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DIRECT SIMPLE SHEAR TESTS ON LEDA CLAY

by

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The direct simple shear device was developed over a period of 5 or 6 years at the Norwegian Geotechnical Institute. The model used in these tests is described fully in a paper by Bjerrum and Landva in Geotechnique, March 1966. Its construction was inspired by a large field shear box, the results from which agreed much more closely with field performance than the values obtained from triaxial tests. The apparatus works extremely well on soft Norwegian quick clays but a problem of sliding at bearing surfaces arose in an attempt to use it on a sample of stiff Leda clay from Hiawatha Park near Ottawa. It was with the hope of solving this problem that the writer went to Norway and conducted the following experiments on samples of Leda clay, the strength properties of which in terms of "peak" and "residual" strengths had been previously determined with triaxial and direct shear tests.

SAMPLE PREPARATION

A device machined to very close tolerances is used to trim and place the bearing plates and reinforced membrane around the soil sample. It is normally mounted in an inverted position above the sample extruder and receives the soil sample which is jacked into it. Rough trimming of the sample is done during jacking to prevent the cutting ring from being fouled, but the fine trimming is effected by the cutting edge on the sampler ring. A rough horizontal cut is made below the sample with a wire and a thin stainless steel plate to separate the test specimen from the sampler tube.

The trimming device is then carefully taken from the mounting bracket, inverted, and the upper and lower surfaces trimmed to receive the bearing plates and filter stones. Following this, the cutting ring is removed and replaced by a reinforced membrane. The sample is then ready to be mounted on the shearing device.

Leda clay samples, being much stiffer than Norwegian clay, were not suitable for this type of trimming and it was necessary to modify the procedure for preparing the samples. The basic difference was the need to shave the edges of the sample to within $\frac{1}{2}$ mm of the cutting edge with a sharp knife and then to advance the cutting ring 2 to 3 mm at a time. This is the same sort of operation as that used in the preparation of consolidation samples at Ottawa, but consumes much more time than is necessary in preparing the Norwegian quick clays. It also takes longer to trim the horizontal surfaces since this cannot be done simply by using a wire saw and one or two deft strokes with a straight-edge. The finished specimen is 50 cm^2 in area (approximately 8 cm in diameter) and 1.45 cm high.

CONSOLIDATION

The sample is transferred to the shearing apparatus by attaching the trimming device to the front of the shearing apparatus and sliding the mounting pedestal into place beneath the loading frame where it is firmly attached to the base plate (Figure 1). The lever arm system is then lowered until the loading plate is in contact with the upper bearing plate. Weights as required are added to the lever arm in the same fashion as in the consolidometer test and vertical displacements with time are recorded. When consolidation under the desired normal stress has been completed, the sample is ready for shearing.

SHEARING

The loading plate is locked to the upper bearing plate by adjusting two horizontal stops. Pins in the loading plate are pulled to allow it to move freely in a horizontal direction and the sample is then sheared by applying a horizontal force (Figure 2).

For undrained constant volume tests, the vertical load is adjusted by attaching the loading arm to an anchor which can be moved vertically by a gear control (Figure 1). If the sample tends to expand or dilate while undergoing shear the normal load must be increased to prevent it from doing so, thus avoiding the setting up of negative pore-water pressures. If, on the other hand, the sample tends to compress, the vertical load must be reduced to prevent positive pore-water pressures from being generated.

A dial gauge mounted above the loading plate indicates the vertical movements that occur between it and the base plate (Figure 1). Control of the volume of the specimen, however, does not simply lie in altering the vertical load to maintain a fixed reading on the dial gauge but must permit those vertical displacements to take place that are concomitant with the compressibility of the loading plate.

Drained tests are performed at an appropriate rate of strain and the sample is permitted to change volume under a constant vertical load. In view of the time allowed for this study it was not practicable to conduct any drained tests which take a week or more to run. The faster undrained tests suited the purpose better since the problem was mainly one of observing whether or not shearing stresses were being transferred from the apparatus to the upper and lower surfaces of the sample without sliding taking place between the bearing plates and the sample.

The normal stresses applied to the samples were kept within the range generally encountered in natural slope stability problems, i.e. up to 1.0 kg/cm^2. Except in the case of one specimen of clay from Gloucester, consolidation was unnecessary since the preconsolidation stresses for the other two samples are considerably in excess of 1.0 kg/cm^2. Higher normal stresses than those at which the specimens were sheared were applied temporarily to most samples only in order to assure good contact between loading plates and the upper and lower surfaces of the specimens. Approximately 2 per cent compression between the base and loading plates, which may be largely seating adjustments, was measured in most tests.

SHEAR TEST RESULTS

The tests are described in sequence with commentary on the efficacy of each and the steps taken at certain stages to improve it. The maximum strengths were compared to those obtained in tests conducted in the direct shear box on sample 94-26 (Figure 3). It was not expected that the values obtained from sets of tests would be identical since the distribution of stresses imposed on the specimens would not be the same and the modes of failure would differ in consequence. All tests recorded here were conducted with rates of strain of 1 mm in 2 hours.

SOILS

Leda clay samples that were tested came from three sites.

1. A very soft, normally consolidated material from C.F.S. Gloucester Naval Station - sample No. 124-24-4. Depth: 14 ft 6 in. to 15 ft 0 in. $p_c = 0.6\ kg/cm^2$
2. A stiff, highly overconsolidated material from the Ottawa Sewage Treatment Plant - sample No. 94-26. Depth: 62 ft 6 in. $p_c = 4.5\ kg/cm^2$
3. A medium stiff, moderately overconsolidated material from the Montreal Road laboratory site - sample No. 20. Depth: 31 ft 3 in. to 31 ft 9 in. $p_c = 1.9\ kg/cm^2$.

The sample from the sewage treatment plant was a block taken from the excavation for the main building in 1962. The other two were 5-in. diameter Osterberg samples obtained in 1965. The testing programme was concentrated on the stiffest samples.

Test No. 1 - Specimen 94-26A

Three blades 2 mm high and 0.2 mm thick had been installed in the bronze filters of two of the bearing plates. One was mounted across the centre and the other two parallel to it on either side, spaced at 20 mm. They were mounted as spacers between sections of sintered bronze and sealed in place with an epoxy resin (Figure 4).

The specimen was trimmed and the bearing plates attached top and bottom by applying a hand pressure to sink the blades into the soil. Care was taken when placing the specimens in the apparatus to be sure that the blades were oriented transversely to the direction of thrust. A normal stress of $0.25\ kg/cm^2$ was applied and the specimen sheared. The maximum developed shearing strength at a reduced normal load was considerably lower than expected.

Much of the measured strain had very obviously not been applied to the specimen. After removal of the specimen from the apparatus the soil surfaces were examined and it was found that the specimen and filter stones had actually touched over only about 5 per cent of their contact areas and that some noticeable disturbance had been caused when the blades were pushed into the clay. Shearing had occurred locally, leaving a space behind each blade which represented a large percentage of the applied strain (Figure 5a).

