Failure response of rocks under different cyclic loading histories

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ABSTRACT: The post-failure instability of rocks was investigated through an extensive experimental study under four different loading histories, including the monotonic quasi-static loading, single-level systematic cyclic loading (SLSCL), multi-level systematic cyclic loading (MLSCL), and post-peak cyclic loading (PPCL). The lateral strain-controlled and double-criteria damage-controlled testing methodologies were implemented for the experiment. A combined post-peak Class I-II behavior to different extents was detected for soft to strong rocks, while the unstable fracture propagation was more dominant for stronger rocks under monotonic loading. Additionally, rocks exhibited more self-sustaining behavior under MLSCL history with increasing the number of cycles before the failure point. On the other hand, the results of the SLSCL tests revealed that rock brittleness reaches its maximum value by applying systematic cyclic loadings at stress levels close to the monotonic strength. However, the effect of post-peak cyclic loading (PPCL) history on the post-failure response of rocks was negligible.

Keywords: Post-failure, cyclic loading, damage-controlled, lateral strain-controlled.

1 INTRODUCTION

Rock material in civil and mining engineering projects may undergo different levels/amplitudes of cyclic loadings, depending on the distance from the seismic source location. Hence, investigating the failure response of rocks subjected to different cyclic loading histories can provide new insights into the damage evolution, rock failure mechanism, and the long-term stability of the rock structures. However, the failure response of rocks under pre-peak and post-peak cyclic loading histories has not been fully understood. This is owing to the lack of an appropriate testing method to control the axial load in the post-peak regime, where the rocks experience an unstable fracture propagation, and failure occurs in an uncontrolled manner (Fairhurst & Hudson 1999, Munoz et al. 2016a and b). In prior rock fatigue studies, the loading systems have been programmed to generate a constant axial load/displacement rate as the feedback signal throughout the tests to control the axial load. However, the load-controlled and axial displacement-controlled methods can only capture the pre-peak and Class I-type (negative drop modulus/stable fracture propagation) post-peak behavior of rocks, respectively. This ensues while the rock specimens collapse violently after showing Class II/snap-back behavior in the post-peak regime. The failure response of rocks cannot be adequately recorded. In contrast, as Munoz et al. (2016a and 2017) reported, regardless of whether the specimen experiences Class I or II stress-strain behavior in the post-peak regime under compression, the lateral displacement evolves at a constant rate throughout the experiment. Thus, the lateral strain, as a control variable, can be adapted to different cyclic loading conditions to measure the complete stress-strain curves of rocks. The current study investigated the post-failure response of various rocks having a wide range of strength (i.e., soft, medium, and strong rocks) under different cyclic loading histories, including the multi-level systematic cyclic loading (MLSCL), single-level systematic cyclic loading (SLSCL) and post-peak cyclic loading (PPCL), through the innovative testing methodologies.

2 MATERIALS AND TESTING SYSTEM

Tuffeau limestone (density of 1.4 g/cm^3), Gosford sandstone (density of 2.22 g/cm^3), Massangis limestone (density of 2.45 g/cm^3), and Alvand granite (density of 2.65 g/cm^3) were adopted in this study. For each rock type, specimens with 42 mm diameter and 100 mm length were prepared, and the aspect ratio (i.e., length-to-diameter ratio) of rocks was maintained at 2.5, as recommended by the ISRM (Fairhurst and Hudson 1999). The study used two fully digital closed-loop servo-controlled testing systems, i.e., MTS-45 and Instron-1282, with maximum loading capacities of 300 kN and 1000 kN, respectively, to perform monotonic and cyclic loading tests. These testing machines were stiff enough to prevent the accumulation of elastic energy in the loading systems. The axial and lateral deformations of the rock specimens during the tests were recorded continuously using a pair of external LVDTs and a chain extensometer, respectively.

