A Finite Element Study of the Stresses Induced on Joint Surfaces in Direct Shear Tests

by
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SUMMARY. The use of a portable Imperial College type shear box for evaluating the relative sliding tendency and shear strength of relatively smooth joint surfaces in rock prompted the present study. It consisted of modelling the complex geometric and loading conditions considered to exist when this shear box is used in testing joint surfaces in rock mechanics investigations. The purpose of the study was to determine the stress distribution along the sliding surface of the discontinuity and to evaluate the method of testing employed. A mathematical model was set up using the finite element method of analysis incorporating Goodman type of joint elements and a Coulomb-Navier type of failure criterion. This method of analysis enabled the investigators to model the loading conditions and testing procedures employed in the laboratory during direct shear tests. The information obtained from the finite element analysis was used to compare the actual distribution of stresses with that assumed to be present in the rock specimen when the laboratory test was carried out. On the basis of this study, it was concluded that the technique could be used in the laboratory with confidence since the experimental parameters obtained from the simulated test compare favourably with the true shear properties of the discontinuity.

1 INTRODUCTION

The direct shear test has been described by Hoek (Ref. 1) as a means of evaluating the relative sliding tendency and shear strength of discontinuities in rock. Goodman (Ref. 2) in discussing the problem of achieving a uniform stress distribution in the direct shear box, stated that a thorough study by modern analytical methods had not been attempted. The stress distribution along the sliding surface of the discontinuity during testing had not been established so that the strength characteristics determined in the tests were questionable. A study has therefore been undertaken by the authors using the F.E.M. to simulate the laboratory direct shear testing of discontinuities and to compare experimental results with the strength characteristics of the discontinuity. In this way the reliability of the testing method might be gauged and the effectiveness of simulation by the F.E.M. shown.

2 THE MATHEMATICAL MODEL

In order to carry out simulation of the direct shear test, a mathematical model must be set up representing the testing equipment and the specimen to be tested. The mathematical model in this case was the finite element mesh of Figure 1. The mesh outlines the upper and lower halves of the metal shear box, the two cement moulds and the rock specimen containing a fifty millimetre horizontal discontinuity. The F.E.M. analysis was carried out on a mesh of unit thickness and under the assumptions of plane strain.

The properties of the various materials simulated in the mesh by triangular elements are given in Table I.

TABLE I

MATERIAL PROPERTIES OF MODEL

Material	Young's Modulus MPa	Poisson's Ratio
Metal in Shear Box	205×10^3	0.25
Patternstone U Cement	14×10^3	0.25
Rock Specimen	34×10^3	0.25

The Goodman type joint element incorporating a Coulomb-Navier failure criterion was used to simulate the horizontal joint MN in Figure 1. The properties of the discontinuity, selected on the basis of data obtained from laboratory tests (Ref. 3) were as follows:

Joint Shear Stiffness = 2.7×10^4 MPa/m
Joint Residual Shear Stiffness = 0.8 MPa/m
Joint Normal Stiffness = 2.7×10^6 MPa/m
Joint Consolidated Normal Stiffness = 2.7×10^9 MPa/m.
Joint Cohesion = 6.89 MPa
Angle of Internal Friction = 30 degrees.

The F.E.M. analysis was executed using a similar loading technique to that used in the laboratory. Normal loads were applied to the upper half of the shear box at points H, I, J of the mesh in Figure 1. Points along the line KL were restrained from moving in the vertical direction. Shear loading was now commenced by applying equal and opposite horizontal forces to points B, C, D and E, F, G of Figure 1. The shear load was increased in increments, keeping the normal load constant, until failure of the discontinuity occurred. The Coulomb-Navier failure criterion described by the joint cohesion and joint internal friction was applied to the stress

