Deformation behaviour of rocks under compression and direct tension

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Synopsis

Although many investigations of the deformation behaviour of rocks have been carried out, most of them are carried out in compression. In all rock engineering practice it is usually assumed that the deformation of rocks in tension is the same as that in compression. However, data from numerous researchers have shown that this assumption is not correct for some rocks.

A new loading frame for testing rocks in compression and direct tension has recently been developed by the authors, with the capacity to conduct both compression and tensile tests on the same rock sample. The results obtained show that the ratios between the average Young's modulus in compression (E_{CA}) and in direct tension (E_{TA}) are 1, 1.16, 2 and 6 respectively in four rock types tested. For Poisson's ratios, analogous relations were obtained. It was observed that, in all cases, the tangent Young's modulus in tension reduces with an increase in the applied tensile stress, while the behaviour of Poisson's ratio is similar, but shows greater variability.

The difference between the Young's modulus of rocks in tension and that in compression could lead, large errors in calculating induced stresses around underground openings, as well as in determining the Brazilian tensile strength of rocks. This may have a significant influence in rock engineering and therefore more investigation is necessary into the tensile deformation behaviour of rocks and its influence.

Introduction

It has been known for some time that, for some rocks, the value of Young's modulus in tension is smaller than that in compression. However, published data on the deformation of rocks under tension are much less abundant than under compression. It is assumed in most theoretical analyses, and in the application of numerical techniques, such as finite element and boundary element methods, that the values of Young's modulus and Poisson's ratio in compression are equal to those in tension, although some authors have reported that this assumption is not correct for many rocks[3,5,6,14,20].

Hawkes *et al.*[3] carried out tests in direct tension following previous compression for three rock types. Their results show that the values of the Young's modulus at 50% of failure stress in compression were usually greater than the corresponding values in tension. For Barre sandstone, the ratio of the two moduli was about 9, for Barre granite the ratio was around 2 and for Indiana limestone the ratio was approximately 1.

Stimpson and Chen[14] carried out uniaxial tension/compression load cycling tests on different rocks. Their results show that the ratios of average Young's modulus in direct tension and the modulus in compression are 0.5, 1.0, 0.7 and 0.3–0.4 in four rock types.

Some authors[1,5,10,13] have pointed out that if E_T is incorrectly assumed equal to E_C, large errors may result due to an actual difference between the value of Young's modulus in tension, E_T, and that in compression, E_C.

Because of the brittle behaviour of rocks, it is not easy to produce a state of direct tension in rock samples, and various techniques have been developed to avoid bending and stress concentration in tensile tests[7]. Hawkes and Mellor[3] performed their tests using a testing frame and loading with non-twist steel cable. Direct tension tests conducted by Changjiang Research Institute[8] using a testing frame having a half sphere joint. Tao[16] carried out his tests with a simple joint system that works under a servo-testing machine. Barla and

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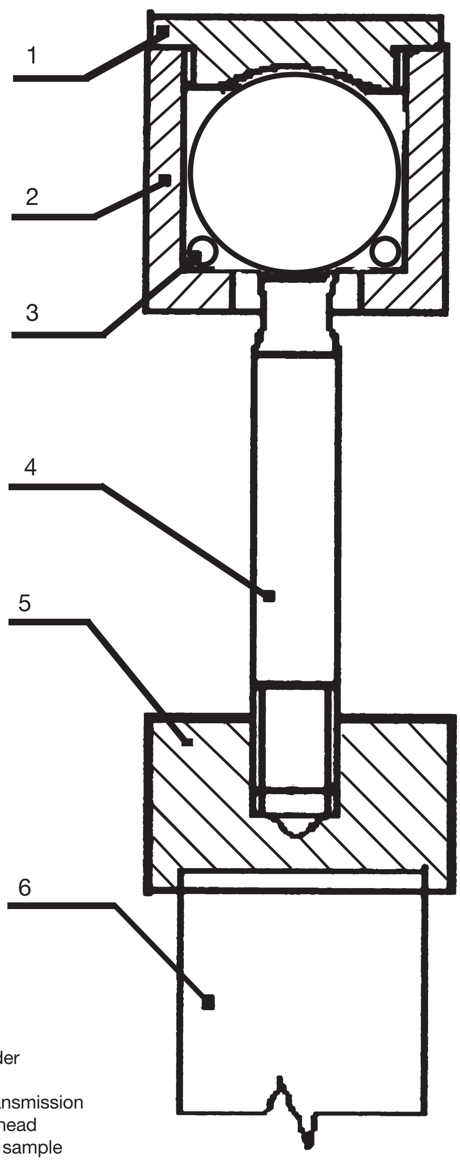
Goffi[4] developed a test unit in which the rock sample to be tested is connected with a joint. Stimpson and Chen[14] carried out their tests on rock samples having a special hollow cylinder geometry. Okubo and Fukui[17] conducted their direct tension tests by gluing the rock samples directly on the platen of the testing machine.