3 LOADING HISTORIES

To undertake monotonic loading tests, the testing system was programmed so that the lateral deformation of rocks was allowed to increase at constant rates of $d\varepsilon_L/dt$= 0.02×10^{-4}/s and 0.18×10^{-4}/s to satisfy static to quasi-static loading conditions.

Three types of damage-controlled cyclic loading tests were designed to appraise the effect of loading and unloading cycles on the post-failure response of rocks: (1) Multi-level systematic cyclic loading (MLSCL): Tuffeau limestone was used for this type of cyclic loading test. The rock specimen was first loaded monotonically at a constant lateral strain rate of 0.02×10^{-4}/s to reach the prescribed stress level at the unstable crack propagation stage. The specimen was unloaded at the same rate until the axial load was almost 0.07 MPa. Then, the cyclic loading commenced with a higher rate of $d\varepsilon_l/dt$= 2×10^{-4}/s. During the cyclic loading stage, the axial load was reversed when either the pre-defined maximum stress level or the maximum lateral strain amplitude, $Amp. \varepsilon_l$=17×10^{-4} was detected (i.e., a double-criteria damage-controlled test method, DCDC). $Amp. (\varepsilon_l)$, was determined based on the trial tests and the obtained lateral strain values for the monotonic loading test. The specimen was transferred monotonically to the second loading level should it not fail during 400 cycles. Thereafter, the loading and unloading cycles were applied again, following the foregoing controlling criteria. This process was continued until the complete failure of the rock occurred. As such, very close to and after the peak stress, the damage extension was controlled properly, and the post-peak stress-strain relationships were captured successfully; (2) Single-level systematic cyclic loading (SLSCL): Gosford sandstone was utilised for this type of cyclic loading test. Similar to the MLSCL tests, the DCDC testing procedure was used for conducting the SLSCL tests, with the difference that the specimens were allowed to individually experience 1500 cycles at stress levels ranging from 86.81 to 96% of the average monotonic strength. Indeed, the cyclic tests were performed beyond the crack damage threshold stress to ensure fatigue failure of the specimens. In these tests, the optimum cyclic loading rate ($d\varepsilon_L/dt$) and $Amp. (\varepsilon_l)$ values were determined as 3×10^{-4}/s and 17×10^{-4}, respectively. (3) Post-peak cyclic loading (PPCL): Four different rock types, including Tuffeau limestone, Gosford sandstone, Massangis limestone, and Alvand granite, were used for PPCL tests. The specimens were initially subjected to monotonic loading under a constant lateral strain rate of 0.18×10^{-4}/s until ε_L from the beginning of the loading reached the prescribed $Amp.(\varepsilon_l)$ value. The values of 20×10^{-4}, 41×10^{-4}, 14×10^{-4}, and 41×10^{-4} were chosen for Tuffeau limestone, Gosford sandstone, Massangis limestone, and Alvand granite, respectively, based on the trial tests and monotonic test results. Then, the axial load was reversed at the same rate, and the subsequent cycles were performed for each rock type, following the defined criterion. The damage values were achieved almost close to the peak strength, and by unloading the specimens at the same rate of 0.18×10^{-4}/s, the subsequent cycles in the post-peak regime were performed while the damage value was maintained constant for each cycle until complete failure occurred.

4 POST-FAILURE RESPONSE OF ROCKS

4.1 Monotonic Loading

Figure 1 shows the representative complete stress-strain curves and the corresponding mechanical properties of two rocks obtained from uniaxial monotonic loading tests. In general, it was observed that the post-failure response of rocks under uniaxial monotonic loading is not solely Class I or Class II but a combined Class I-II behavior to different extents.

