Verification of post failure behaviour of rock using closed-circuit servo-controlled testing machine

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Abstract— The analysis of the stress-strain curve is a fundamental aspect in the field of rock mechanics. Most rock masses are not intact but have discontinuities. It is important to study the stress-strain curve beyond the peak failure as to assess the characteristic of intact rock against non-intact rock. However, several difficulties arise in obtaining the complete stress-strain curve. Since most rocks exhibit brittle behaviour, they fail violently and uncontrollably when tested on conventional compression machines. In this study, two series of uniaxial compression test were performed on sandstone samples. The first test was conducted using a 2000 kN MaTest conventional compression testing machine and the results were compared with a 3000 kN Tinius Olsen servo-controlled testing machine. Based on the results obtained from sandstone samples, post-peak failure can be achieved by using the servo-controlled testing machine. Comparison between the modes of failure observed from the tests on both types of machines clearly show that violent fracture is not the intrinsic characteristic of the rock but due to the rapid release of strain energy from the loading machine.

Keywords: Closed-circuit servo-controlled testing machine, complete stress-strain curve, excavation in rock, sandstone

Abstrak— Analisis lengkungan tegasan-terikan merupakan aspek asas di dalam bidang mekanik batuan. Oleh kerana kebanyakkan jasad batuan mempamerkan kelakuan dengan kewujudan ketakselaran dan bukannya batuan yang utuh. Dengan itu, adalah penting untuk memahami sifat-sifat lengkungan tegasan-terikan selepas kegagalan puncak sekiranya ingin mengkaji ciri-ciri batuan tak-utuh. Walaubagaimanapun, terdapat kesulitan di dalam memperolehi lengkungan tegasan-terikan yang lengkap, ini adalah disebabkan kebanyakan batuan adalah bersifat rapuh dan gagal secara tiba-tiba jika diuji dengan mesin ujikaji mampatan biasa. Di dalam kajian ini, dua siri ujikaji mampatan satu paksi dijalankan ke atas sampel batu pasir. Ujikaji pertama dijalankan dengan menggunakan mesin ujikaji mampatan biasa MaTest berkapasiti 2000 kN dan keputusannya dibandingkan dengan mesin kawalan-servo Tinius Olsen dengan kapasiti 3000 kN. Berdasarkan keputusan yang diperolehi daripada sampel-sampel batupasir, pasca-kegagalan puncak dapat dicapai dengan menggunakan mesin ujikaji berkawalan-servo. Jelasnya, perbandingan di antara kedua-dua mod kegagalan ini mengesahkan bahawa kegagalan secara tiba-tiba bukanlah sifat sebenar batuan, tetapi disebabkan oleh tenaga terikan yang dibebaskan oleh mesin ujikaji itu sendiri.

INTRODUCTION

Rocks always display ultimate compressive strength, which is the maximum stress that a rock can support in compression as a function of strain. Recently, more studies are being focused on the behaviour of rock beyond its ultimate strength or its post failure behaviour (He, *et al*., 1990; Speath, *et al.,* 1995). The curve of the stress-strain data is also termed as complete stress-train curve. The curve represents the total mechanical behaviour, in terms of uniaxial strength, from the initial loading to the complete destruction of a tested specimen. It shows the rock capability to sustain load beyond its peak strength with increasing strain.

However, several difficulties arise in obtaining the complete stress-strain curve. Since most rocks exhibit brittle behaviour, they fail violently and uncontrollably when tested on conventional compression machines. The violent collapse of a compressed specimen is not its intrinsic characteristic but rather due to the rapid release of strain energy from the machine components (e.g. loading columns), after the maximum load bearing capacity of the specimen has been exceeded. Therefore, consideration must be given to reducing the amount of strain energy stored in the loading system. One possibility is to increase the rigidity of the testing frame and more recently, by accommodating a servo-controlled system in the loading system. The system has been successfully used to obtain the complete stress-strain curve of rock specimens deforming under compression until reaching its post-failure.

