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Determination of Post-Failure Characteristic Behaviour of Rocks under Conventional Method Based on the Mechanism of Rock Deformation Process

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Abstract**—**This work is intended to study the post-failure characteristic behaviour of rocks and the techniques of controlling the post-failure regime based on the mechanism of rocks deformation process. It is impossible to determine the post-failure regime of rocks using conventional laboratory testing equipment. This is because most testing machines are soft and therefore no information can be obtained after the peak load. Stress-strain deformation tests were conducted using both conventional and unconventional method (i.e. the closed loop servo-controlled testing machine) in accordance to ISRM standard. Normalised pre-failure curves were constructed to show the stages in the deformation process. The first type contains the Class I and progress to Class II with low strength soft brittle rocks. The second type shows entirely Class II characteristic behaviour. The third type is extremely brittle under axial loading, resulted in explosive failure, so its class could not be determined. The difficulty in obtaining the post-failure curves increases as the total volumetric strain approaches a positive value. The author's use of normalised pre-failure curves enables identification of additional type of deformation process with very brittle response under axial loading. Testing the third type without confinement could cause equipment damage. Identification of the deformation process with the rock classes using conventional test could guide the personnel conducting tests using closed-loop servo-controlled system, to avoid equipment damage when testing rocks with third type deformation process so that testing is performed safely. It has also improved our understanding on total specimen failure and brittleness of rocks (e.g. brittle for Class II and less brittle or ductile for Class I).

Keywords**—**Closed-loop servo-controlled system, conventional testing equipment, deformation process, post-failure, pre-failure normalised curves, rock classes.

I. INTRODUCTION

THERE is difficulty with the laboratory determination of the post-failure curve of rocks using conventional equipment. Rock specimens are often in an unstable state at the point of failure as most testing machines tend to be soft. Rock specimens break explosively at their ultimate strength and no further information could be obtained. Simon et al. [1] observed that the laboratory determination of the post-failure behaviour of rocks under uniaxial compression test of brittle rocks is often difficult to realise. Shimizu et al. [2] concurred that there are still complications in achieving post-failure stress-strain curves of brittle rocks in the laboratory experiments. Javier and Alejano [3] opined that significant success has not been realized in the techniques for estimating good post-failure regime of rocks, primarily due to the difficulties associated with achieving complete stress–strain curves. However, Alejano et al. [4] achieved fairly good complete stress-strain curves under unconfined compressive tests for a partially weathered granite rock. Similarly, Brijes [5] presented post-failure tests results obtained for different coal mines in West Virginia and Hiawatha. Nonetheless, it is almost impossible to obtain good post-failure curves on homogeneous hard brittle rocks without explosive breakage in unconfined condition.

A testing machine using a closed loop servo-controlled system is the only practical way that will avoid explosive breakage of rock specimen at the peak strength of the rock. Fig. 1 shows the principle of a closed loop, servo-controlled testing machine. A transducer is attached to the rock specimen. It generates a signal that is compared with the program instruction where constant strain rate or deformation is considered as the control variable. If the transducer signal is not equal to the program instruction value, the hydraulic system automatically adjusts the servo-valve until the transducer signal matches up with the program instruction set. The efficiency of the testing machine therefore relies on the capability of the servo-controlled valve to respond quickly enough to adjust the error and avoid release of the stored energy in the specimen when the ultimate strength is reached.

A. Class I and Class II Rocks

Fig. 2 shows the pre-failure and post-failure stress-strain curves that were obtained from a closed-loop servo-controlled testing machine. Rocks are classified into Class I or Class II according to their post-failure characteristic behaviour of the stress-strain curve in uniaxial compression tests [7]. After the ultimate strength is reached, there may be increase in strain or not. If there is a continuous increase in strain, it is classified as Class I, but if not then it is classified as Class II. The striking distinction between the two types of rock classes is the non-elastic strain [8]. As the load-bearing capacity of the rock specimen decreases, both curves show decrease in the elastic strain in the post-failure region. For instance, if the non-elastic strain increases faster than the elastic strain, the rock is classified as Class I, otherwise Class II.