It was obvious that a higher seating load was necessary in order to obtain better contact. To reduce disturbance caused by pushing the blades into the surface of the specimen, they were filed down to $1\frac{1}{2}$ mm high and the edges sharpened.

Test No. 2 - Specimen 94-26B

This test was run beginning at the same normal stress of 0.25 kg/cm^2 after a seating load of 2.00 kg/cm^2 had been imposed. During the test the sample appeared to dilate and the normal stress was increased to a maximum of 0.58 kg/cm^2 (Figure 3). The maximum τ was 0.5 kg/cm^2 but there was obvious displacement between the loading plates and the specimen. When the specimen was examined following the test it was found that the surfaces of the clay had again been disturbed when the blades were pushed into them and that failure had developed in the same manner as in the previous test. Local failure at the blades was again evident, and much of the applied strain could be accounted for by the width of the spaces behind the blades and by the length of the scratch marks in the drag pattern made by the bronze filters.

Contact between the specimen and filters had been improved but there was still an area of about 40 per cent of the total where the clay had not been marked by the filters. Upon closer examination it was discovered that the separate sections of porous stone between the blades had not been replaced with their surfaces in the same plane. Some ends were higher than the rim of the bearing plate, and others were lower, so that it was not possible except with a very soft material to obtain 100 per cent contact over the surface of the sample.

Test No. 3

One more attempt was made using this technique but this time a softer sample (124-24-4C) was used. The blades were easily pushed into the surface of the sample. A seating load of only 0.4 kg/cm^2 was used because the preconsolidation pressure of this material is so low, and a normal load of 0.2 kg/cm^2 was applied at the beginning of shearing. The profile of the specimen and bearing plates again indicated sliding at the surfaces at an early stage in the test so the shearing stress was released and the normal stress increased to 0.4 kg/cm^2. Shearing stresses were again applied and some small increase in τ was noticed, but sliding at the surfaces was again obvious. As in the cases of the two previous tests, local failure at the blades had occurred, but some shearing planes in one zone of the sample indicated that plane strain conditions had been imposed to a limited extent (Figures 5b and 7). Some disturbance at the blades was evident as in the previous tests and although surface contact was much improved, it was still not complete.

At this stage it was realized that improved filters were needed and new ones made of ceramic material to facilitate moulding were ordered. These were to have five parallel grooves 2 mm by 2mm spaced at about 15 mm, into which stainless steel razor edges could be installed. Casting the grooves would ensure that the surface of the filter would be in contact with the surface of the specimen and the sharp thin blades would cause little disturbance when pushed into the soil.

In the meantime, two other tests were conducted in which the effects of the disturbance were reduced by setting the thicker blades in grooves filled with plaster of Paris to form keys. A tool was made in the form of a chisel with a cutting edge 2 mm wide (Figure 6). To ensure a constant depth for the grooves a shoulder stop was made 2 mm plus the thickness of the straight edge from the cutting edge. The grooves were made 2 mm wide by 2 mm deep to allow for slight misalignment and errors in positioning the blades (the blades were not all straight; some curved as much as 1 mm from one side to the other) and to be sure that the plaster of Paris keys were continuous beneath the bottom edges of the copper blades of the bearing plates. The grooves were cut carefully and cleanly in the positions marked by the edges of the blades on the surface of the sample. They were filled with liquid plaster of Paris and allowed to set after the bearing plate had been lowered into position. Both surfaces were treated in this manner.

Tests Nos. 4 and 5

Tests were then conducted on samples 94-26C and E using seating loads of 3.5 kg/cm^2 and 2.0 kg/cm^2 respectively, both with an initial normal stress of σ_n = 0.75 kg/cm^2.

Sample E was tested first and a considerable increase in shear strength was obtained. It was necessary when τ had reached about 0.4 kg/cm^2 to increase the normal stress since the specimen appeared to be dilating. σ_n climbed to about 1.0 kg/cm^2 and τ continued to increase even when σ_n was again reduced. Maximum stresses approached those values obtained using the direct shear box (Figure 3).

It was unnecessary at first to vary the normal stress on specimen 94-26C, which was subjected to a higher seating load since it appeared neither to dilate nor to compress. When τ reached about 0.5 kg/cm^2 however, it exhibited a tendency to shrink and the normal stress was reduced. After about 1 mm of strain had been imposed, and some sliding had obviously occurred, the shearing stress was released and was reapplied while the normal stress was maintained at 0.74 kg/cm^2. A peak shear strength of 0.55 kg/cm^2 was reached before sliding again occurred.

Both specimens, when examined after the tests (Figure 8), exhibited shearing planes in the same locations as in all the previous tests, the only difference being that the shearing planes were longer, probably in proportion to the maximum shearing stress obtained. No attempt was made to measure their length.

Preparation of these two specimens differed only in one aspect. For the first, 94-26E, an attempt was made to put just the right amount of plaster of Paris in the grooves, but a small excess resulted. When the bearing plates were pushed down on the surfaces of the specimen, this excess spread between the specimen and filter plate (Figure 5) thus producing a thin void between them. As visible in Figure 8, contact between specimen and filter was still not complete. Local failure occurred at the plaster of Paris keys as it did before and the resultant upward force produced a dilation effect. When the second sample was prepared the slight excess of plaster of Paris was removed by a straight-edge when still liquid and none appeared afterward to have flowed between specimen and filters. This, together with the higher seating load of 3.5 kg/cm^2, gave better contact and the specimen failed without any indication of dilation.

<u>Test 6</u>

One other test was conducted on a soft sample, 124-24-4D. No blades were used in the filter but the specimen was subjected to a load in excess of the preconsolidation pressure and sheared at an initial σ_n of 0.7 kg/cm^2. Actual consolidation under a load of 1.00 kg/cm^2 was 2.2 mm, or 15 per cent. It effected better contact between bearing plates and sample but it failed primarily by sliding with some small indication of imposed plane strain conditions.

Tests 7 and 8

Specimens 94-26D and F were tested next, using the new filter stones in which thin stainless steel razor blade edges had been installed. These were less than one-half the thickness of the original blades and the edges were extremely fine. Care was taken when the blades were set in epoxy resin to set them normal to the surface of the filters, but they were not exactly in line; nor were they continuous, since more than one blade edge was needed in each groove to reach from side to side.

Stainless steelblades were selected for several reasons but primarily because they are resilient. It was considered that rigid blades would produce less uniform conditions in the specimen than resilient blades. They were also less subject to being snapped off when not in use and had the advantage of being rust-proof. The blades were pushed into the surfaces of the specimen with ease, and examination subsequent to testing showed no obvious signs of disturbance.

Both specimens were tested at initial normal stresses of 0.6 kg/cm^2 after being well seated at 3.5 kg/cm^2 after being well seated at 3.5 kg/cm^2. The mode of failure, however, was the same as before, the only improvement being that the total area of the shear planes was approaching that of the specimen. It became clear that a sufficiently large number of blades would induce failure through the entire area of the specimen on a plane passing through the tips of the blades and that these measures were no closer to imposing plane strain conditions on the specimen than the first attempts had been.