EXCAVATION IN ROCK

The design of an excavation in a rock mass requires the knowledge on deformation characteristics of the rock material at the immediate vicinity of the excavation face. This portion of the rock mass usually fractured and failed during the excavation work. The basic approach in understanding the deformation behaviour of a fractured or failed rock is by studying its complete stress-strain curve under uniaxial compression.

The information on the shape of the post-peak region of rock samples is an essential parameter in designing an excavation in a rock mass. This is because in any rock excavation, it is necessary to reach the post-failure zone in order to carry out excavation work. Once the excavation

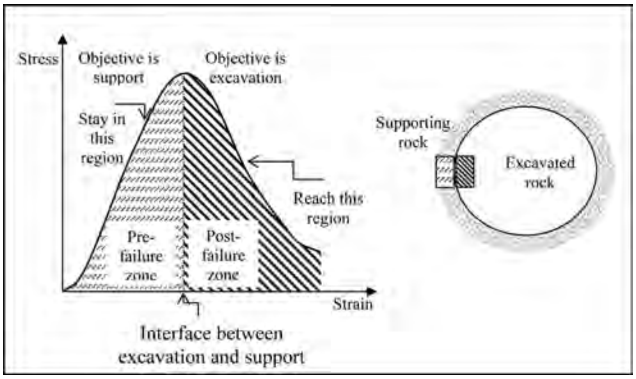

Figure 1: Relationship of complete stress-strain curve on rock excavation work (after Hudson, 1989).

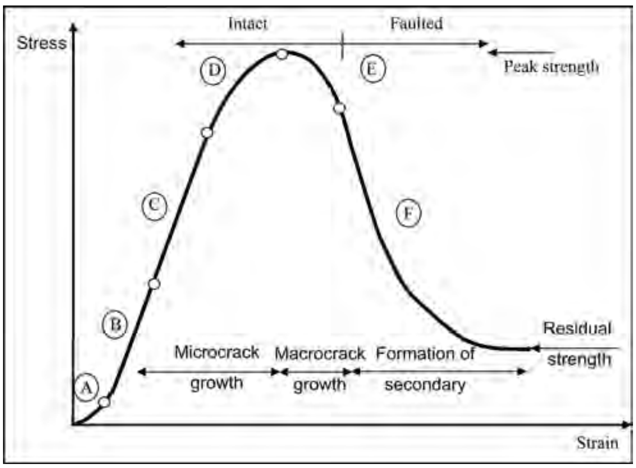

Figure 2: A description of rock deformation (after Farmer, 1982).

area is completed, most of the rock material surrounding it is in the pre-failure zone (Figure 1). Thus, the rock defining the excavation boundary is at the interface between the two major objectives of rock engineering activities, i.e. causing failure and avoiding failure. To cause failure, a rock sample must be loaded beyond the post-peak region and to avoid failure the loading must be within the pre-peak region. The knowledge on the post failure phase would also help in reducing any potential hazards that contribute to the economic advantages of construction.

STRESS-STRAIN CURVE

The analysis of stress is a matter of pure static, quite independent of the properties assumed for the material, which may be elastic or plastic. Meanwhile the analysis of strain is a fundamental study of the deformation of any material. A complete description of rock deformation includes five stages (Figure 2), which are indicated by the letters A to F (after Farmer, 1982):

1. Stage A – Closing of pre-existing micro-cracks in the rock at lower stress level. An initial linearity of the stress-strain curve. Strain increases in decelerating manner.
2. Stage B and Stage C –Near linear increase in volume and axial and lateral strain that is largely recoverable within the region of elastic compression. Strain increases in a constant manner. Stage of stable crack propagation regime.
3. Stage D – This stage is characterized by a rapid acceleration of microcracking events and of volume increase. Strain increases in an accelerating manner, unstable crack propagation regime. Cluster of cracks in the zones of highest tensile stress and tend to coalesce and start to form tensile fractures or shear planes.
4. Stage E – This is the stage where the rock has passed the peak stress, but is still intact, even though the internal structure is highly disrupted. In this stage the crack arrays fork and coalesce into macrocracks or a fault. In this description, at peak stress the test specimen starts to become weaker with increasing strain. Thus further strain will be concentrated on weaker elements of the rocks, which have already been subjected to strain.
5. Stage F – In this stage the rock has essentially parted to form a series of blocks rather than an intact structure. These blocks slide across each other and the predominant deformation mechanism is friction between the sliding blocks.