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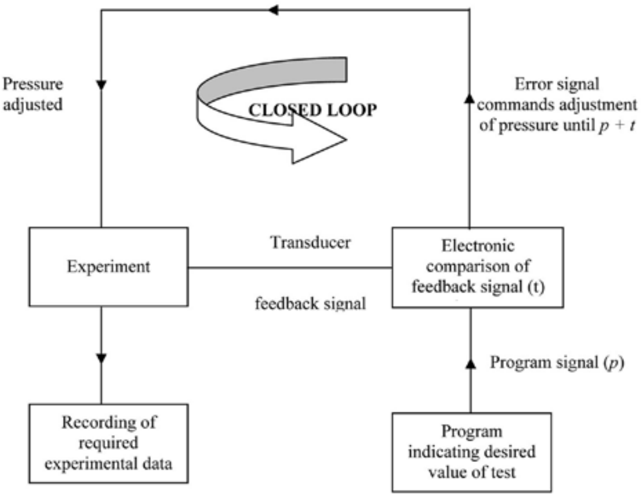

Fig. 1 Principles of closed-loop servo-controlled system [6]

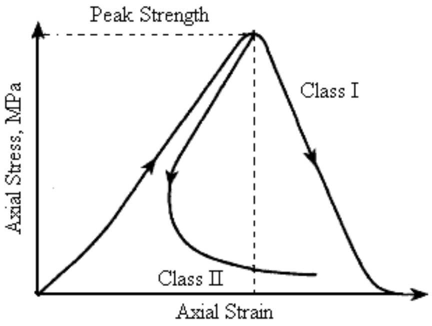

Fig. 2 Classification of rocks based on post-failure characteristic behaviour in compression [9]

This research therefore intended to study the possibility of identifying the rock classes (Class I or Class II) from deformation behaviour of the rocks studied from normalised axial stress-volumetric strain curves using tests result from conventional machine. A stiff testing system which is the only practical way to determine rock classes is a difficult test to perform (requiring sufficient personnel training and vigorous specimen preparation). The use of conventional test to classify rocks (into Class I or Class II) will be helpful in the routine determination of rock classes and rock's brittleness determination. In addition, it would be helpful in the estimation of the rocks brittleness (e.g. brittle for Class II and less brittle or ductile for Class I) since the post-failure part is the part that actually characterises the brittle behaviour of a rock. Similarly, the knowledge of the post-peak behaviour of rocks will assist in the evaluation of the potential failure of an excavation and the rockburst potential near underground openings (e.g. Class I failure gradual, Class II failure explosive). Identification of these deformation processes with their rock classes could guide the personnel conducting tests with closed-loop servo-controlled system, if dangerous situation or equipment damage could occur so that testing is performed safely.

II. LITERATURE REVIEW

Deformation and fracture characteristics of brittle rock have been studied by many researchers [10], [8], [11]. The common agreement among them is that the failure process occurs in stages. The stages are determined from stress-strain characteristic curves obtained from axial and lateral deformation measurements during laboratory uniaxial compression test.

Evaluation of stress-strain deformation behaviour rocks and the brittle fracture process are classified into stages [13], [14] (Fig. 3) as follows:

- Fracture closure (stage I),
- Linear part of the stress-strain (or initiation cracks) (stage II),
- Stable crack growth (Critical energy release) (stage III),
- Unstable crack growth (rock failure) (stage 1V) and
- Failure and post-failure behaviour (or structure failure) (stage V).

In order to evaluate the stages of deformation in rocks, Martin [14] conducted uniaxial compression tests on cylindrical samples of continuous, homogenous, isotropic, linear and elastic (CHILE) massive Lac du Bonnet Granite obtained from the Underground Research Laboratory (URL) at 420 m below ground surface. The test was carried out to identity a suitable site for the disposal of radioactive wastes. The stages in the failure process are identified in the stress-strain curves (Fig. 3).

