency for off-centre fracture initiation in rocks.

3.3.1.7.2 Addinall and Hackett (1965) observed experimentally and by semigraphical methods that the origin of failure in a given disc under given loading conditions is a function of the contact area. They showed that origin of failure for a classical Griffith material in a Brazilian test, is not the centre of the disc. However for wider contact areas i.e. more than 9° the point of origin of fracture moved quite abruptly towards the centre of the specimen.

3.3.1.7.2.1 Addinall and Hackett (1965) observed for rings that cracks bypassed the hole and left the hole in a solid piece. They also concluded that fracture pattern for disc with small value of q was similar to those observed in solid disc, there being a diametral crack and also weldefined secondary cracks. As 'q' increased secondary cracks becomes less defined and with large ratios (i.e. q = 0.5) they were often not present.

3.3.1.7.3 Hobbs (1964) measured tensile strength of rocks in a Brazilian test using solid discs. He observed that rock discs failed in tension along the loaded diameter. He compared the obtained values with the ring test. He observed that due to greater shearing stresses close to the loading platens the solid discs fails at higher loads. He also studied the effect of laminations and orientations of solid discs and rings and concluded that tensile strength is greatest when applied tensile stress is at 0° to the lamination and smallest at 90° to the laminations. He opined that a relationship exists between tensile and compressive strength of massive an laminated rock.

3.3.1.7.4 Colback (1966) analysed the validity of Brazilian test using modified Griffith criterion and concluded that failure must originate at the centre of the disc if the test is to be valid. This condition can only be achieved by a distributed load with a cardboard or wood.

3.3.1.7.5 Jaeger and Hoskins (1966) have studied the failure of rock materials in the form of rings subjected to line loadings on either internal or external surfaces. The sandstone and trachyte behaved as ideal brittle substances failing quite suddenly. They would hold loads slightly less than those necessary to cause failure for hours. The marble was used because it has the useful property of failing slowly so that some indication of the mechanism of failure can be obtained. However, for external loading, cracks can be observed in marble at the inner surface under substantially lower loads. These cracks do not propagate so that complete failure does not occur.

3.3.1.7.5.1 The question of the mechanism of failure has been confused by the fact that in some cases, wedges are observed leading from the platens, and these suggest that failure might have initiated at the platens. However, these wedges are probably a secondary effect produced during catastrophic failures and in slow testing of marble, it is easily possible to produce cracks which run from the interior to one platen only and also to show that there is no other evidence of failure (e.g. twinning) near the platens.

3.3.1.7.5.2 A very shallow stress concentration results with a small central hole even if q = 0.1, the stress concentration does not penetrate beyond D /5. This shallow stress concentration explains the rapid fall of curves of upto q = 0.4. If failure does take place at the inner surface, the crack does not propagate. Such cracks can be observed in marble.

3.3.1.7.6 Mellor & Hawkes (1971) established that cracking does not start at the platen contacts in a properly conducted Brazilian test, but in a properly conducted ring test, primary fracture invariably occurs along the loading diameter and the crack initiates at, or near the surface of the hole. Thus, in ring test interest centres on the distribution of tensile stress along the loading diameter and particularly on the critical points where the loading diameter intersects the hole boundary.

3.3.1.7.6.1 The results of ring tests on rock give no reason to doubt that cracks initiate at or near the points predicted by simple theory. They prove quite conclusively that, in a properly conducted test, cracking does not start at the platen contacts, since in many tests, both ring and Brazil, the diametral crack terminated about D/10 from the outer boundary. The diametral cracks in some solid discs tended to widen in the mid section suggesting that failure probably started in the mid-section.

3.3.1.7.6.2 The primary cracks propagated along the diametral plane as predicted by theory. Ring tests on

Lucite gave fracture surfaces which appeared perfectly plane when tested with a straight edge. With suitable equipment and technique, primary cracks in both disc and ring specimens ceased to propagate when they reached the platen contact zones. In ring tests it was possible to initiate cracks in rock specimens without immediately driving those cracks through to the contact zones, in Lucite, specimens it was not possible to create and then halt a crack although a pre-formed crack could be driven progressively through the specimen.

3.3.1.7.6.3 A variety of secondary crack patterns were formed in disc and ring specimens. When loading was inattentively continued after primary failure. It was demonstrated that cracks other than the main diametral cracks were, in fact, secondary, and it was shown that with suitable technique failed specimens remained substantially free from secondary cracking. Various combinations of primary and secondary cracks ('crescentic', hourglass etc.) have sometimes been regarded as 'characteristic' fracture patterns but it should be noted that secondary cracks are actually characteristic of imperfect testing technique.