In the tests described in this paper, a new test frame was developed by the authors for conducting direct tension tests immediately following a compressive phase on the same rock specimen. The frame is shown in Figure 1 and is different from others previously published. For symmetry reasons, only part of the frame is shown in Figure 1. When conducting the tests, the rock specimen is cemented to the cap of the frame with epoxy resin, and the grips of the testing machine hold the frame instead of the rock specimen. The tension force is transported through a ring of steel spheres within the frame, so that the frame can rotate easily to avoid the introduction of bending and axial deviations of applied loads.



1 - Cover; 2 - Holder
3 - Steel spheres
4 - Bar of force transmission with spherical head
5 - Cap; 6 - Rock sample

Figure 1—The test frame (upper part)

To prove the effectiveness of the testing technique, steel bars were tested in direct tension. Strain gages were bonded to the steel bars to measure the bar deformation during the tensile loading phase. The forces applied by the testing machine, and the resulting strain measurements at different positions on the steel specimen are shown in Figure 2. These results show that there was no significant deviation from uniformity of tension, nor were there bending influences in the test. The frame was therefore considered to be suitable for performing direct tension experiments.

Testing methodology

Four rock types were chosen to conduct direct tension and compression tests. These rocks were sandstone from Dayao copper mine, granite and sandy-mudstone from Songshujiao tin mine of Yunnan Tin Co., and granite-gneiss from Xiaowan hydropower station. All samples were cylindrical and were taken from exploration boreholes from mines and/or engineering sites of Yunnan Province, P. R. China. Sample diameters were around 50 mm and sample length to diameter ratios were always 2. All specimens were air dried before testing.

Variability in mechanical properties complicates the comparison of test results from different rock samples. To avoid this influence, the new test frame was designed to perform compression and direct tension tests on the same specimens. The cylindrical rock sample was first cemented to the steel cap of the frame to carry out the compression test. Thereafter, the sample, as well as the cap, was connected with the rest of the frame to apply the direct tension, so that both compression and direct tension could be conducted on the same specimen, a procedure that may be called the compression-tension test.

Electric resistance strain gauges were bonded to the specimens to determine the strains under both compression and tension. The electric signals produced by the strain gauges were amplified by a dynamic strain indicator. The

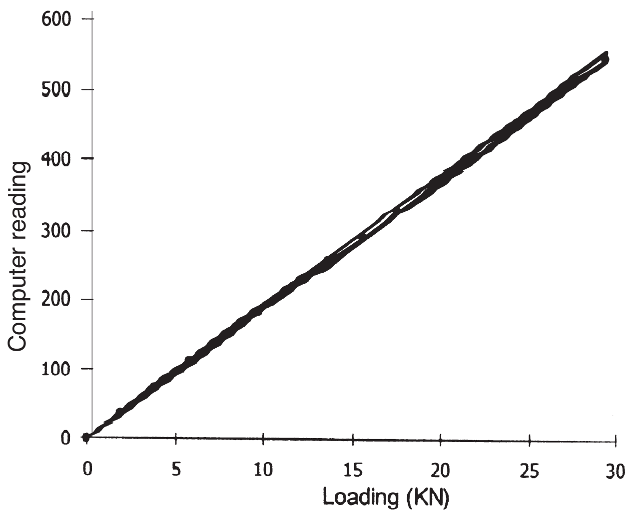


Figure 2—Inspection of the frame

signals were then transformed into digital ones by an analogue/digital (A/D) converter and were recorded with a computer. The tensile load was measured by the strain gauges bonded on the bar of the frame. The characteristics of the A/D converter allowed rapid strain changes, such as those that occur during the processes of failure and unloading, to be recorded.