Yathavan and Stacey [15] summarised the procedure for obtaining the stages of the deformation process from laboratory tests, as shown in Table I. This summary is adopted in this work to plot the stress-strain curves and to identify the stages of the deformation process.

III. METHOD FOR AXIAL STRESS-VOLUMETRIC STRAIN CURVES

Stress-strain curves were determined for different 18 rock types (ranging from soft Quartz Arenite of 35 MPa to Quartzite2 of about 514 MPa; and with different rock types, igneous, sedimentary and metamorphic) in unconfined uniaxial compression test using conventional Amsler rock testing machine in accordance to ISRM [9]. Stress-axial, radial and total volumetric strain curves were constructed according to [11] and [13] to show the stages in the deformation process (using Table I) and group them into the different deformation process.

A. Method for the Determination of Complete Stress-Strain Curves

During the determination of the post-failure stress-strain curves using the servo-controlled testing machine, the following control steps were employed:

The axial extensometer was installed at 120^0 apart and contacts the specimen at 25% and 75% of its full length while the circumferential extensometer was located at mid-height of the specimen. The specimen was then installed on the lower platen of the load unit assembly. A small preload was applied with the force cell drive to contact the specimen in force control mode using the output of the axial force as the feedback signal. This made the specimen 'seat' to the lower loading platen and the upper loading platen becomes spherically seated. The readings of both axial, radial extensometer and axial force were reset to zero.

Ductile (i.e. less brittle) specimens were continuously loaded at an axial strain rate of 0.001 mm/mm/sec. This was continued up to 70% of the predetermined peak load of the specimen determined using the conventional method. After this point the loading rate was reduced by switching to a lower strain rate of 0.000001 mm/mm/sec. The loading continued at an axial strain rate of 0.000001 mm/mm/sec until the applied load drops close to 50% of its peak load. At this point, a post-failure load-deformation curve was obtained.

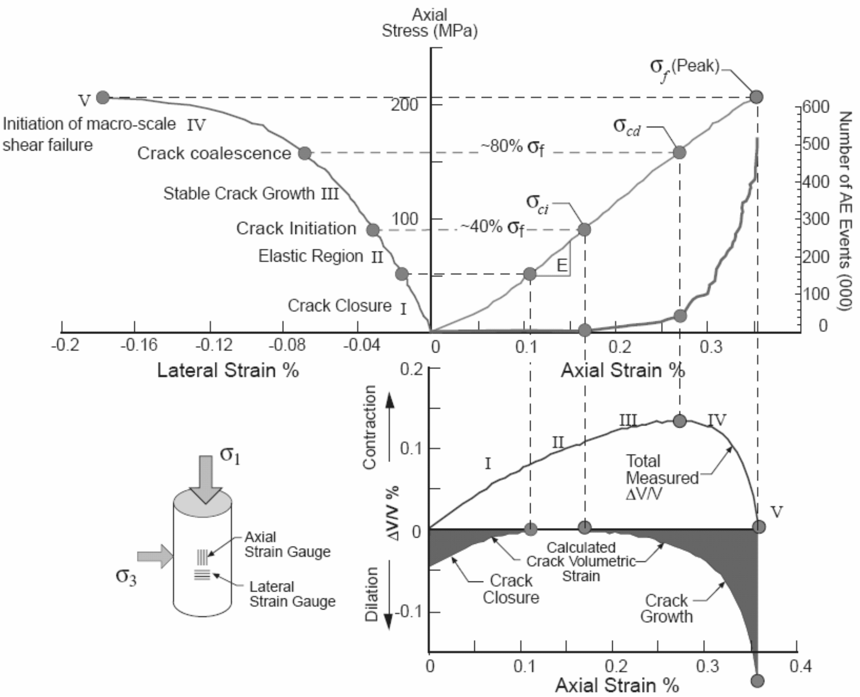

Fig 3 Stress-strain diagram showing stages in the failure process [11], [14]

TABLE I
METHOD OF IDENTIFICATION OF DEFORMATION STAGES BASED ON STRESS-STRAIN CURVES [15]