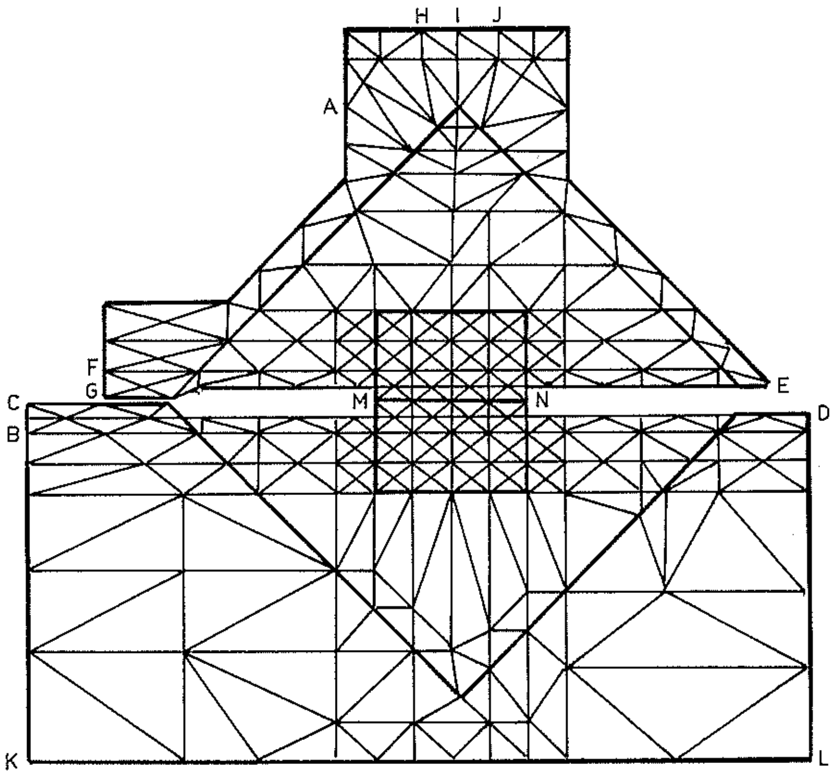

Fig. 1 Shear box finite element mesh

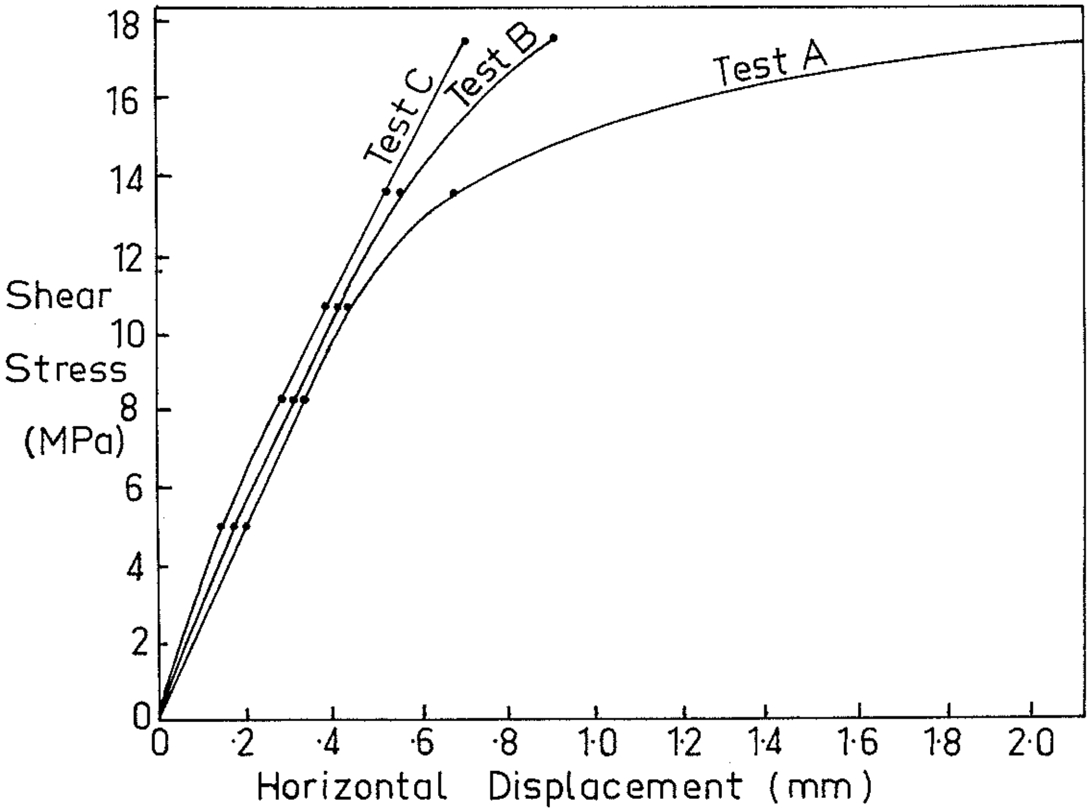

Fig. 2 Shear stress versus displacement for varying normal stress on discontinuity