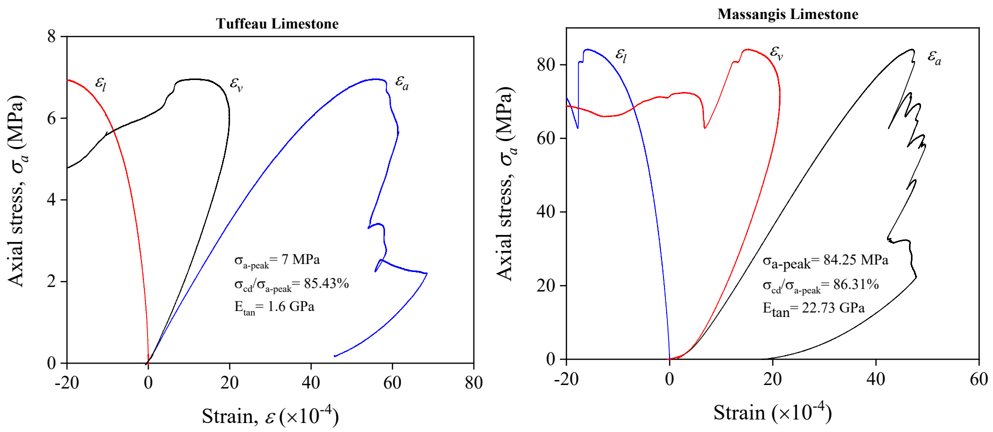


Figure 1. The results of the uniaxial monotonic loading tests.

4.2 Multi-Level Systematic Cyclic Loading (MLSCL)

Three MLSCL tests were conducted on Tuffeau limestone specimens. The results, which are shown in Figures 2a-c demonstrate the success of the double-criteria damage-controlled (DCDC) testing methodology in capturing the complete stress-strain responses of rocks subjected to the pre-peak systematic cyclic loading. In this figure, the overall post-failure behavior of the specimens has been highlighted by connecting the peak stress points of loading cycles (i.e., red dotted lines). As seen in Figure 2, different post-failure responses can be detected depending on the number of cycles the specimens have experienced before the failure point. Additionally, all the conducted cyclic loading tests exhibited a residual strength that was lower than that observed for the monotonic test. Figure 2d plots the normalized residual strength ($\sigma_{res}/\sigma_{a-peak}$) versus the axial strain at the failure point (ε_{a-peak}). The figure shows whatever the specimen experiences more axial strain before the failure point due to an increase in fatigue life, the difference between the peak strength and the residual strength increases, resulting in more self-sustaining failure behavior compared to the monotonic loading conditions. This behavior can be attributed to the more strain energy accumulation and rock compaction during the multi-level systematic cyclic loading tests.

4.3 Single-Level Systematic Cyclic Loading (SLSCL)

Figure 3 compares the normalized complete stress-strain results of some representative SLSCL tests at different fractions of the monotonic strength (σ_a/σ_m) with that recorded for the monotonic test. To prevent Figure 3 from becoming crowded, only the post-peak stress-strain curve of the monotonic test has been shown. The measured crack damage threshold stress of Gosford sandstone is almost 58.27%. Thus, it can be assumed that all the SLSCL tests have been conducted in the unstable crack propagation stage. In general, as might be visually observed from Figure 3, the difference between the post-peak stress-strain relations of cyclic and monotonic loading tests, representing the excessive energy induced by the snap-back behavior of rocks, increases progressively by applying cyclic loadings at higher stress levels.