	Identifying Methods	Crack Closure	Crack Initiation	Crack Damage
Brace et al. [12] Bieniawski [10], [13]	Axial strain	Point of nonlinear Zone changes to linear zone		
	Lateral strain		Point of departure from linearity to non-linearity	
	Volumetric Strain		Point of departure from linearity to non-linearity	Point of reversal
Martin and Chandler [11]	Crack Volumetric strain		Dilation begins after crack volume unchanged during elastic deformation	

In the case of specimens with a brittle behaviour (i.e. Class II), the control switch over method is as follows. The control mode was switched from axial force to axial strain control mode. The specimens were continuously loaded at an axial strain rate of 0.001 mm/mm/sec. This was continued up to 70% of the predetermined peak load of the specimen. At 70% of peak load, instead of a slower or reduced axial strain rate, the control mode was switched to circumferential control mode at a rate of 0.0001 mm/mm/sec. This continued until the applied load reduces to about 50% of peak load. At this point a post-failure load-deformation curve was obtained. Five tests were performed per each rock type and average result is reported.

IV. RESULTS AND DISCUSSION

Apart from [11], [13], another deformation process is identified showing very brittle condition during compressional loading. Together there are three types of deformation process. The first type has a negative total volumetric strain while second type has positive total volumetric strain with both types having a point of reversal at crack damage stress. However the third type has a positive total volumetric strain without a reversal point [16].

The four stages of deformation process are identifiable with the first and second types while only three stages of deformation process are identifiable with the third types. As the total volumetric strain increases, the difficulty in determining the post-failure curves also increases. Thus difficulty in obtaining the post-peak stress-strain curves increases from the first type to the third type [16]. For rocks that exhibit the first type of deformation process, the normalised stress-axial, radial and total volumetric strain curves and post-failure curves are shown in Figs. 4 and 5; Figs. 6 and 7. The post-failure stress-strain curves for this type of rock was relatively easy to perform.