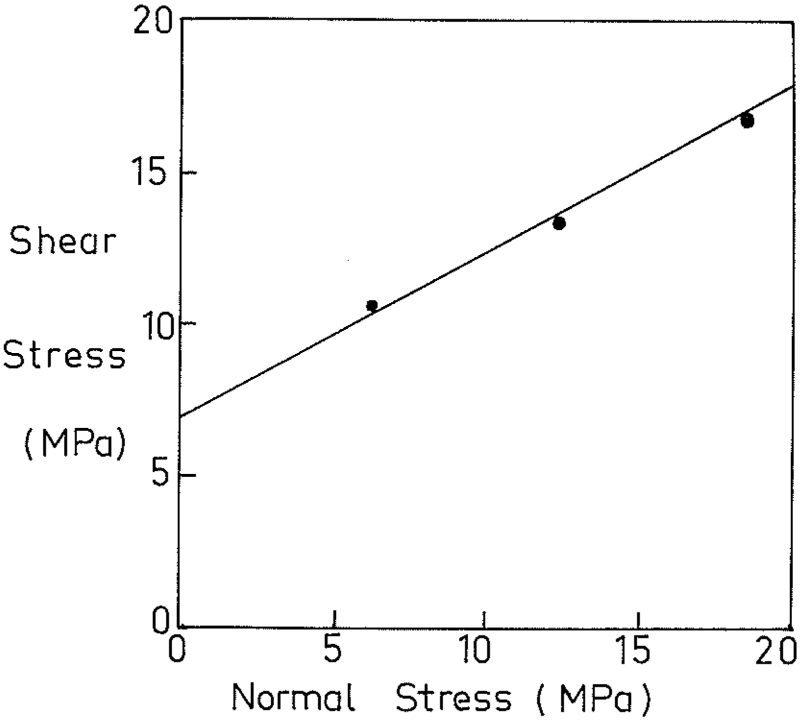

Fig. 3 Failure envelope for discontinuity

conditions in the joint finite elements after each load increment. If the stress state was not compatible with the mechanical properties of the element, the properties were adjusted for the next load cycle. Failure of the discontinuity was represented in the F.E.M. model by a rapid increase in the horizontal displacement of the point A in Figure 1 and the computed shear failure of the inner joint finite elements.

3 SIMULATION RESULTS

Similar to the laboratory direct shear tests, the simulated mathematical model test yielded the results of horizontal joint displacement for increasing shear stress. The test was carried out at three levels of normal stress. The results of the shear test simulation are given in the following tables. Horizontal displacement of the discontinuity was obtained using the measuring technique employed in the laboratory, i.e. by noting the horizontal deformation of the point A in the mesh. The elastic deformation of the metal box and mould cement was neglected and the total horizontal deformation of the point A was assumed to be entirely due to the horizontal displacement of the discontinuity being tested. The shear stress was that assumed to be acting across the discontinuity and was obtained by dividing the applied shear force on the box by the bearing area of the discontinuity.

The shear stress versus displacement curves for the three normal stress cases are shown in Figure 2. From these results the computed laboratory shear stiffness characteristics may be obtained and compared to the actual shear stiffness used in the numerical analysis. Calculating the shear stiffness at a displacement of 0.25 mm, Table III was constructed.

TABLE II

SIMULATED SHEAR TEST RESULTS

Shear Stress (MPa)	Horizontal Displacement (mm) Normal Stress (MPa) 6.2	 12.4	 18.6
5.00	0.198	0.175	0.153
6.40	0.261	0.241	0.219
8.25	0.342	0.322	0.299
10.30	0.444	0.428	0.403
12.80	0.691	0.567	0.540
17.60	2.540	0.895	0.715

TABLE III

COMPARISON OF CALCULATED AND ACTUAL SHEAR STIFFNESS

Test	Nominal Normal Joint Stress (MPa)	Shear Stiffness (MPa/m) Calculated	Actual
A	6.2	2.39×10^4	2.7×10^4
B	12.4	2.60×10^4	2.7×10^4
C	18.6	2.82×10^4	2.7×10^4

This table shows that the shear stiffnesses calculated from the simulated shear tests on the discontinuities agree with the actual shear characteristics used in the numerical analysis. Agreement is closer in the higher normal stress range of 12 to 18 MPa than in the lower stress levels, due to the shear failure of the two middle joint elements at lower confining pressures.