Test results

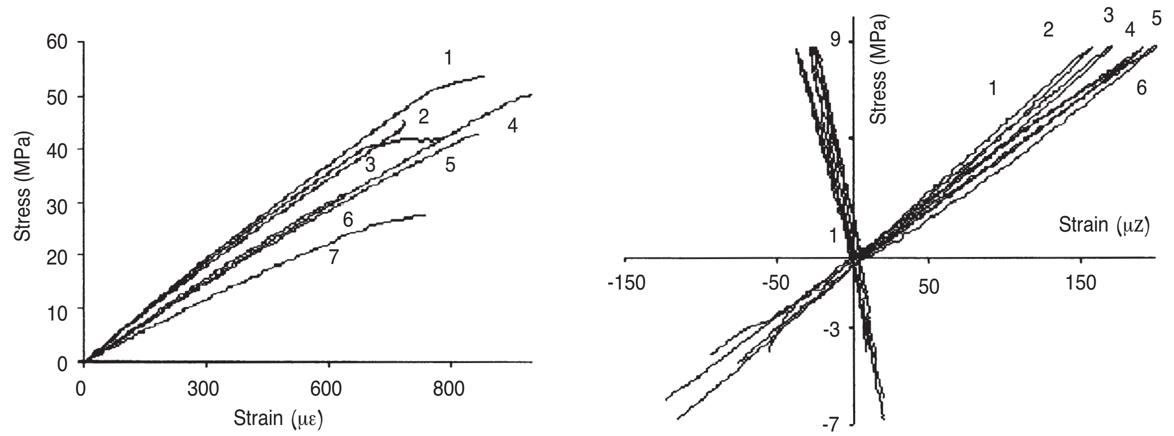
Since there are several ways to define and to calculate the values of Young's modulus, E, and Poisson's ratio, ν, an initial definition is necessary. For the purposes of the present research, average values of E and ν are adopted. These are determined from the average slopes of the 'more or less straight line portions' of the axial stress-axial strain and axial stress-lateral strain curves, as recommended by ISRM[9].

Compression and compression-tension tests were thus conducted on the four rock types, obtaining the stress-strain curves that are presented in Figures 3 to 6. As Poisson's ratio depends on not only the axial strain but also the lateral strain, both stress-axial strain and stress-lateral strain curves are given in the figures. In most samples, the stress-strain curves in both compression and tension are approximately linear, although some curves are non-linear to some extent. So the whole curve was used as the straight line portion to calculate the average Young's modulus, E_A, and average Poisson's ratio, ν_A.

Dayao sandstone

Dayao sandstone from a copper mine in Yunnan was selected for the tests. This is a fine-grained and isotropic rock with few joints and cracks. The stress-strain curves from compression and compression-tension tests are shown in Figure 3(a) and Figure 3(b) respectively, where both curves of axial stress-axial strain and axial stress-lateral strain are given. For each sample shown in Figure 3(b), the curves of loading and unloading in compression, as well as the curve of loading in tension, are represented.

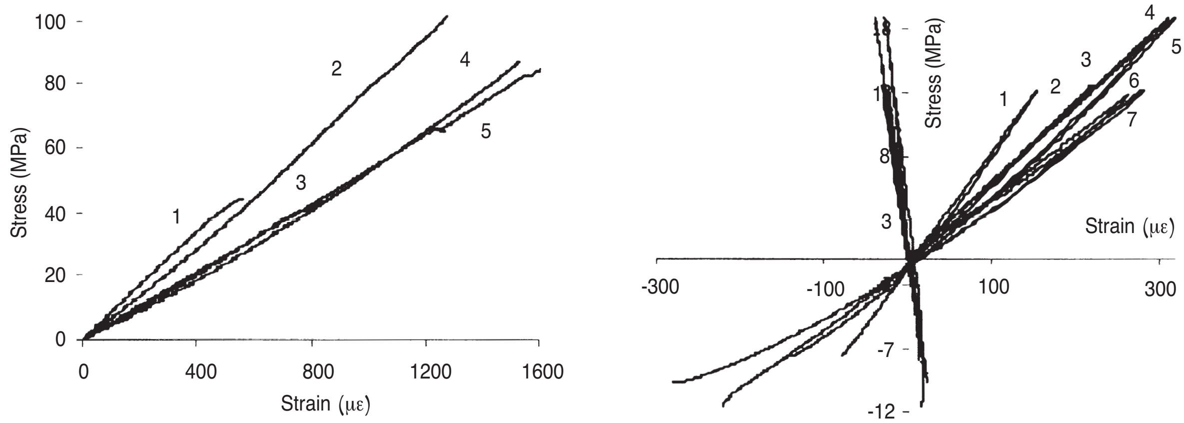
The test results show that the stress-strain curves in both compression and tension are almost linear. Of the five