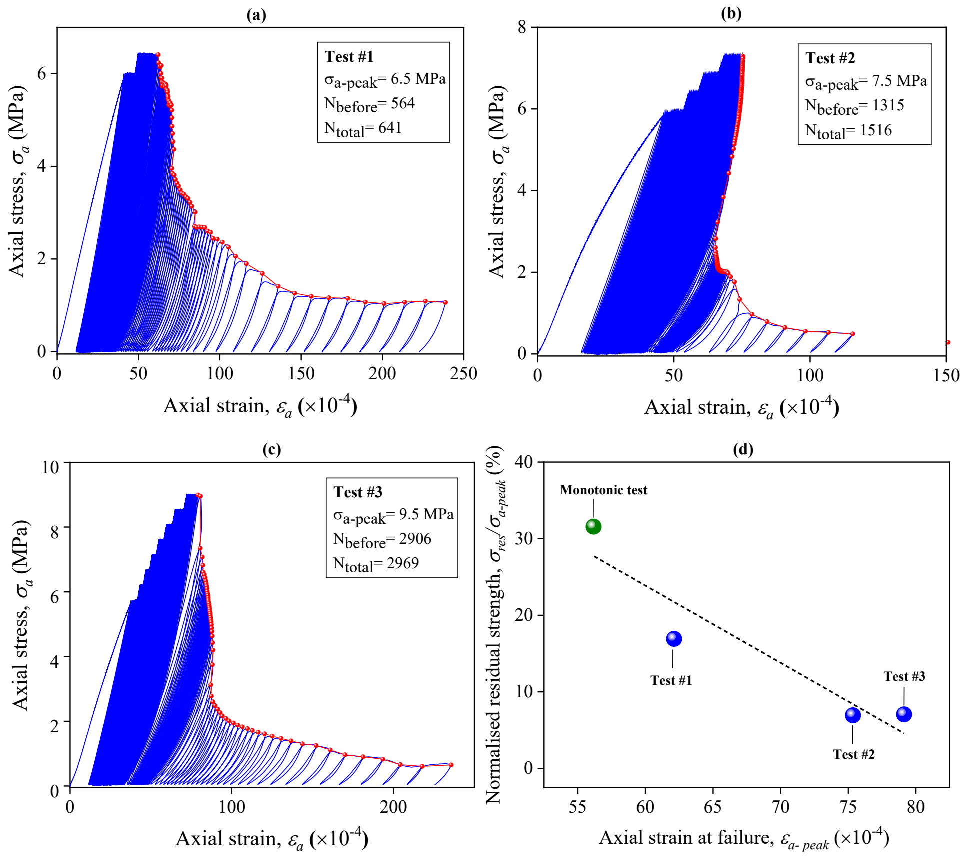
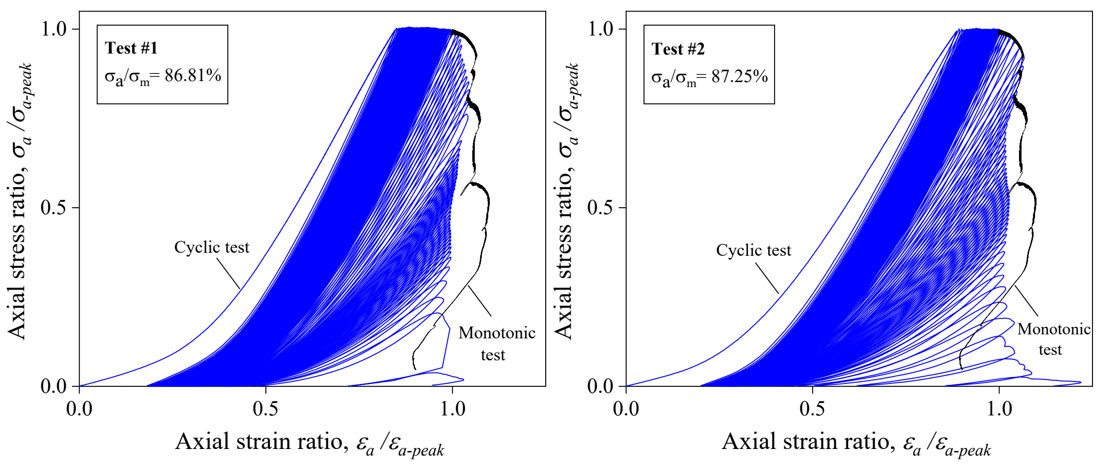


Figure 2. The normalized stress-strain results of the MLSCL test for Tuffeau limestone.