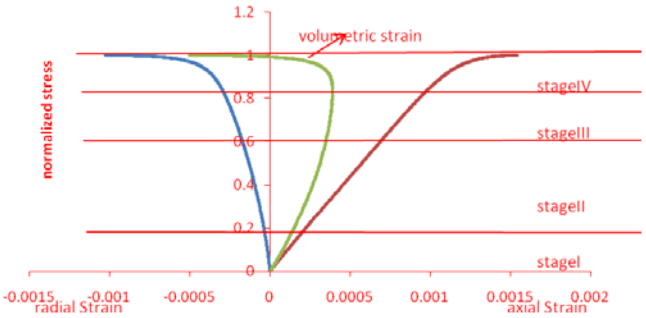

Fig. 4 Normalised stress-strain curves, Marble specimen

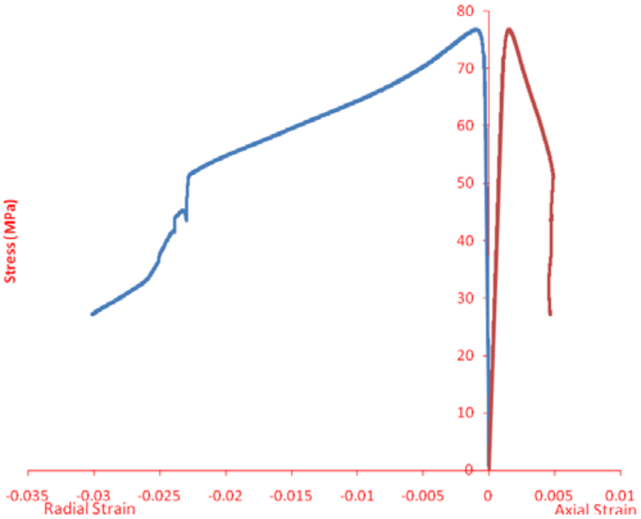

Fig. 5 Post-failure stress-strain curves, Marble specimen

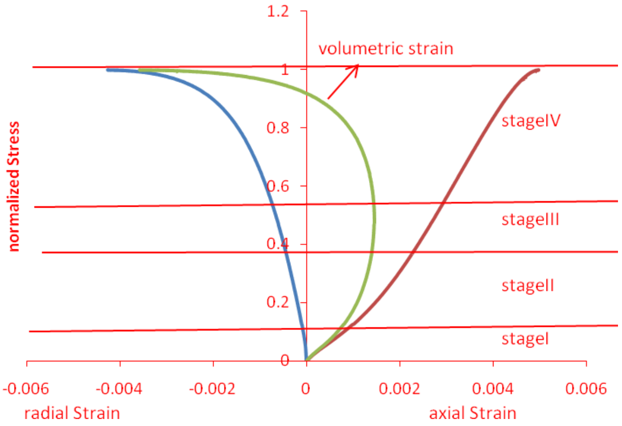

Fig. 6 Normalised stress-strain curves, Sandstone specimen

Figs. 8-11 show the second type and the stages of deformation process. For this type of stress-axial, radial and total volumetric strain curves, the process of unstable crack propagation (stage IV) has a small duration and for this reason cracks propagate on their own accord. Thus, the rocks exhibit a higher velocity of micro-cracking propagation. This made it difficult to control the post-failure curves than the type one stress-axial, radial and total volumetric strain curves because of the short duration of the crack damage stress threshold to rupture. The normalised stress-axial, radial and total volumetric strain curves and the post-failure curves are shown in Figs. 8-11.

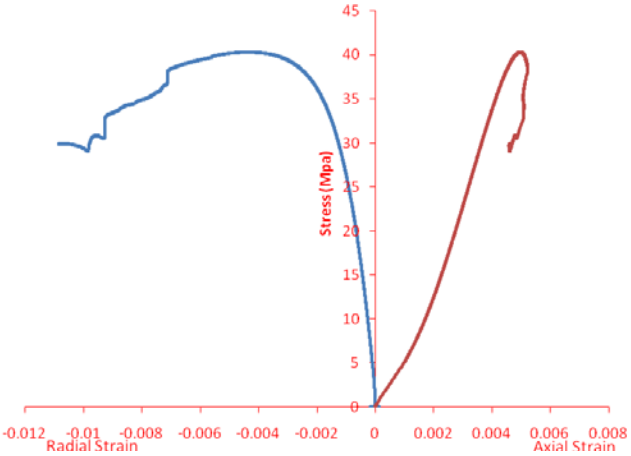

Fig. 7 Post-failure stress-strain curves, Sandstone specimen

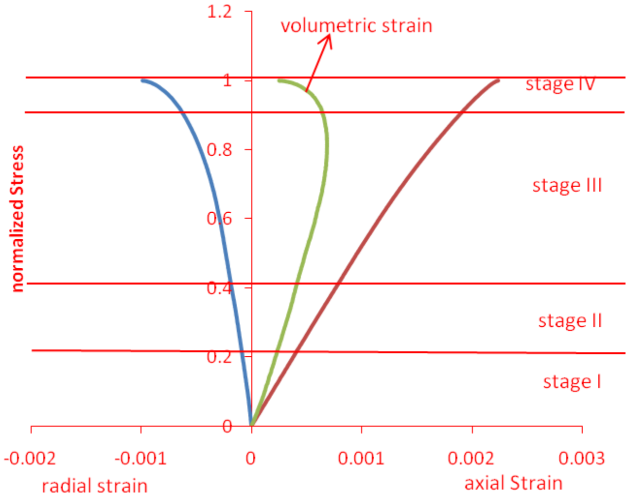

Fig. 8 Normalised stress-strain curves, Troctolite specimen

For the third type of stress-axial, radial and total volumetric strain curves, the crack induced stress and the structural failure of the rock specimen occurred together (Figs. 12, 13). The rock volume continues to decrease since there is no reversal of the total volumetric strain. The circumferential strain does not increase with applied load. So the process became a self-sustaining failure and, as a result the micro-cracking of the material continued on its own [16]. Furthermore, unstable fracture propagation starts at the onset of the fracture initiation stress. The onset of crack damage stress threshold commenced earlier for this type than observed with others. In this situation Griffith theory of brittle fracture ceases to exist while the fracture propagation process is controlled by crack growth velocity [16]. These specimens exhibit high micro-crack propagation velocities at peak strength. As unstable crack growth continued the velocity increases rapidly to reach terminal velocity and the many micro-cracks coalesce.