(a) Simple compression tests

(b) Compression-tension tests

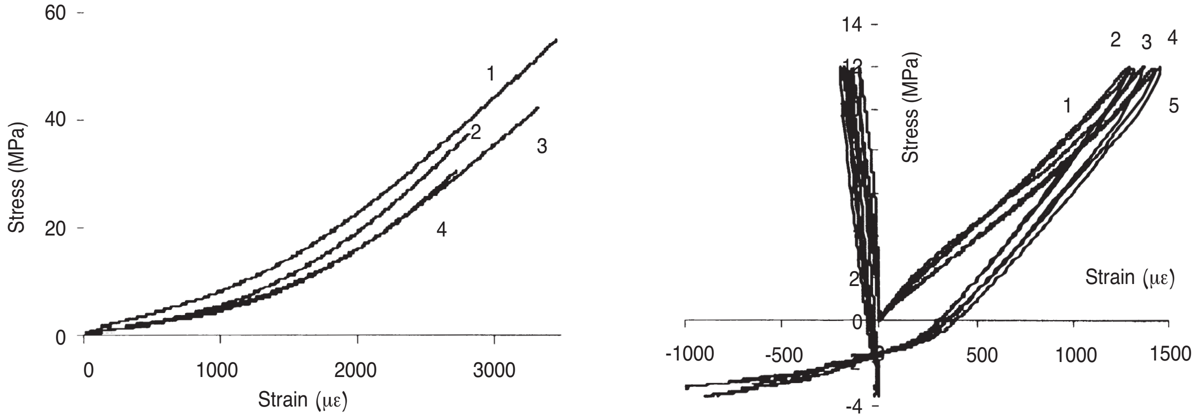
Figure 3—The stress-strain curves of Dayao sandstone



(a) Simple compression tests

(b) Compression-tension tests

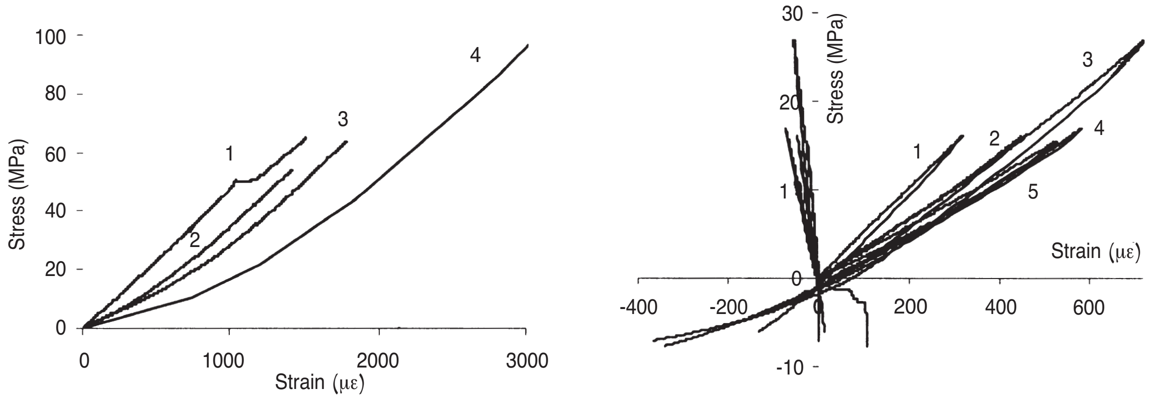
Figure 4—The stress-strain curves of Songshujiao granite



(a) Simple compression tests

(b) Compression-tension tests

Figure 5—The stress-strain curves of Songshujiao mudstone



(a) Simple compression tests

(b) Compression-tension tests

Figure 6—The stress-strain curves of Xiaowan granitite-gneiss

specimens subjected to the compression-tension test, the average Young's moduli in compression (E_{CA}) were greater than those in tension (E_{TA}) for three specimens. In the other two specimens, $E_{CA}<E_{TA}$. The average value of E_{CA}/E_{TA} for all of the specimens was 0.98. As the deformation behaviour of the rock is almost linear, the authors consider that the small difference can be neglected and the ratio E_{CA}/E_{TA} can be taken as 1.

The lateral deformation curves were also approximately straight lines. For all the specimens, the average Poisson's ratio in tension, ν_{TA}, was smaller than that in compression, ν_{CA}. The value ν_{CA}/ν_{TA} is within 1.05 and 1.47, with an average value of 1.28.

Songshujiao granite

Songshujiao granite is a hard and homogenous rock with average crystal size around 2 mm and an average compressive strength of over 100 MPa. The stress-strain curves in compression are approximately linear, with almost constant Young's moduli. However, the curves in tension are slightly non-linear and for most specimens the values of E_T decrease with an increase in the applied tensile loading.