Maximum τ for the second test on 94-26F was considerably below that for 94-26D and probably resulted from sprinkling finely ground silica gel on the surfaces of the specimen in an attempt to improve surface contact. On the contrary, this step probably only served to increase disturbance and to reduce contact. All of these measures, with the exception of that used in testing 124-24-4D, imposed stress conditions on the specimens that were not uniform. The result was that stresses were concentrated and failure occurred where they were highest.

REASSESMENT OF APPROACH

In order to impose uniform strain conditions on the specimens some method had to be devised by which the transfer of stress could be accomplished over the entire area of the contact surfaces.

Two adhesives were tried but without success; the first, an epoxy resin, which had been used successfully to glue rocks together under water, and the second, a wax found in whale oil which has the ability to replace water in clay and is sometimes used in the preparation of thin sections of soil. Both are comparatively impermeable but if successful could have been applied in lattice fashion to the surfaces of the specimens to permit drainage when necessary. Samples of soil were attached to plates of glass using these two adhesives but both failed at the interface of soil and adhesive. Bond between glass and adhesive appeared to be quite strong.

Two other possibilitites presented themselves - first, to use porous filters in which many small teeth had been cast and pressed into the surfaces of the specimen, and secondly to roughen the surfaces of the specimens and cast some material against them.

The first alternative involves remoulding the soil at the surfaces which, in the case of soft clays, results in a stiffened and stronger layer adjacent to the bearing plates after the material has been consolidated but may be still weaker after consolidation than the undisturbed material for a soil such as Leda clay. A modification of this technique, that of using porous bronze filters in which pin-points could be installed, was considered worth trying since any remoulding that would take place would not be continuous and, therefore, not conducive to local failure. As a start, 200 pin-points protruding $1\frac{1}{2}$ to 2 mm and on 5 mm centres were fitted in each of the two filter plates.

The second possibility, that of roughening the surface of the specimen, could be accomplished without remoulding simply by picking out indentations in each surface of the specimen. Plaster of Paris, which is comparatively porous, could be used to cast against the roughened surface and form the necessary protrusions. This second possibility, because all materials were immediately available, was tried first.

Tests 9 and 10 - Specimens 20A and 20B

It was found that by using the pointed tip of a sharp blade held on a slope of approximately 45° holes could be picked out of the soil surfaces which, when filled with plaster of Paris, formed small protrusions shaped roughly like three-sided pyramids. These were as much as 2 mm deep and were cast contiguously with wafers about 1 mm thick against the surfaces of the bronze filters. Less than 50 per cent of the original plane surfaces remained intact following this treatment (Figure 5c).

Specimen 20A was seated at a vertical stress of 2.0 kg/cm^2 which was reduced to an initial normal stress of σ = 0.6 kg/cm^2 for testing. After the shearing resistance had reached 0.27 kg/cm^2 the specimen developed a tendency to dilate which was counteracted by gradually increasing the normal stress until it had climbed to 0.9 kg/cm^2. It was held at this stress while it underwent further horizontal strain and until a maximum shearing stress of 0.56 kg/cm^2 was reached (Figure 9). Further shearing was accompanied by a diminishing normal load until plane strain conditions were clearly imposed. Examination of the specimen after the test showed unimpaired contact between the soil surfaces and the plaster of Paris that was not easily broken by hand, and there was no visual evidence of slipping (Figure 5c). The stress-strain curve shows that there was a smooth increase of shearing stress with strain until a peak strength was reached, followed by a gradual reduction with continuing strain (Figure 10).

Specimen 20B was prepared in the same manner but tested beginning with a lower initial normal stress. The stress path imposed in maintaining a constant volume is similar in pattern to that for specimen 20A (Figure 9). The stress-strain curve is also similar but exhibits a flattened peak indicating that some slippage may have occurred, thus reducing the maximum measured shear strength (Figure 10).

Tests 20C, D and E

These tests were conducted using filters to which pin-points had been fitted. All were seated at 2 kg/cm^2 and testing began with normal stresses of 0.58, 0.29 and 0.89 kg/cm^2 respectively. The resulting stress-strain curves show that some slippage occurred with specimens 20C and D but that very little is indicated for specimen 20E. The three stress paths are considerably different; that for 20C indicates a much lower peak strength than the other tests, apparently the result of sample disturbance. A much larger moisture content change between the beginning and end of tests bears this out, i.e. 17 per cent; that for specimen 20D shows that it alternately tended to dilate and compact; and that for 20E, unlike all the others, showed no tendency to dilate but reached its maximum shear strength at initial normal stress, after which it tended to decrease in volume as the shear strength dropped.

All of these results, with the exception of 20C, exhibit a unique relationship between τ and σ when peak shear strength were reached; an envelope sloping at 22° and intercepting the ordinate at $\tau = 0.2 \text{ kg/cm}^2$ very closely represents all the measurements made in this range after the peaks were attained (Figure 9).

A summary of the test results is given in Table I with brief descriptions of the method used to improve the contact surfaces, and the mode of failure. Tests 1 to 10 were conducted while the author was at the Norwegian Geotechnical Institute in June and July 1966. Tests 11 to 13 were later conducted there at the author's request.

CONCLUSIONS

This direct simple shear device was developed for testing Norwegian clays which are similar to Leda clay in many respects, but which in general have lower strengths.

As has been shown by the results of these experiments, a difficulty arose in attempting to impose plane strain conditions on specimens of comparatively stiff Leda clay in that stress range respresentative of field slope failures. This was occasioned by the incapability of the apparatus to transfer shearing stresses to the upper and lower surfaces of the specimen. Attempts to prevent sliding and to improve stress transfer by the use of various types and combinations of blades, plaster of Paris keys, and adhesives were unsuccessful.

Only two approaches to the problem appear to have been effective - that of using plaster of Paris wafers cast in place between the roughened surfaces of the specimen and the porous bronze filters, and that of using filters from which many small pin-points protrude.

The first is a tedious operation that is time-consuming both in the preparation of the clay surfaces and in the mixing and casting of plaster of Paris - but it appears from the stress-strain curves and the condition of the specimen after test to have been most effective.

The second method is no more time-consuming than the normal operation of preparing a specimen for testing in this device, and is, therefore, more to be desired. The shapes of the stress-strain curves in this limited number of tests indicate that it may be almost as effective as the first method.

From these tests it is concluded that this simple shear device is not suited for tests of relatively stiff specimens of Leda clay in the range of stress encountered in slope problems.

ACKNOWLEDGEMENTS

The work was carried out at the Norwegian Geotechnical Institute with the kind permission of the Director, Dr. Lauritz Bjerrum. The author is also very grateful for the assistance of Einar Stensby who instructed him in the use of the apparatus and of Toralf Berre in preparing some of the modified bearing plates, and for the interest and encouragement of other members of the staff of the Norwegian Geotechnical Institute.