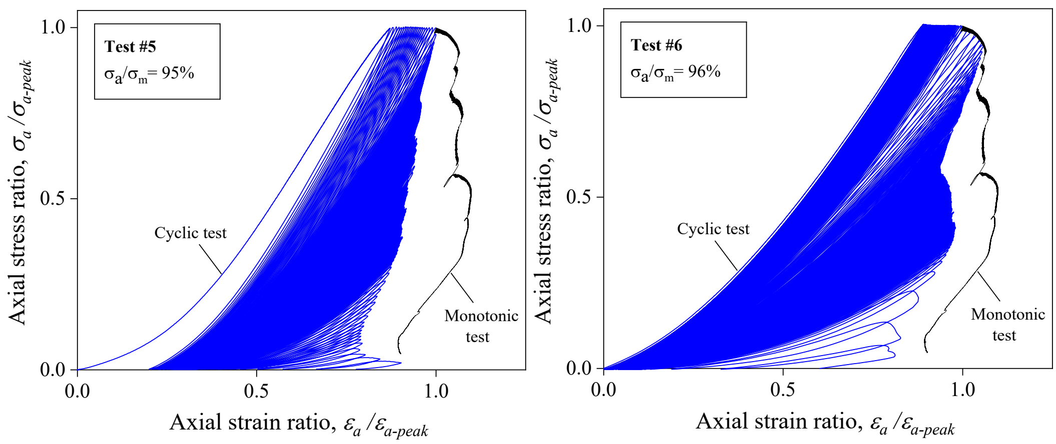


Figure 3. The normalized stress-strain results of the SLSCL (pre-peak and post-peak regimes) and monotonic loading tests (post-peak regime) for Gosford sandstone.