Compression-tension tests were conducted for seven specimens, and the resulting curves are shown in Figure 4. For one specimen (No. 2), the average Young's modulus in compression, E_{CA}, is smaller than that in tension, E_{TA}, with an E_{CA}/E_{TA} ratio of 0.985. For all of the other specimens, E_{CA} was between 1% and 30% greater than E_{TA}.

For every specimen subjected to the compression-tension test, the average Poisson's ratio in compression, ν_{CA}, was greater than that in tension, ν_{TA}, with the ν_{CA}/ν_{TA} ratio being between 1.06 and 1.59. The average ν_{CA}/ν_{TA} value was 1.33.

Songshujiao sandy-mudstone

The sandy-mudstone from Songshujiao tin mine is formed from compacted mud and fine sand. The samples are homogenous and strong, with an average compressive strength of over 50 MPa. One remarkable characteristic of Songshujiao mudstone is that the values of Young's modulus are not constant and the slopes of the stress-strain curves in compression rise regularly with increasing stress, as shown in Figure 5(a). In comparison, the slopes of the curves in tension fall regularly with increasing tensile stress.

For this rock type, the values of E and ν in compression were much greater than those in tension. From compression-tension tests, E_{CA} was greater than E_{TA} for every specimen. The average value of E_{CA}/E_{TA} was as high as 3.35.

In the compression-tension test, the maximum compressive loading stresses were much smaller (around 20%) than the rock's compressive strength. As a consequence of the non-linearity of the compressive stress-strain curves, the compressive Young's moduli calculated from the compression-tension test are smaller than those from the simple compressive tests. To obtain the correct ratios of E_{CA}/E_{TA}, the E_{CA} values from the compression-tension test need to be corrected using data from the compression test. The maximum compressive loading stress in the compression-tension test was about 11.5 MPa. In the simple compressive tests the average Young's modulus calculated from the whole compression process (i.e. the full loading stress range from zero to failure) is about 80% higher than the moduli calculated from the loading stress range of 0 to 11.5 MPa. The ratio E_{CA}/E_{TA} should then be corrected from 3.35 to 6.03.

The behaviour of Poisson's ratio is similar to that of Young's modulus, i.e., the average Poisson's ratio in compression (ν_{CA}) is greater than that in tension (ν_{TA}). In the compression tests, the tangent value of ν also increases with an increase in the applied stress. The ν_{CA}/ν_{TA} values from compression-tension tests should also be corrected as for the Young's modulus. The average value of ν_{CA}/ν_{TA} then changes from 2.56 to 6.19.

Xiaowan granite-gneiss

Xiaowan granite-gneiss is also a homogeneous and compact rock, with an average crystal size slightly smaller than that of the Songshujiao granite texture. For most compression specimens the stress-strain curve slopes were slightly curved, with slopes increasing with an increase in the loading stress. In the tension segment of the compression-tension test, the slopes of the stress-strain curves fall regularly with the increasing tensile loading, and the average Young's modulus in tension becomes smaller than that in compression. The E_{CA}/E_{TA} ratio in the compression-tension test was 1.60.

Using the same reasoning as for Songshujiao mudstone, the E_{CA} value obtained in the compression-tension test is smaller than that obtained in compression tests and consequently the E_{CA}/E_{TA} ratio from the compression-tension test needs to be corrected using data from compression tests. The average Young's modulus calculated from the full compression stress-strain curves was about 28% higher than that calculated from the first part of the same stress-strain curves when the maximum stress equals the highest stress obtained in the compression-tension test. Therefore, the E_{CA}/E_{TA} ratio should then be corrected from 1.60 to 2.05, for this rock.

Regarding Poisson's ratio, the average value obtained in the compression phase of the compression-tension tests is

Table I

Test results (average values) of four rock types

	The parameters	Dayao sandstone	Songshujiao granite	Songshujiao mudstone	Xiaowan granitite-gneiss
Uniaxial compression test	E_{CA} (GPa)	49.35	66.39	12.32	41.98
	Variation coefficient (%)	18	20	9	15
	E_{C50} (GPa)	50.44	65.40	11.35	36.36
	Variation coefficient (%)	19	29	28	20
	ν_{CA}	0.181	0.153	0.449	0.226
	Variation coefficient (%)	15	31	5	40
	ν_{C50}	0.155	0.134	0.305	0.163
	Variation coefficient (%)	14	63	5	26
Compression-tension test	E_{CA} (GPa)	49.36	58.60	8.37	36.18
	Variation coefficient (%)	11	25	5	24
	E_{TA} (GPa)	51.31	52.03	2.54	23.49
	Variation coefficient (%)	9	36	16	42
	E_{T50} (GPa)	51.52	55.47	4.51	28.61
	Variation coefficient (%)	17	34	10	33
	ν_{CA}	0.171	0.124	0.110	0.100
	Variation coefficient (%)	20	33	22	38
	ν_{TA}	0.168	0.096	0.043	0.086
	Variation coefficient (%)	15	40	36	48
	ν_{T50}	0.144	0.119	0.050	0.104
	Variation coefficient (%)	32	37	25	42
The ratio	E_{CA}/E_{TA}	1	1.16	6.03	2.05
	Variation coefficient (%)	11	12	14	27
	ν_{CA}/ν_{TA}	1.28	1.33	6.19	2.14
	Variation coefficient (%)	18	18	14	57