SUMMARY OF TEST RESULTS

Test No.	Specimen No.	Seating Load	Change in w/c (%)	σ_n Initial kg/cm^2	τ_{max} kg/cm^2	$\frac{\tau}{\sigma_n}$ max	Contact Improvement	Mode of Failure
1	94-26A	(Pushed by hand)		0.25	0.16	1.27	3 copper blades 2 mm x 0.2 mm	Local shear failure at blades
2	94-26B	2.00	0	0.25	0.50	1.20	3 copper blades 1.5 mm x 0.2 mm	Local shear failure at blades
3	124-24-4C	0.4	0	0.20	0.10	0.08	3 copper blades 1.5 mm x 0.2 mm	Local shear failure at blades
4	94-26C	3.5	0	0.75	0.53	1.05	3 copper blades and plaster of Paris keys.	Local shear failure at keys.
5	94-26E	2.0	0	0.75	0.74	1.05	3 copper blades and plaster of Paris keys	Local shear failure at keys.
6	*124-24-4D	1.0	0	0.70	0.20	0.7	None	Sliding at surfaces - some indication of plane strain.
7	94-26D	3.5	0	0.60	0.67	1.11	5 stainless steel razor edges 1.5 mm high	Local failure at blades.
8	94-26F	3.5	0	0.60	0.46	1.0	5 stainless steel razor edges 1.5mm high and finely ground silica gel.	Local failure at blades

9.	20A	2. 0	0	0. 60	0. 56	1. 65	Plaster of Paris wafers	Plane strain.
10.	20B	2. 0	1	0. 30	0. 49		Plaster of Paris wafers	‡ Plane strain and some slipping.
11.	*20C	2. 0	17	0. 6	0. 37		Pin-points 200 at 1. 5 to 2. 0 mm high	‡ Plane strain and slipping.
12.	20D	2. 0	4	0. 3	0. 34		Pin-points 200 at 1. 5 to 2. 0 mm high	‡ Plane strain and slipping.
13.	20E	2. 0	2.3	0. 9	0. 52		Pin-points 200 at 1. 5 to 2. 0 mm high	‡ Plane strain and some slipping.

* Specimen consolidated.

‡ Specimens not examined. Condition assumed from stress-strain curves.

θ Normally left on overnight.