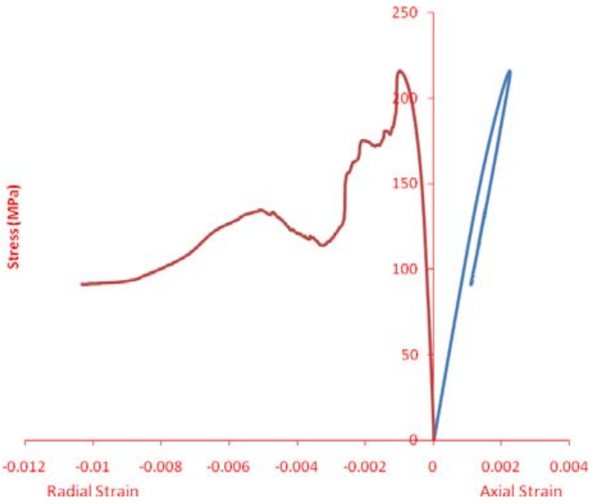

Fig. 9 Post-failure stress-strain curves, Troctolite specimen

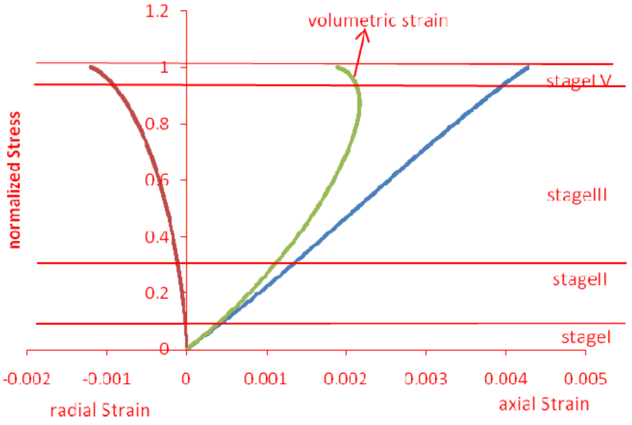

Fig. 10 Normalised stress-strain curves, Quartzite1 specimen

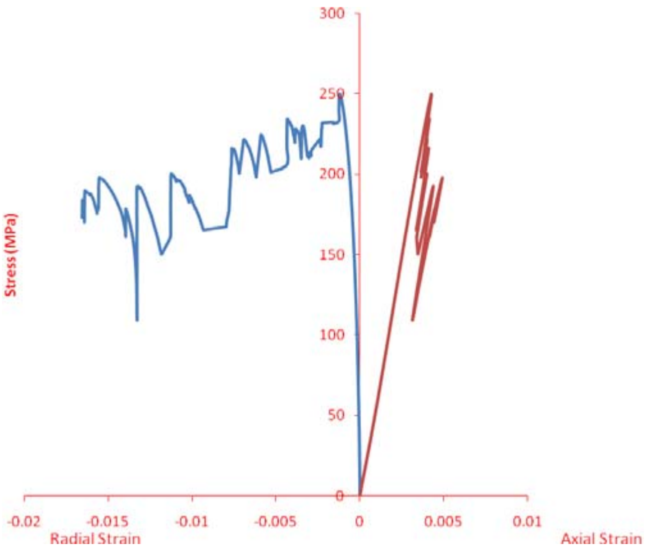

Fig. 11 Post-failure stress-strain curves, Quartzite1 specimen

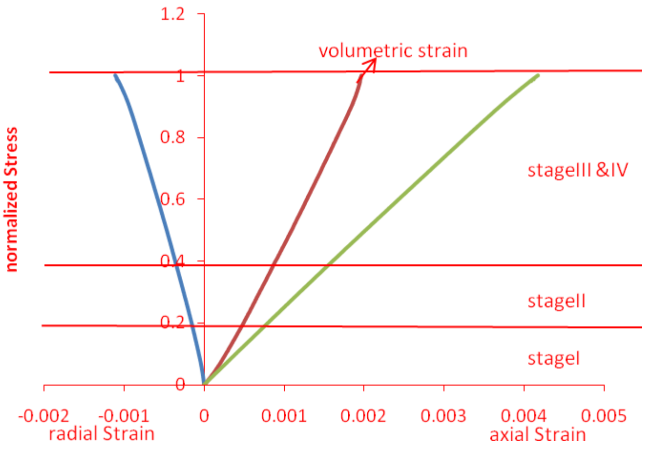

Fig. 12 Normalised stress-strain curves, Gabbro specimen

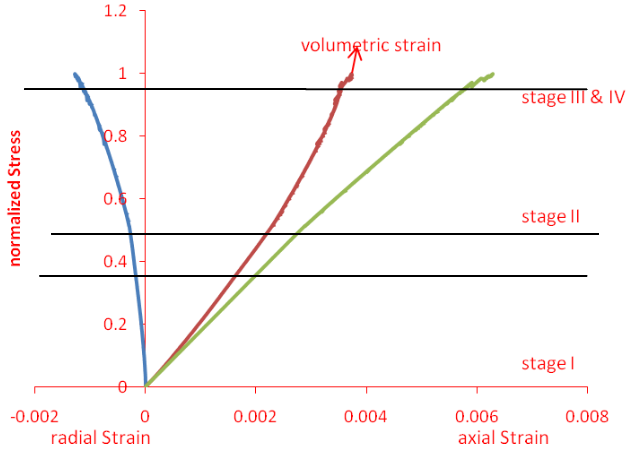

Fig. 13 Normalised stress-strain curves, Quartzite2 specimen

Fracture propagation continues to grow as the stored elastic strain energy release rate has attained a critical value even when the load was reduced. The cracks continued to extend because the elastic strain energy stored within the specimen is released [16]. As a result of the high UCS of the rocks (390 MPa for Gabbro and 514 MPa for Quartzite2), the elastic strain energy stored in the specimen at pre-failure phase was much more than the work the specimen can do at post-failure phase [17]. It leads to the violent failure of the rocks accompanying equipment damage (Fig. 14).

Several attempts to determine the post-failure regime under low confinement range (up to 15 MPa) were unsuccessful. The rock specimen produces cracking noise once the load approaches ultimate strength with catastrophic failure. It is opinion of the author that this type of rock could only be successfully tested under high confinement in excess of 100 MPa, if it could be possible for the load cell to accommodate the failure load at such high confinement. This is because for hard and brittle rocks, the instability and brittleness increases even at low confinement but they become controllable under high confining pressure since all rocks become ductile under high confinement. This type of rock deformation characteristic is extremely brittle under axial loading and result in explosive failure, so its class could not be determined. The first type deformation process contains the Class I and progress to include the Class II with low strength soft brittle rocks while the second type shows entirely Class II characteristic behaviour.