usually greater than that recorded in tension, with the ν_{CA}/ν_{TA} ratio being 1.16. Again, the Poisson's ratio is smaller than the value obtained in the full compression test and, for the same reason as in the case of Young's modulus, the ν_{CA}/ν_{TA} ratio should be corrected to 2.14.

Discussion

In the compression phase of the compression-tension tests involved in this paper, the values of E and ν at 50% of failure stress cannot be obtained for each test since the maximum stress applied in the test is much lower than the failure strength. For this reason, average Young's moduli and Poisson's ratios are used in this paper, while the values at 50% of the failure stress in simple compression and tension have been determined from 'conventional' tests for the purpose of comparison, as Table I indicates.

For Songshujiao mudstone and Xiaowan granite-gneiss, the E_{CA}/E_{TA} ratios are much greater than the E_{C50}/E_{T50} ratios (E_{CA} and E_{C50} here are the results obtained from simple uniaxial compression). The main reason for this is that the stress-strain curve slopes in compression increase monotonously with the applied compressive stress, while the slopes in tension fall monotonously with the applied tensile stress. This leads to a higher Young's modulus in compression and lower value in tension as the applied stresses increase.

For Songshujiao granite, Young's moduli also reduce in tension, though the reduction is not as remarkable as for Songshujiao mudstone and Xiaowan granitite-gneiss. For Dayao sandstone, Young's modulus maintains approximately constant in tension.

It is well known that for most compact rocks the variation of Young's modulus in compression is less variable than that of Poisson's ratio under the same loading conditions. In fact, ν usually increases with increasing compressive loading stress, and can even exceed 0.5, which means that dilation appears in the specimen. For the rocks studied in this paper ν also increases with the compressive loading stress. The increase for Dayao sandstone was not as noticeable as in the other rock types.

In direct tension, the values of Poisson's ratio are more variable than those of the Young's modulus. For Songshujiao granite, the tangent Poisson's ratio in tension, ν_T, falls with increasing tensile loading stresses. However, the rate of the decrease for different samples is variable depending on the nature of the rock. Usually ν_T decreases sharply when the stress is low and then gently until failure occurs. For some samples ν_T diminishes constantly until failure. The curves of applied stress vs. Poisson's ratio of two samples are shown in Figure 7.

For Xiaowan granite-gneiss the ν_T behaviour is similar to that of Songshujiao granite, though the conditions of its reduction are more variable. For one sample, the average Poisson's ratio in tension is 20 times higher than that in compression, but this difference was probably due to cracking in the sample.

For Songshujiao mudstone, the tangent value of ν_T remains approximately constant until the tensile loading stress reaches about two thirds of the failure stress, then ν_T decreases with the loading stress and can even be negative near failure. A typical axial-lateral deformation curve of that rock is shown in Figure 8.

The tangent value ν_T of Dayao sandstone increases with the applied tensile stress and it falls slightly near failure. However, compared with the other rocks, the variations of E and ν of Dayao sandstone in both compression and tension are much smaller, and E and ν values of this rock can roughly be regarded as constants.

Hawkes *et al.*[3] found in their tensile tests that both Young's modulus E and Poisson's ratio ν are initially high, and then fall continuously as stress increases to the failure point. They have also found that the Poisson's ratio in tension can be greater than 0.5 at very low stresses. Pandey and Singh[11] pointed out that Poisson's ratio reduces with an increase of applied stress in uniaxial tension. In the tests described in this paper, the reduction of E and ν is observed for some rocks, though the phenomenon of ν_T greater than 0.5 was not found.