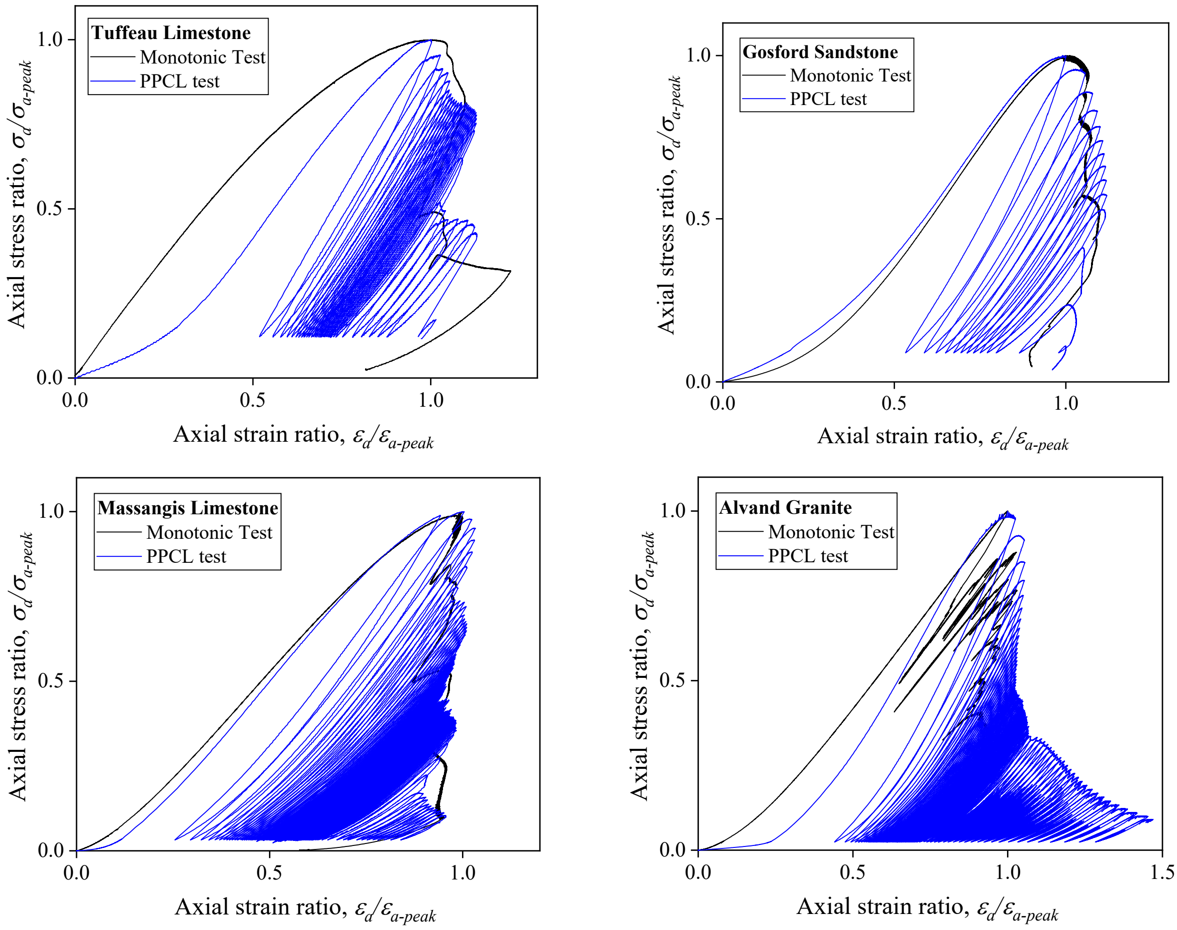


Figure 4. Normalized stress-strain curves of monotonic and cyclic loading tests for different rock types.

4.4 Post-Peak Cyclic Loading (PPCL)

The results of the undertaken PPCL tests and monotonic loading tests for Tuffeau limestone, Gosford sandstone, Massangis limestone, and Alvand Granite were plotted as normalized stress-strain curves in Figure 4. The figure shows that the post-peak cyclic loading (PPCL) history has a negligible effect on the failure response of soft to strong rocks, and similar to the monotonic loading tests, the post-failure behavior of cyclic tests can be characterized as a combined Class I-II behavior to different extents. Other researchers also reported similar results. For instance, Martin and Chandler (1994) and Yamashita et al. (1999) compared the stress-strain curves of the conventional monotonic loading tests with those obtained from the axial displacement-based and axial load-based damage-controlled cyclic loading tests for Lac du Bonnet granite (σ_{a-peak}> 200 MPa) and Kurihashi granite (σ_{a-peak}= 132 MPa), respectively. They found that the failure process and mechanism of fatigue loading and conventional monotonic loading are closely related to each other, and both loading conditions result in almost similar pre-peak and post-peak stress-strain relations.

5 CONCLUSIONS

In this study, the post-failure response of soft-to-strong rocks subjected to different loading histories, including monotonic loading (quasi-static loading), multi-level systematic cyclic loading (MLSCL), single-level systematic cyclic loading (SLSCL), and post-peak cyclic loading (PPCL), was investigated in uniaxial compression. Under quasi-static loading conditions, all rocks exhibited a combined Class I-II behavior to different extents in the post-peak regime, depending on the rock's brittleness. However, Class I (stable fracture propagation) and Class II (unstable fracture propagation) behaviors were more dominant for soft to medium rocks (e.g., Tuffeau limestone and Gosford sandstone) and strong rocks (e.g., Massangis limestone and Alvand granite), respectively. The results of the MLSCL tests on Tuffeau limestone specimens revealed that the post-failure instability of rocks slightly increases with increasing the number of cycles in the pre-peak regime (fatigue life), and the specimens reach a residual strength much lower than that in monotonic loading conditions. Also, according to the conducted SLSCL tests on Gosford sandstone at different stress levels, the increase in the applied stress level resulted in an increase in rock brittleness in a linear fashion, which was manifested by more self-sustaining behavior in the post-peak regime. On the other hand, PPCL history did not create further damage throughout the post-peak domain of different rock types, and almost similar post-peak stress-strain curves were identified for both PPCL and monotonic loading tests.

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