From the simulated laboratory tests, the failure envelope of the joint may be plotted. Noting the shear strength values for the three loading cases Figure 3 was constructed. Failure

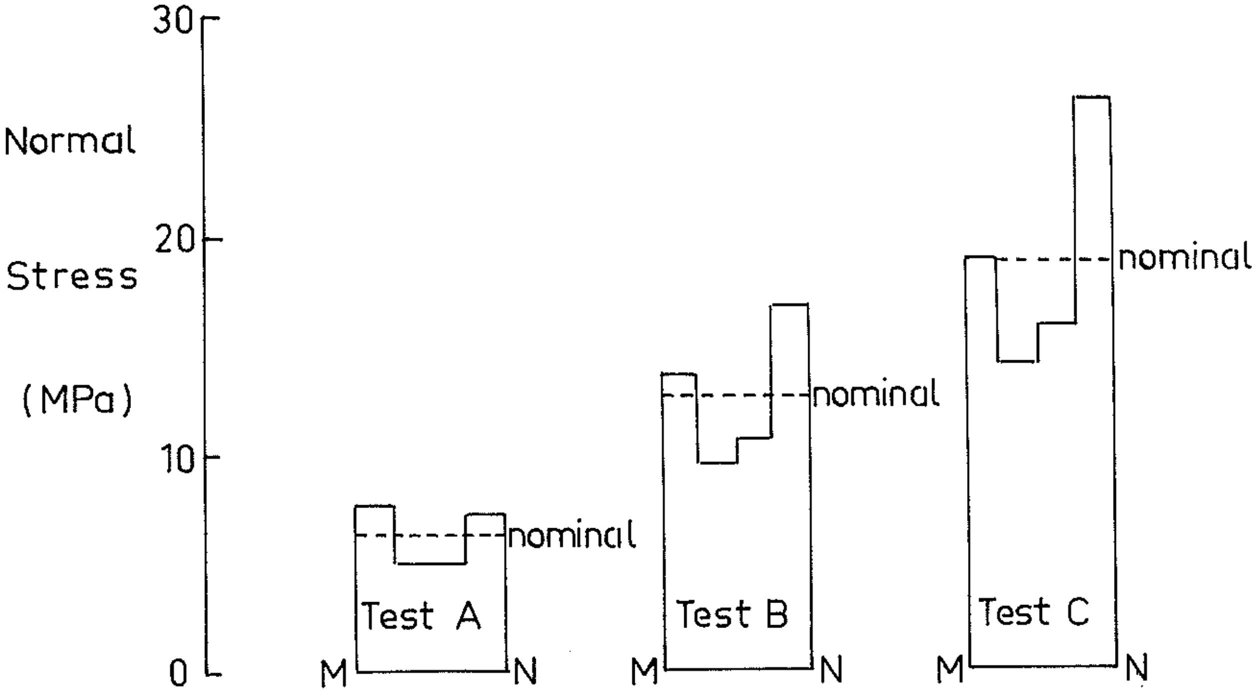

Fig. 4 Normal stress distribution across discontinuity MN for three test cases

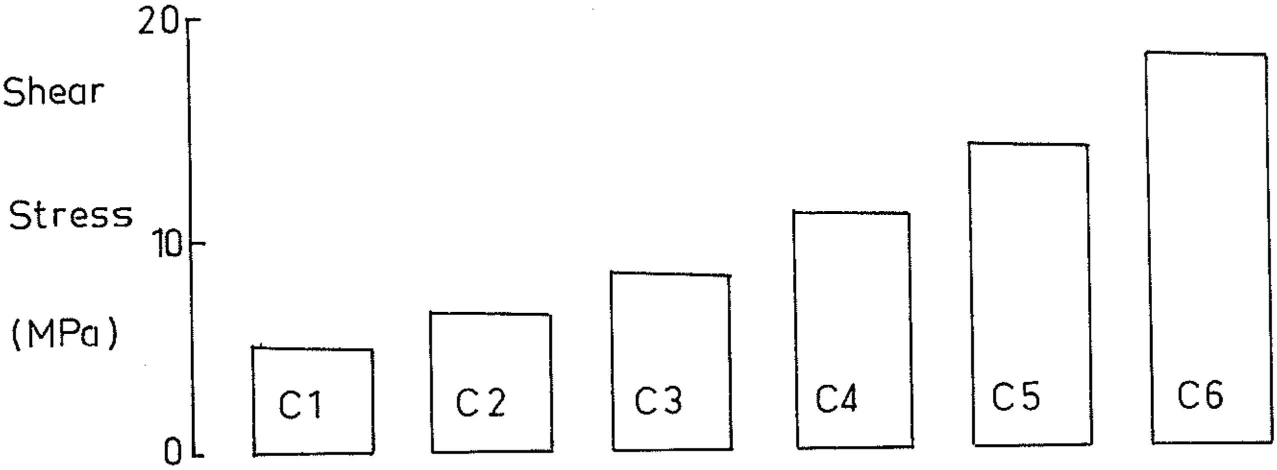

Fig. 5 Shear stress distribution across discontinuity MN during test C.

of the joint was defined as the point when the horizontal displacement of the point A increased in large non-linear steps for small linear increases in the shear force. The nominal shear stress and normal stress on the joint at this point were used in constructing the failure envelope. Although only three cases were considered, the consistent nature of the results are shown.

From the failure envelope of Figure 3, the calculated shear strength parameters may be obtained and compared to the actual values used in the numerical analysis, Table IV.

TABLE IV

COMPARISON OF CALCULATED AND ACTUAL SHEAR STRENGTH PARAMETERS

Parameter	Calculated from Simulated Test Data	Actual Values Used in Numerical Analysis
Joint Cohesion (MPa)	7.23	6.89
Angle of Internal Friction (degrees)	29	30

With a variation of less than 5%, the above results show the accuracy of the direct shear box technique in evaluating the engineering properties to describe the joint's failure envelope.

The problem of the stress distribution achieved along the sliding surface of the discontinuity during testing may now be studied by noting the normal and shear stresses in the four joint elements of the mathematical model. The elements are situated along the line MN in Figure 1, joint one opposite N.

Figure 4 shows the actual normal stress distribution along the discontinuity calculated from the F.E.M. analysis. The assumed or nominal normal stress distribution is also shown by the broken line. The assumed stress distribution was constant across the discontinuity for all normal stress levels and equaled the applied normal forces on the shear box divided by the bearing area of the discontinuity.