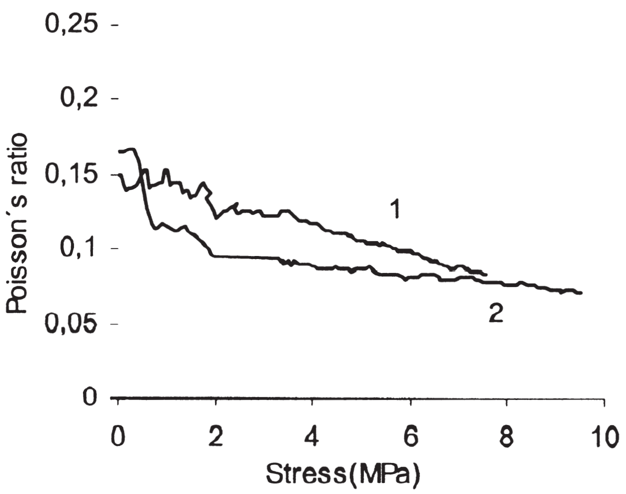


Figure 7—Variation of Poisson's ratio in tension of Songshujiao granite

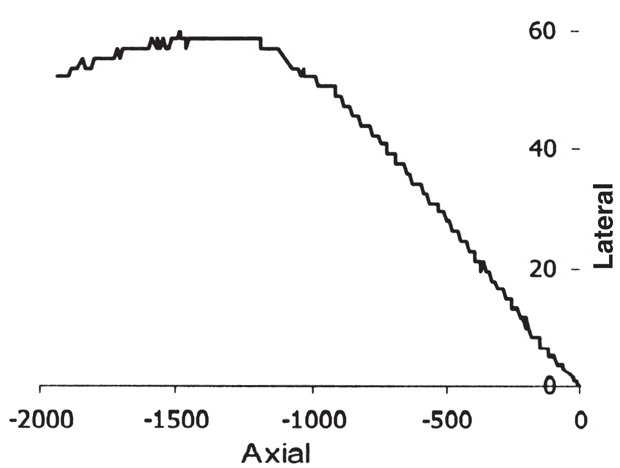


Figure 8—The axial-lateral deformation of Songshujiao mudstone

A noticeable result was that for all rock types the unloading curves in compression and the loading curves in tension are continuous and smooth in the transition between compression and tension, though the values of E_C and E_T are quite different for some rocks. This result is more remarkable for Songshujiao mudstone and Xiaowan granite-gneiss.

The results also show that in the compression-tension tests the variation coefficients for both E and ν in tension are greater than those in compression. Since the same specimens are adopted in both tests, the implication is that rock behaviour under tensile conditions is more irregular than in compression.

Timoshenko[1] has pointed out that, for a beam with a rectangular cross-section which has a Young's modulus in tension (E_T) smaller than that in compression (E_C), the effect of a decreased Young's modulus in tension is to move the position of the neutral axis towards the concave side of the beam. As a consequence, the absolute value of the maximum tensile stress at a section of a beam, σ_{tmax}, would be smaller than the maximum compressive stress at the same section, and σ_{tmax} would also be less than the tensile stress in a conventional beam in which the Young's modulus in tension equals the modulus in compression. This explains partly why values of tensile strength from beam tests on rocks are greater than those from direct tension and Brazilian tests.

Sundaram *et al.*[10] have shown with results from finite element analyses that, if the value of E_T is different from E_C, the tensile strength determined from a Brazilian test, using the conventional formula:

$$\sigma_t = 2P/\pi Dt$$

would overestimate the tensile strength of such a rock. In fact, the tensile stress distribution in the loaded disk of rock is dependent on the E_T/E_C ratio. When E_T is smaller than E_C, the tensile stress in the disk reduces with an increase in the E_C/E_T ratio. For a ratio of 5, the tensile stress would be 27% less than the value calculated from the above formula. Figure 9 shows their results, in which σ_B is the tensile stress calculated from the finite element program and σ_L is the tensile stress obtained from the above formula. When the E_C/E_T ratio is greater than 1, use of the above formula will lead to an overestimation of the tensile strength of the rock samples from the Brazilian test.

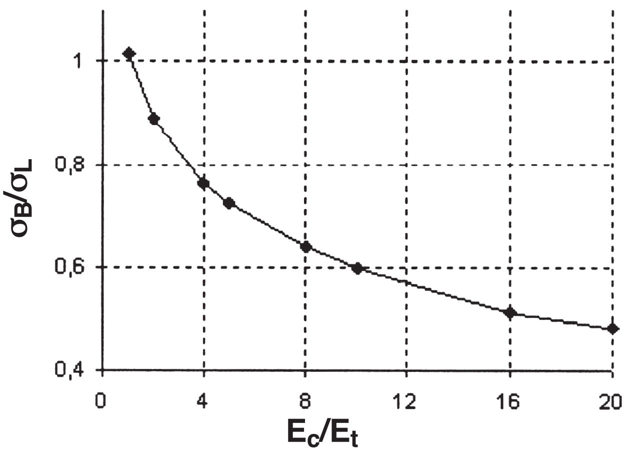


Figure 9—The relationship between E_C/E_T and σ_B/σ_L when ν equal 0.2 (Sundaram *et al.*, 1980)

For the ring test, Chen and Stimpson[13] presented the stress distribution using finite element analysis. Their results showed that the E_C/E_T ratio has a large influence on the calculated stresses—the larger the ratio E_C/E_T, the more the calculated stress values diverge from the results from the normal elastic solution.