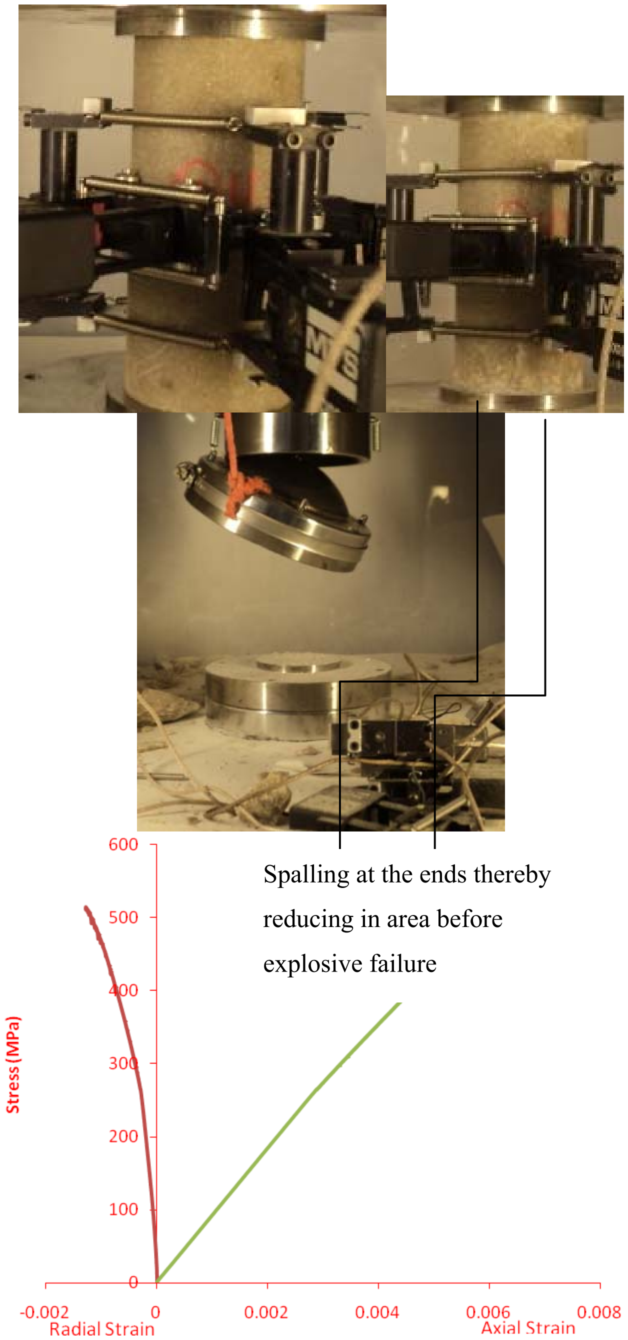

Fig. 14 Explosive damage of testing equipment in an attempt to determine post-failure curves for Quartzite2

V. Conclusion

This research has demonstrated the possibility of using results from conventional laboratory equipment to classify rocks into Class I and Class II with the use of deformation process of rocks constructed according to [11] and [13]. It is therefore possible to have knowledge of the post-failure regime of rocks using conventional testing system.

Three types of deformation curves were identified. The first type contains the Class I and progress to include Class II with low strength brittle soft rocks e.g. Quartz Arenite. The second type is entirely Class II rocks. The rock class for the third type could not be determined since it is very brittle and explosive at peak strength.

Identification of the deformation process could guide the personnel conducting tests using closed-loop servo-controlled system, if dangerous situation or equipment damage could occur especially with the third type of deformation process so that testing is performed safely. In addition, it can be used to determine brittleness of rocks and routine determination of rock classes. It could indicate rocks brittleness (e.g. brittle for Class II and less brittle or ductile for Class I) since the post-failure part is the part that actually characterises the brittle behaviour of a rock. Moreover, the knowledge of the post-peak behaviour of rocks will assist in the evaluation of the potential failure of an excavation and the rockburst potential near underground openings (e.g. Class I failure gradual, Class II failure explosive).

VI. Further Research

Further research could be initiated to study the normalised pre-failure curves to serve as a measure of rocks brittleness potential and for predicting fragmentation. As it is shown that there is a connection between obtaining a post-failure curve and the total volumetric strain as its approaches a positive value, therefore the total volumetric strain may be explored for estimating post-failure moduli of rocks. In addition, such research could study the first type of deformation process in order to demarcate precisely the line between the rocks that contains the Class I and low strength soft brittle Class II rocks.

Additionally, research could be initiated to study various sensor guidance technologies that could improve the control performance of closed-loop servo-controlled testing system for post-failure determination of very brittle rocks. Sensor based programmable systems such as laser scanning, infrared (IR), ultrasonic and high speed micro-acoustic sensors etc. could be explored for reliable and safe operating control of the third type deformation process with very brittle response under axial loading.

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