Kimachi sandstone does not have to fail under larger stress

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ABSTRACT: Series of uniaxial compression tests combining constant strain rate and four patterns of cyclic loading were carried out on Kimachi sandstone to clarify the timing of rock failure. It was found that rock failure timing was random in triangular, reverse triangular and small amplitude triangular loading tests and all rocks failed during larger strain in large amplitude triangular loading tests. The results suggest that rock specimens did not have to fail under larger strain when the stress amplitude was smaller than a certain value and gave us clues to explain why rocks do not always fail under larger stress. The mechanism behind the experimental results was explained based on strain rate-dependent rock strength and fatigue damage.

1 INTRODUCTION

It is instinctively expected that giant earthquakes occur around spring tide because the tidal stress variation around spring tide is the largest. Fujii et al. (2013) however found that there were dangerous lunar phases in which giant earthquakes concentrated for each subduction zone and the lunar phases did not have to be around spring tides. Another example is that rock cliffs do not always collapse during earthquakes while buildings always collapse. These phenomena demonstrate that rock masses do not have to fail under larger triggering forces.

To clarify the mechanism behind these phenomena, series of uniaxial compression tests were carried out on Kimachi sandstone. In the experiments, constant loading of 10^{-5} s^{-1} for 50 s and five triangular waves with different amplitudes for 50 s were alternatively applied to the specimens. This paper describes the results of the experiments and discusses the mechanism behind the results based on strain rate-dependent rock strength and fatigue damage.

Figure 1. Thin sectional image of Kimachi sandstone (Dassanayake, 2015).

2 EXPERIMENT

Kimachi sandstone was sampled at Shimane prefecture, Japan, and is a relatively well-sorted clastic rock with a typical grain size range of 0.4–1.0 mm (Fig. 1). It mostly consists of rock fragments of andesite; crystal fragments of plagioclase, pyroxene, hornblende, biotite, and quartz; calcium carbonate and iron oxides; and matrix zeolites (Dhakal et al., 2002). The 30 mm $\phi \times 60$ mm cylindrical specimens were made with a parallelism of 20 ìm at both ends through drilling, cutting and grinding. Then specimens were dried in an 80°C oven for 48 hours and kept at room temperature
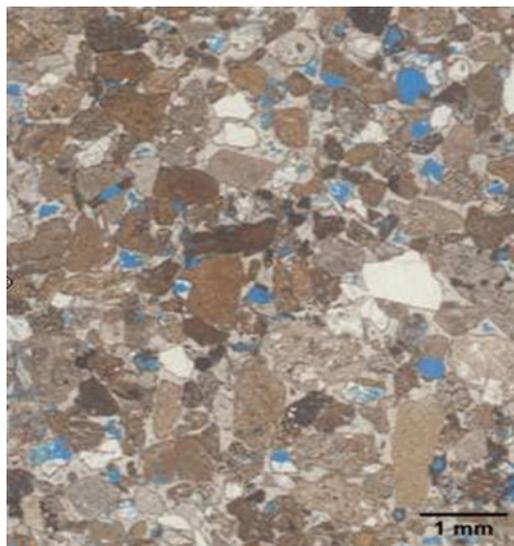
at least 5 days before the test. Specimens were alternatively subjected to constant loading rate of 10^{-5} s^{-1} for 50 s and five waves of triangular loading, reverse triangular loading, small amplitude triangular loading or large amplitude triangular loading (Fig. 2) for 50 s until failure. Experimental results (Figs. 4–7) were summarized based on rock failure timing. A sudden stress drop was considered to be rock failure. The explanation for failure timing including "constant loading" and "cyclic loading" is shown in Figure 3.