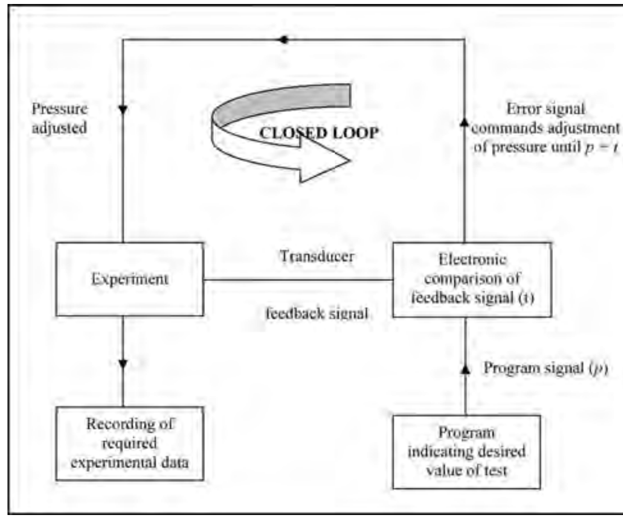

Figure 3: Principles of closed-circuit servo-controlled system (after Hudson *et al.,* 1971).

TESTING MACHINE

Testing machines have become increasingly sophisticated and versatile since they were first introduced in the early eighteenth century. Two recent advances in testing machine technology are of particular importance for laboratory studies of rock failure are the development of machine with stiff frames and the use of feedback control systems.

Machine with servo-controlled system

The principle of the closed-loop servo-controlled testing machine is given in Figure 3. A signal from an experiment is generated by the transducers and electronically compared with the program instruction. If an error occurs (i.e. the transducer feedback signal is not equal to the programmed value), a servo-valve in the hydraulic system automatically

Table 1: Summary of the laboratory test.

Test	Set a	Set b
Machine & capacity	MaTest (2000 kN)	Tinius Olsen (3000 kN)
Machine type	Conventional	Servo-controlled
Sample type	Sandstone	Sandstone
No. of sample	5	5
Loading mode	Load controlled 0.7 kN/s	Strain controlled 0.00001 mm/mm/s

Table 2: Summary results of sandstone for Test a.

Sample	Strain at failure (%)	Uniaxial compressive strength, UCS (MPa)	Young's modulus, E (GPa)	Residual strength (MPa)
S1a	2.12	43.72	4.4	N.A
S2a	1.93	32.42	3.8	N.A
S3a	1.68	43.42	2.9	N.A
S4a	2.58	41.30	3.7	N.A
S5a	2.17	39.34	3.5	N.A

adjusts until the transducer response coincides with the program value. The success of the system depends on the ability of the servo valve to correct the error rapidly enough as to prevent the release of enough energy to cause disintegration. The quick response time of the servo valve and the readjustment of the error are therefore important aspects in a servo system.

Testing machines equipped with a servo-controlled system have also been developed for the purpose of generating a constant strain rate. Here, when the strain or displacement is regarded as a control variable, the failure of rock can be controlled, where the strain is monotonically increased at the specific rate until the post failure region. However, if the force is regarded as a control variable in the experiment, where the rock is tested at constant loading rate, the unstable failure may occur when peak strength is reached.

LABORATORY TEST

Figure 4 show ten core samples of sandstone prepared by the process of coring, cutting and lapping, as to obtain the required sample size and shape (Fairhust & Hudson, 1999). Then two series of laboratory uniaxial compression test (UCS) were performed on five samples each, first by using a 2000 kN MaTest conventional compression testing machine (Figure 5A) and then a 3000 kN Tinius Olsen servo-controlled testing machine (Figure 5B). The summary of the laboratory tests is shown in Table 1.