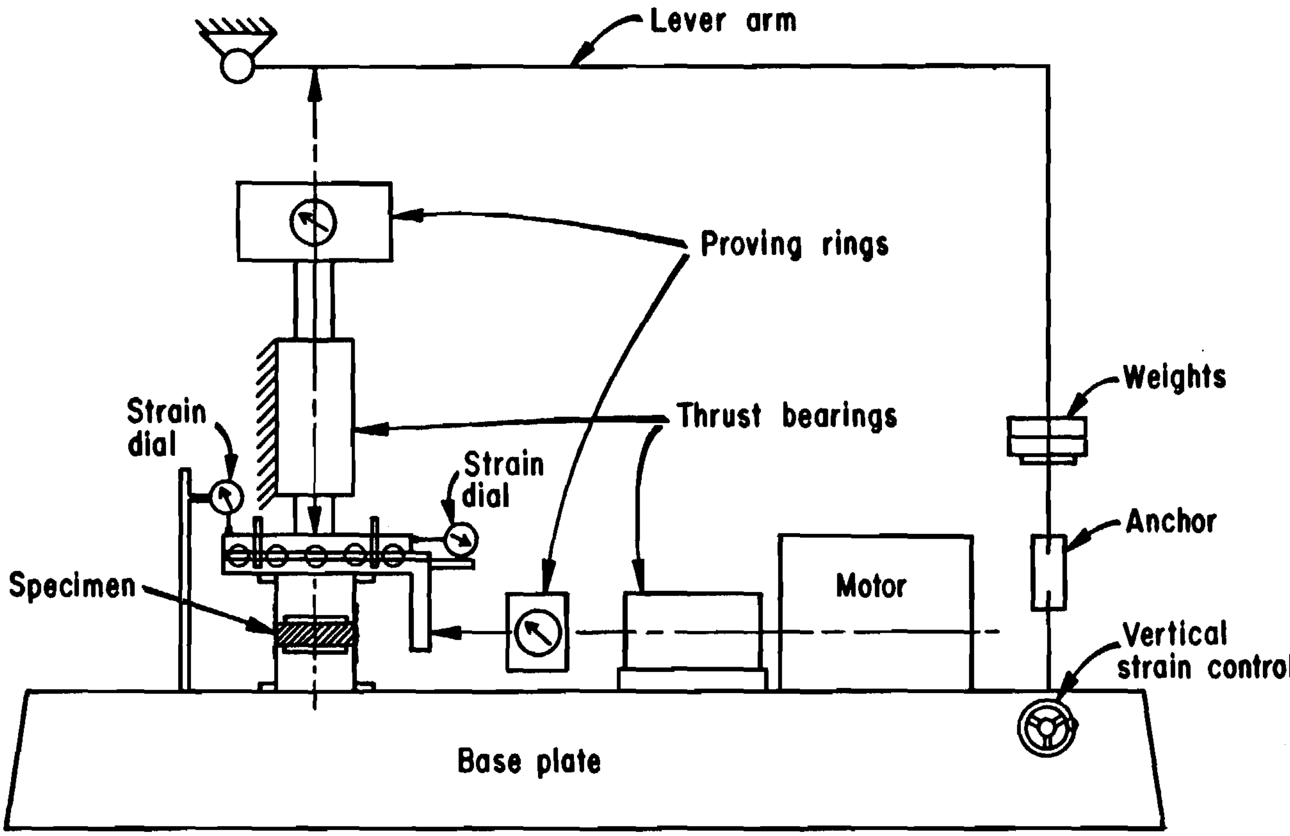

FIGURE I
SCHEMATIC DIAGRAM OF N.G.I. DIRECT SHEAR DEVICE

BR 4210-1

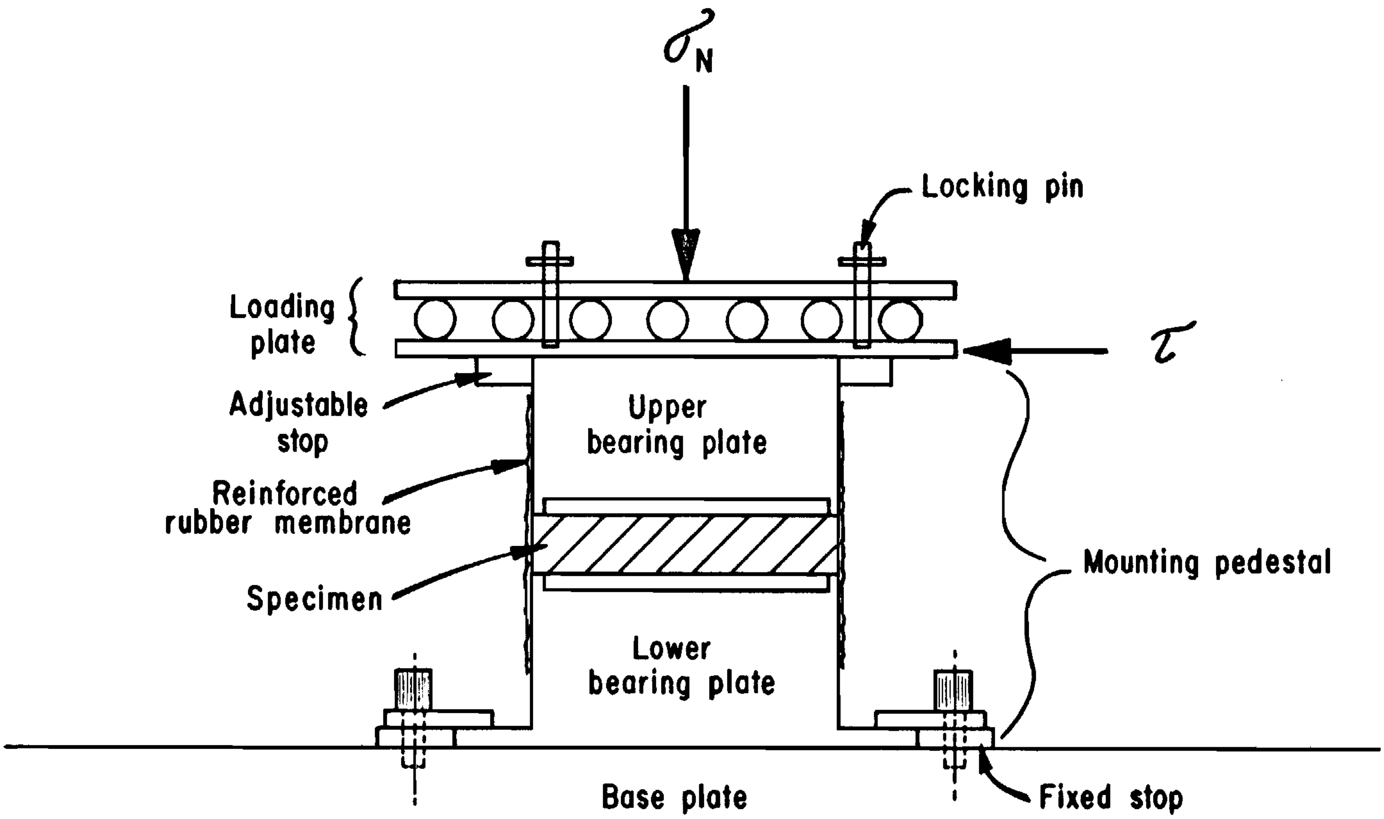

FIGURE 2
DETAIL OF MOUNTED SPECIMEN

BR 4210-2

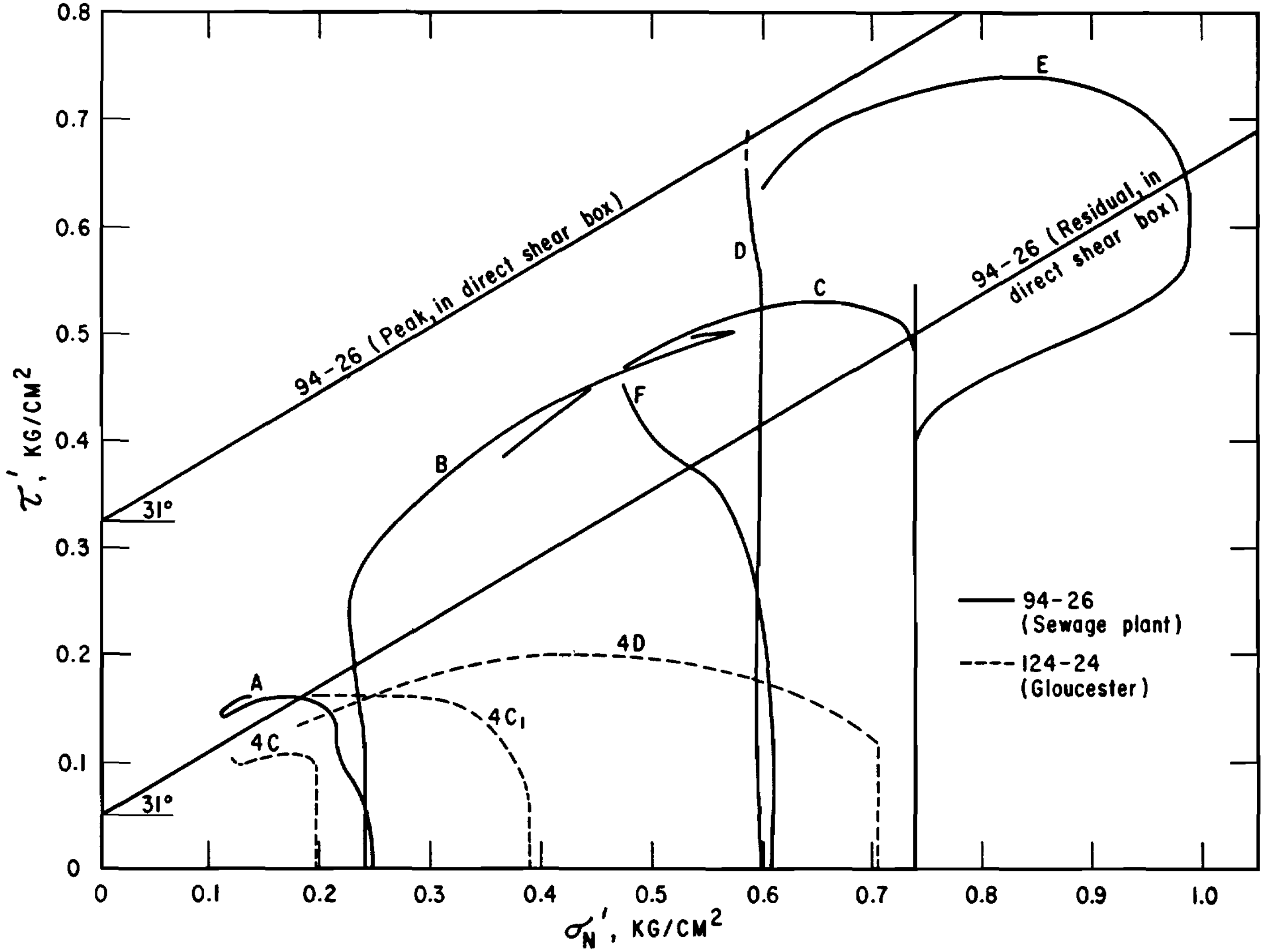

FIGURE 3
DIRECT SHEAR TESTS – N.G.I. APPARATUS

BR 4210-3