3.3.1.7.6.4 Problems of off-centre fracture initiation were probably avoided with the technique used but in any case there is no experimental evidence that off-centre fracture invalidates test results. Hudson (1969) deliberately induced off-center fracture, and found no significant change in the load bearing capacity of the disc.

3.3.1.7.6.5 The Griffith failure criterion essentially predicts when cracks will initiate, not when structural failure will occur, and there is considerable evidence to show that in unaxial tests on rocks, cracks start to form when the load is 50% to 75% of the ultimate value reached at final failure. For nearly all rocks, the ratio of uniaxial compressive to tensile strength is greater than 8 which implies that the Griffith criterion will still be applicable, as it is borne out by experimental data.

3.3.1.7.6.6 Most rocks fail by progressive growth or development of numerous internal microcracks over a finite period of time and consequently the apparent strength of a uniaxial test specimen increases with increasing loading rate. The same effect can be expected in ring and Brazil tests. This effect works in the opposite sense to the visco-elastic effect. It appears that for common rocks it is the dominant effect for tests at typical loading rates.

3.3.1.7.6.7 A typical speed range for high capacity hydraulic testing machines of older type is from about 0.001 to about 3.0 inches/min. For lower capacity screw drive machines a typical range is from 0.002 to 2.0 inches/min. At the top of these ranges, failure of a small ring or disc specimen is virtually instantaneous and the response of a dial pointer or a pen recorder may be too slow to give reliable readings. An electrical load cell with oscilloscope readout is then required. At the highest loading rates, disc and ring specimens usually suffer both primary and secondary cracking and may affect the test result. A low rate of loading which may be perfectly acceptable for a highly elastic rock may be wholly unacceptable for materials which creep easily.

3.3.1.7.7 Hudson, Brown and Rummel (1972) studied controlled failure of granite and marble discs in a servo controlled machines using lateral displacement as a control signal in order to determine the location of failure initiation and the subsequent mode of specimen collapse. On all the tests contrary to the observation of Mellor and Hawkes failure initiated under loading points even though loads were distributed in some cases. This was witnessed by cracks radiating out from a crushed zone below the loading points, and the absence of any crack in the centre of the disc. It was also observed that when q = .03 in ring test the failure did not initiate at the hole but always initiated at the loading points for point loads, but for distributed loading, failure initiated at centre. From there observation they concluded that Brazilian test is not valied for measurement of tensile strength.

3.3.1.7.8 Lajtai (1972) examined the possibility of using a'stress gradient' approach to the problem of tensile fracture initiation from flaws. Only a few relatively simple cases were examined and the universality of the proposed approach is far from established. Nonetheless, it appears that the approach should replace the maximum stress concentration model to explain fracture initiation under compressive loading. There is a merit in the approach that it takes in to account the 'size effect'.

3.3.1.7.9. Barla and Innaurato (1973) investigated rock discs and rings with transversely isotropic behaviour under diametral loading. They observed that gneiss specimen fails mostly along the diameter of the load application while the schist is seen often to fail along the laminations. This shows that the tensile testing of anisotropic rocks by diametral loading of circular discs might be a suitable technique only for rocks which exhibit a moderate anisotropy (e.g. the granitoidic gneiss). However even in this case a theoretical relationship must still be established in order to define the dependence of tensile strength upon the orientation of the lamination. In fact, the known formula for tensile strength calculation ($To = 2F/\pi Dt_d$)based upon the classical theory of elasticity, would not be applicable.

3.3.1.7.9.1 The ring thickness influences the results only slightly as a maximum 10% deviation. The rings with smaller thickness generally fail first along the line of loading. Subsequently, new fractures arise along the laminationas and in some cases, fractures are also seen to develop at 5 - 15 degrees with respect to the laminations. Therefore it can be concluded that rocks which are markedly anisotropic can be tested for tensile strength using diametral compression of circular rings.

3.3.1.7.10 Yanagidani, Sano, Terada and Ito (1978) studied the crack initiation, crack propagation velocity and the stress field due to the dynamic crack in diametrally compressed rock disc, using strain gauges as a crack detector. They introduced a transient recorder (TR) in order to make high speed measurements.

3.3.1.7.10.1 Their results show that the main crack did not initiate from the loading point. The crack initiates at some point in a maximum tensile stress zone and propagates radially inspite of some effects arising in three dimensional propagation in a plate.