For a thick-walled cylinder under internal pressure, as the condition of a borehole in a hydraulic fracture test, the solution obtained by Haimson and Tharp[5] also shows that when $E_T < E_C$, tensile stresses would be smaller than those obtained from the conventional formula.

In underground openings such as tunnels and stopes, tensile stress appears frequently in the roofs and/or sidewalls, often contributing to failure in those areas. The conditions in an underground opening are more or less similar to that of a beam, and the effect of bending near the free surfaces of the openings would change the tensile stress values when the E_T value of the rock is different from that of E_C. This means that, for most underground openings, tensile stress values obtained from conventional analyses (closed form analytical elastic solutions, finite element and boundary element analyses, etc.) may contain significant errors if $E_T < E_C$. Therefore, predictions of deformation and failure around excavations according to the conventional analyses may be unreliable. Unfortunately, commercially available numerical stress analysis packages do not consider such a condition, although no technical difficulty exists in doing so.

The phenomenon of $E_T < E_C$ appears not only in rocks, but also in concrete and composite materials. A new constitutive model named 'bimodularity', or more specifically 'double elasticity' has been developed for such conditions in which deformation in both compression and tension is linear and elastic, though $E_T \neq E_C$[12]. The results of Haimson and Tharp[5], Sundaram *et al.*[10], Chen and Stimpson[13], and Exadaktylos *et al.*[18], are all from that model.

Jaeger and Cook[6] concluded that, for the majority of rocks, the value of Young's modulus in tension is generally less than that in compression. If this conclusion is true, the results from all our theoretical equations and numerical techniques may need to be modified, and this may have a large influence in rock engineering. Unfortunately, research on deformation of rocks in tension is limited and our knowledge in this field is similarly limited. Therefore, more investigations are needed into the tensile deformation behaviour of rocks, and into the influence of the E_C/E_T ratio on stress distributions and the stability of rock structures.

Conclusions

A new loading frame with the capacity to conduct both compression and direct tension tests on the same rock sample was developed by the authors. Compression-direct tension tests were performed on four rock types from mines and an engineering site of China. The following conclusions are drawn from the results obtained:

- The average Young's moduli of the rock in tension, E_{TA}, are normally smaller than those in compression, E_{CA}. For Dayao sandstone, E_{TA} is almost equal to E_{CA}, but for the other rocks, the E_{CA}/E_{TA} ratios were respectively 1.16 (Songshujiao granite), 2 (Xiaowan granitite-gneiss) and 6 (Songshujiao mudstone).
- The average Poisson's ratios in tension, ν_{TA}, are generally smaller than those in compression, ν_{CA}. The obtained ν_{CA}/ν_{TA} ratios obtained were respectively 1.1 (Dayao sandstone); 1.3 (Songshujiao granite), 2.1 (Xiaowan Granitite-gneiss) and 6.2 (Songshujiao mudstone).
- For all rocks tested, tangent Young's moduli in tension reduce with the increasing stress, while tangent Young's moduli in compression keep approximately constant or increase. The behaviour of Poisson's ratio is similar, but more variable. For Songshujiao granite and Xiaowan granite-gneiss, tangent value of ν_T reduces with the applied tensile stress. For Songshujiao mudstone, ν_T is approximately constant and then falls near failure. For Dayao sandstone, ν_T increases initially and then slightly diminishes near failure.
- Tensile strengths determined by means of Brazilian tests must be viewed with some circumspection. In the case of $E_T < E_C$, the tensile strength calculated from the conventional formula is larger than the real stress value in the sample, leading to a misinterpretation of the strength value.
- When trying to predict deformation and failure around excavations using numerical analyses such as finite element and boundary element methods, significant errors could result in the predictions, especially in the 'unloaded' zones adjacent to the free surfaces of the excavation, in the case of $E_T < E_C$.
- Since significant influences may exist in rock engineering when the deformation behaviour of rocks in tension is different from that in compression, more investigations into the tensile behaviour of rocks are necessary.

Acknowledgement

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