DISCUSSIONS

Figures 6 and 7 show the stress-strain curves of sandstone tested using conventional and servo-controlled testing machine, respectively. The results are summarised in Tables 2 and 3. The curves for the sample loaded under different loading modes (load- and strain-controlled), differ in terms of the post-peak region (Figures 6 and 7). It is clearly shown in Figure 6 that samples tested on a conventional machine exhibited uncontrollable and violent failures at peak strength and consequently, only pre-peak region of the stress-strain curve data could be acquired throughout the tests. In contrast to those tests conducted on servo-controlled machine the acquired tests data represents the complete stress-strain curve of the rock samples, implying a controllable failure even beyond peak strength (Figure 8).

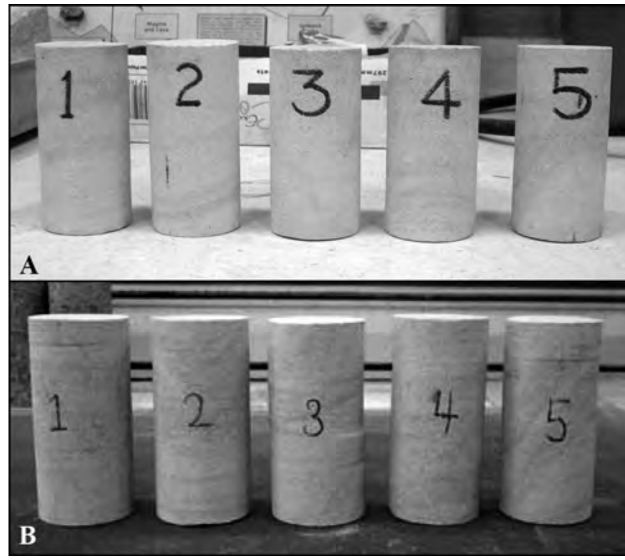

Figure 4: Sandstone samples for testing using (A) MaTest conventional compression testing machine and (B) Tinius Olsen servo-controlled testing machine.

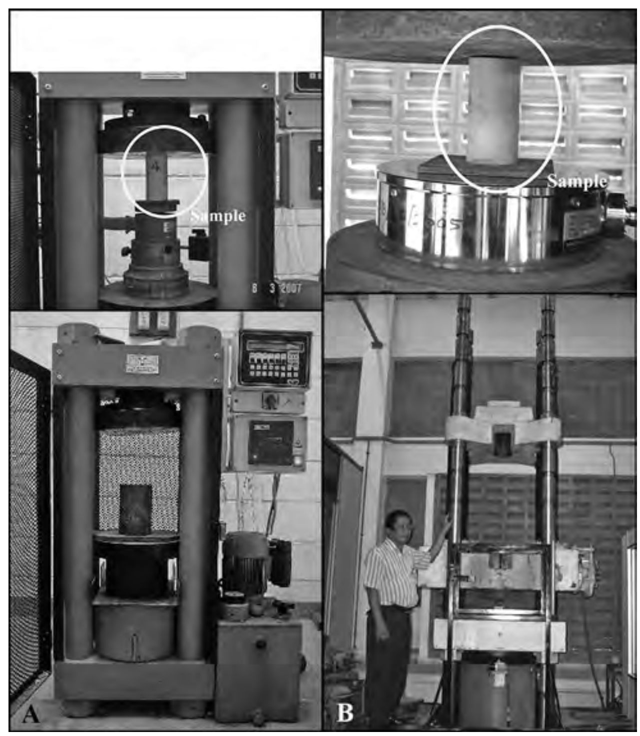

Figure 5: A) MaTest conventional compression testing machine prior to testing. B) Tinius Olsen servo-controlled testing machine prior to testing.

In pre-peak region, both Figures 6 and 7 show similar deformation behaviour, in terms of range of Young's

Table 3: Summary results of sandstone for Test b.