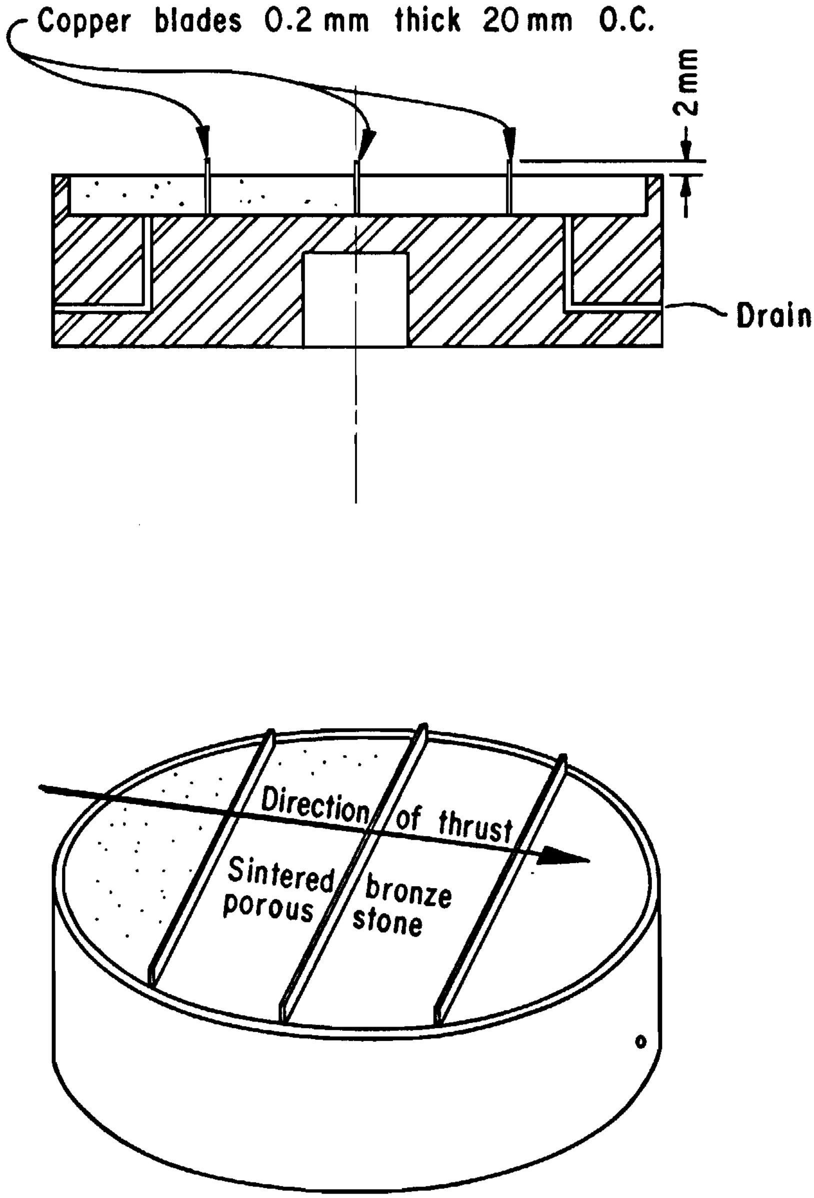

FIGURE 4
BEARING PLATE WITH BLADES
INSTALLED TO REDUCE SLIDING

BR 4210-4

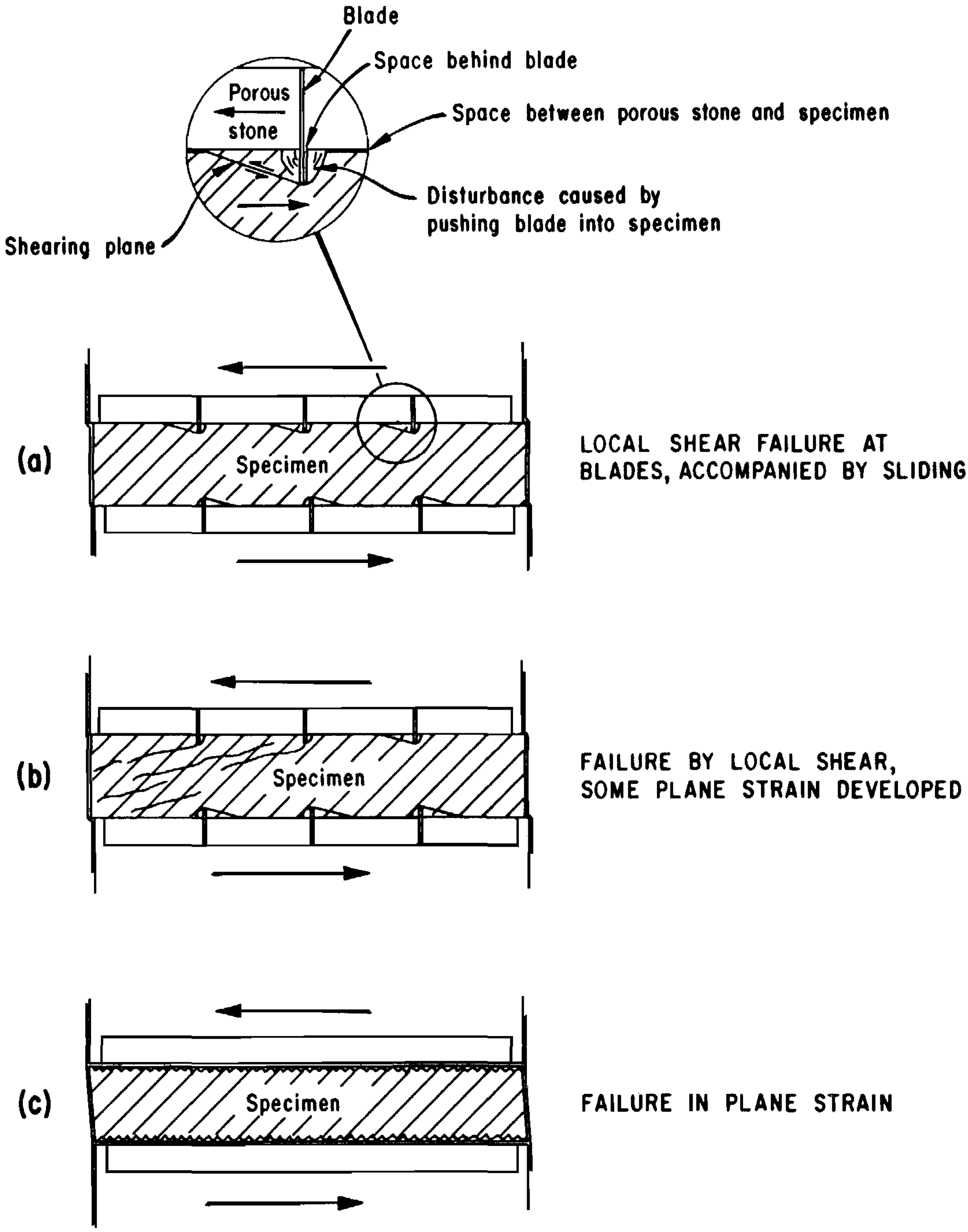

FIGURE 5
MODES OF FAILURE IN VARIOUS TESTS

BR 4210-5

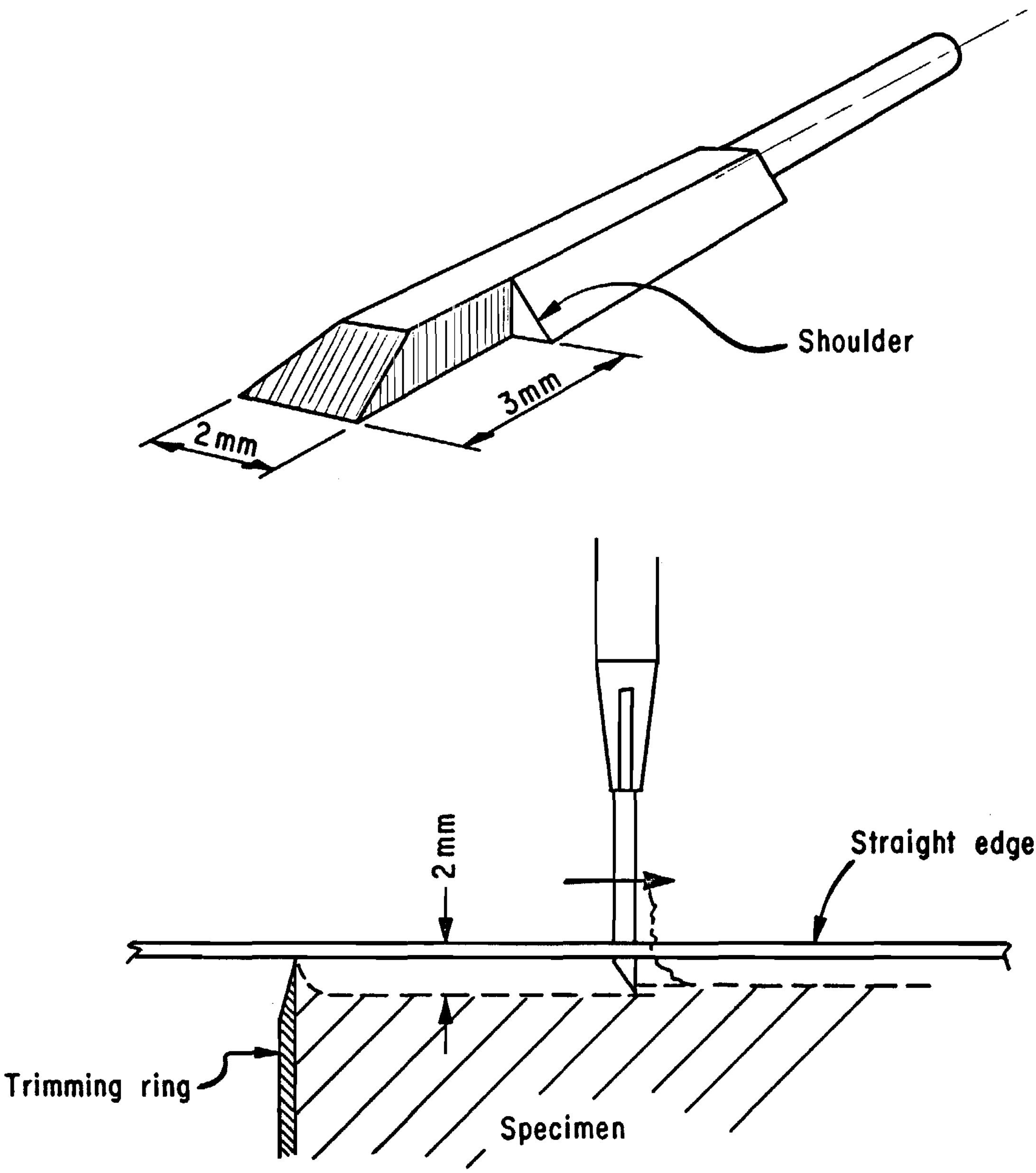

FIGURE 6
GROOVING TOOL

BR 4210-6