3.3.1.7.10.2 The initial low crack velocity is considered to have little effect on the determination of the crack origin even if the terminal velocity is adopted as an average crack propagation velocity, because the crack can not run for a considerable distance if it has a low velocity. Further the dynamic stress at the crack is affected by the wave radiations from the crack tip.

3.3.1.7.10.3 The evidence of crack initation in the central part of the disc confirms the capability of Brazilian test for giving good measurement of uniaxial tensile strength.

3.3.1.7.11 Sundaram and Corrales (1980) investigated the Brazilian tensile strength of rocks with different elastic properties in tension and compression. Their study shows that that the principal tensile stress at the centre of the disc is sensitive to the change in ratio of the moduli in tension and compression. Hence they suggest that if the elastic properties of rock in tension are different from those in compression, then the estimation of Brazilian tensile strength by the conventional method generally gives an overestimate of the Brazilian tensile strength.

3.3.2 Miscellaneous experimental studies:

3.3.2.1 Obert, Windes and Duvall (1951) prepared 6" long cylindrical specimens of different diameters from various rocks and tested them under 3 point loading. The 3 point loading gives constant moment in central third of the specimen. The results given by them show that the tensile strength is independent of the diameter of the specimen.

3.3.2.2 Protodyakonov (1961) suggest a test procedure to overcome the effect of concentration of stresses at points of supports. The specimen is placed in vertical position and bent under influence of two couples. He tested rings by subjecting them to internal hydrostatic pressure of putty (consisting resin 75% and paraffin 25%) placed in the central hole and compressed by coaxial punches. The tensile strength is determined by equation:

$$\sigma_t = - \frac{F}{\pi r_i^2} \left\{ \frac{r^2 + r^2}{r_o^2 - r_i^2} \right\} \qquad . \qquad . \qquad . \qquad 3.7$$

3.3.2.2.1 Recently Hardy and Jayaraman (1970) used this method for determination of tensile strength of rock, by the hoop stress loading. The thickness of the specimen ranged from 2.5" to 4.0" and the internal and external diameter were 1" and 2" respectively. The experiments were carried out with the aid of a loading jig designed to allow a thin walled rubber tube to be hydraulically pressurised inside the hollow test specimen utilised in this test. Pressure transducer was incorporated in the associated hydraulic system to monitor the applied.

3.3.2.3 Sundararaja and Chandrashekhara (1962) obtained a theoretical solution assuming the pressure distribution under the indenters as uniform, parabolic arc resulting from "constant displacement" on a semi-infinite boundary, for different ratios of indenter width to side of square. They also extended the solution to orthotropic materials.

3.3.2.4 Pomeroy and Morgans (1956) tested ractangular samples of size 4" x 1" x 0.1" and 4" x 0.25" x 0.25" by applying 4 equal line loads symmetrical about centre in a bending machine. The values obtained are 2-3 times higher than that obtained in direct tests, it is because of small area of specimen under tension.

3.3.2.5 Shih (1963) obtained modulus of rupture on 2.2 cm diameter cores of different length. The results conclude that strength decreases with increasing span.

3.3.2.6 Davies and Stagg (1964) used two test arrangement using square shaped specimens. The loading was applied through steel or timber packing on the top face and supported on the bottom face either in similar packings or directly on lower platens of the testing. The stress distribution was obtained by a linear elastic finite element analysis. However these tests can not be regarded as a true indicating of intrinsic tensile strength of rock samples as sudden failing always occured and was initiated under the upper loading point.

3.3.2.7 Hiramatsu and Oka (1966) analysed the stresses in the specimens mathematically and photoelastically. The tensile strength is calculated with the equation:

$$\sigma_t = - \frac{0.225\ F}{r^2} \quad . \quad . \quad . \quad . \quad . \qquad 3.8$$

They concluded that the tensile strength obtained is nearly same as obtained from Brazilian test.

3.3.2.8 Jaeger (1967) observed the failure spheres by an extension fracture i.e. the spheres shattared in to two parts. In trachyte he observed the division of sphere in to three lines of angles approximately 120° apart.

3.3.2.9 Sinha and Singh (1968) observed that strength decreases with increase in the thickness of the beam. The rectangular specimens show smaller strength compared to circular specimen if cross-section area is same.

3.4 Concluding remarks:

The survey of experimental investigations conducted by number of research worker employing varieties of test setups reveal that discs and rings under diametral loading produce consistent results. Further these results are interpretable by available theoretical analysis. The only important requirement for the validity of the test is the application of uniform line load. It has been shown that properly designed grips enable discs and rings under diametral loading to fail along the loaded diameter as per theoretical analysis.