Sample	Strain at failure (%)	Uniaxial compressive strength, UCS (MPa)	Young's modulus, E (GPa)	Residual strength (MPa)	Residual strength as % of UCS (%)
S1b	2.030	38.78	3.5	22.40	57
S2b	1.530	32.08	4.1	24.06	75
S3b	2.246	24.31	4.7	15.79	65
S4b	1.412	38.60	5.5	13.03	34
S5b	1.736	24.76	3.2	13.50	54

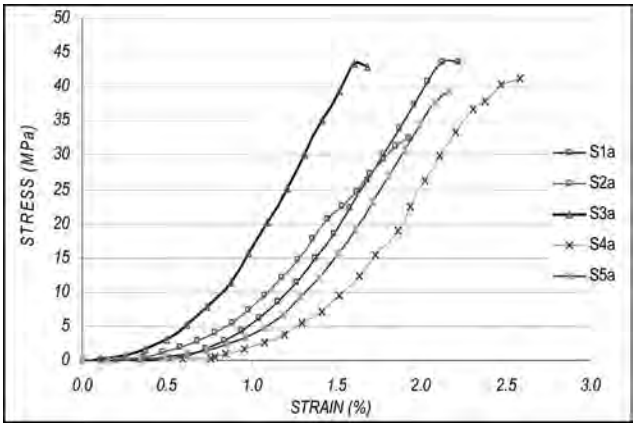

Figure 6: Stress-strain curve for sandstone tested under conventional testing machine.

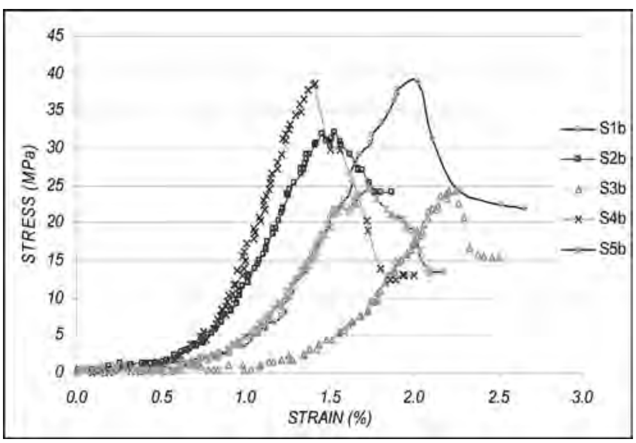

Figure 7: Stress-strain curve for sandstone tested under servo-controlled machine.

modulus, E (2.9 – 5.5 GPa). The deformation behaviour of sandstone for both tests display plastic-elastic-plastic behaviour with some densification of sample during the early stage of loading and followed by gradual fracturing of sample towards failure. The densification implies the closing of void spaces in this porous rock. The range of strain at failure is between 1.5% and 2.2% and the UCS is about 24 MPa to 43 MPa.

The post-peak region displayed by samples tested on the servo-controlled machine indicates that sandstone does exhibit residual strength of about 13 to 24 MPa, or about 34 to 75% of UCS. The ability to display the residual strength is mainly due to the test being conducted under constant strain rate (instead of stress rate). In other words, the servo-controlled unit helps to increase the stiffness of the compression machine, allowing more controllable failure of the rock sample. There are two speed settings, namely Speed1 (0.1 mm/minute) and Speed2 (0.08 mm/minute). Such loading modes allow for a more controllable and gradual failure of the samples. Speed1 was used during early the stage of loading and this was changed to Speed2 when the tested sample was approaching approximately 60% of the expected peak strength.

The results show that the sandstone still exhibits some strength although it has been compressed beyond the peak strength and explosive failure (a sudden drop in peak strength) is not an intrinsic characteristic of a rock but it is rather due to a sudden release of strain energy stored in the loading columns of the testing machine. A gradual drop in peak strength can be achieved by conducting the test on a closed-circuit servo-controlled testing machine.

CONCLUSIONS

Based on the laboratory tests on sandstone samples using a conventional testing machine and a servo-controlled machine, the following conclusions can be derived:

Both set of test results on sandstone show a similar pre-peak behaviour, where samples exhibit plastic-elastic-plastic deformation.

The stress-strain curve from tests on the conventional testing machine display a pre and peak strength, and samples failed violently (explosive failure).

Tests using a closed-circuit servo-controlled machine have enabled the complete stress-strain curves for sandstone to be obtained.

A violent failure is not the intrinsic characteristic of a rock, but rather due to the rapid release of strain energy in the loading columns when sample reaches its peak strength.

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