Figure 7 Sample 124-24-4C showing shearing plane through the specimen and partially imposed plane strain conditions.

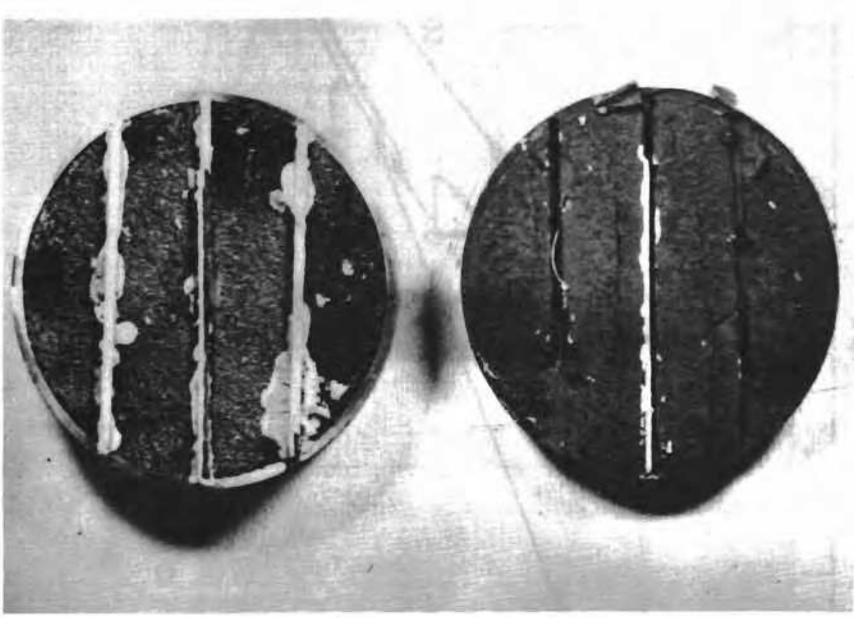

Figure 8 Left: Bearing plate with Plaster of Paris keys still attached to blades

Right: Specimen after test showing outer limits of shearing planes. (Shearing stress acting from L to R).