The actual normal stress distribution is non-linear with peaks in joint elements one and four, while the middle two joint elements were subjected to normal stresses 20% lower than the assumed normal stress. This stress state caused premature shear failure in the centre of the discontinuity. However, the overall stiffness of the joint plane was maintained due to the higher normal stresses near the edge of the discontinuity, causing an increase in the factor of safety for these two joint elements.

The actual shear stress distribution along the discontinuity is shown in Figure 5. These plots represent the shear stress in the joint elements during each of six shear force load cycles during Test C, i.e., with a constant nominal normal stress of 18.6 MPa. Only one test is presented, but in all cases the variation between the actual shear stress across the joint and the assumed shear stress was below 5% and negligible as shown by comparing the shear stress levels in Figure 5 (actual) and Table II (assumed).

4 CONCLUSIONS

The analyses described in this paper reveal that the stresses induced on joint surfaces during direct shear tests using the portable Imperial College type shear box, are satisfactory for evaluating the true shear strength parameters of discontinuities in rock. The actual shear stress distribution was found to be linear and in close agreement with the assumed stress level while the actual normal stress distribution showed a non-linear variation across the joint plane which was nevertheless satisfactory compared to previously pessimistic non-linear assumptions. Additionally it was shown that the horizontal displacement of the smooth joint surface may be satisfactorily obtained by horizontal deformation measurements taken on the top section of the shear box relative to the bottom.

The technique can therefore be used in the laboratory with confidence. Care must be taken with specimen preparation, the alignment of the discontinuity and horizontal displacement readings. Nevertheless, the direct shear box technique, for evaluating the relative sliding tendency and shear strength of discontinuities in rock, gives satisfactory experimental results which compare favourably with the true shear properties of the discontinuity.

5 ACKNOWLEDGEMENTS

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