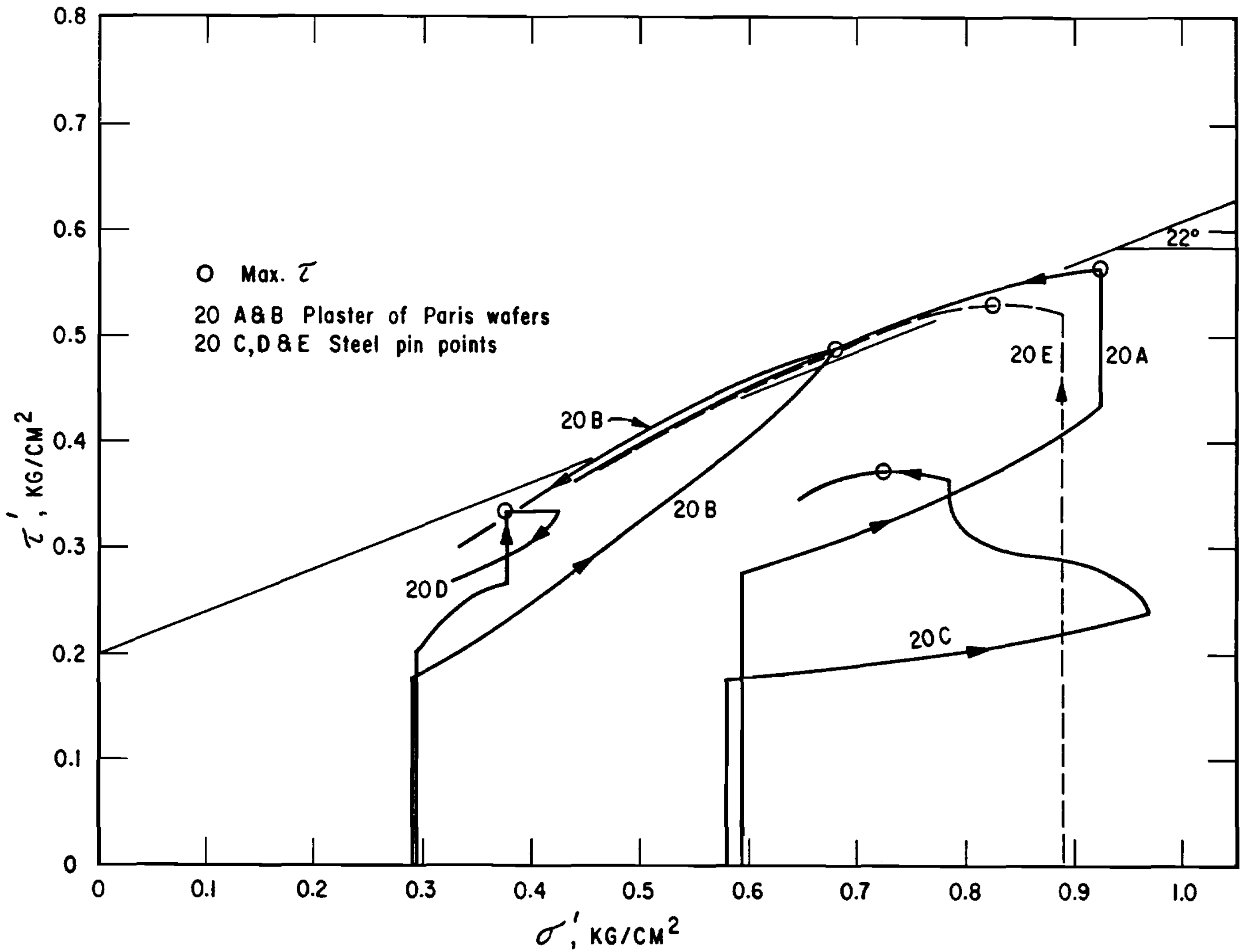

FIGURE 9
DIRECT SHEAR TESTS - N.G.I. APPARATUS *(SAMPLES FROM MRL SITE)*

BR 4210-7

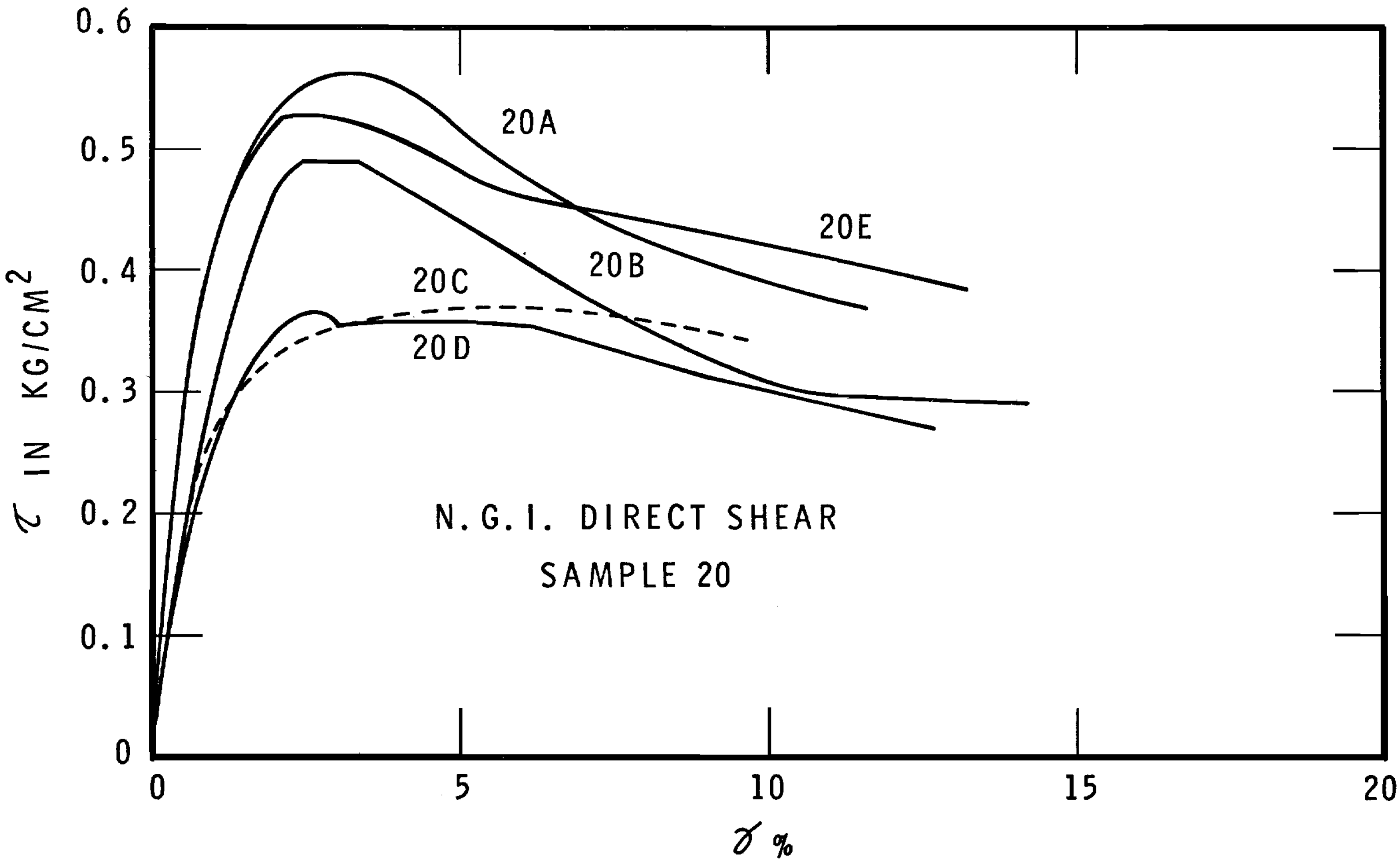

FIGURE 10

TYPICAL STRESS STRAIN RELATIONSHIPS

BR 4080-3