The probability *p* of the random null hypothesis which assumes that rock failure timing is random for
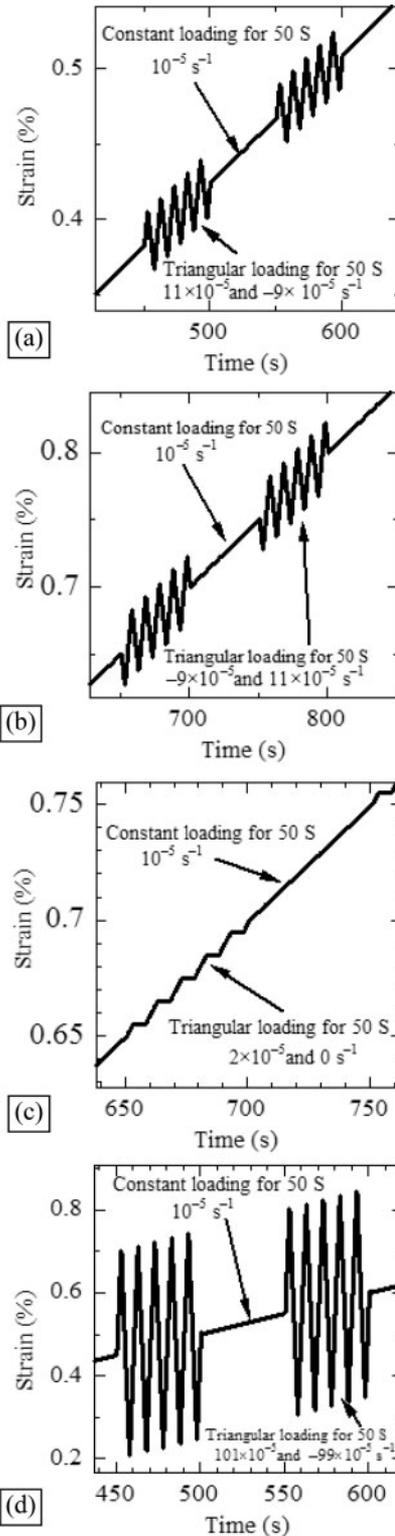
Figure 2. Four loading patterns. (a) Triangular loading, (b) Reverse triangular loading, (c) Small amplitude triangular loading and (d) Large amplitude triangular loading.
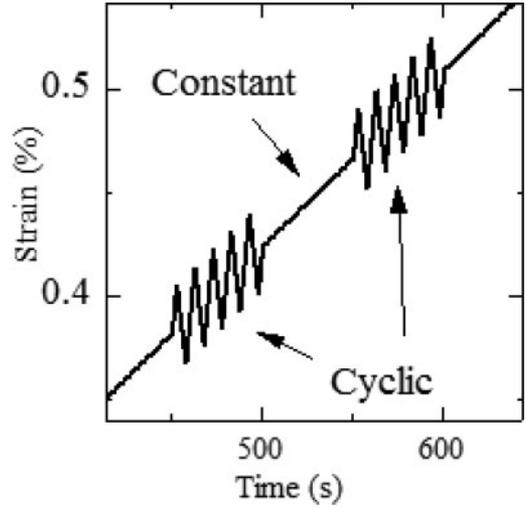

Figure 3. Explanation of "constant loading" and "cyclic loading".

Table 1. Summary of the results (p: the probability of the random null hypothesis to have m or more specimens failing during cyclic loading).

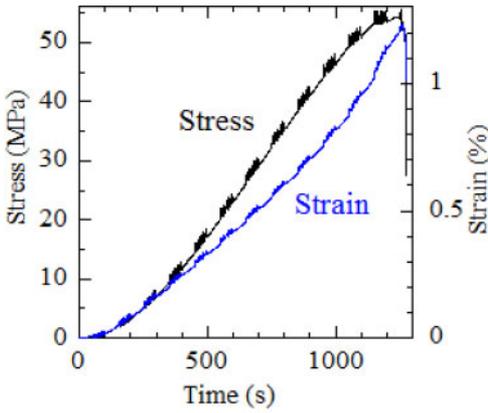| Loading pattern	Constant	Cyclic	p (%)
Triangular	10	8	76
Reverse	10	16	16
Large	0	5	3
Small	2	3	50

the case where m or more rock specimens fail during cyclic loading was calculated using the following equation.

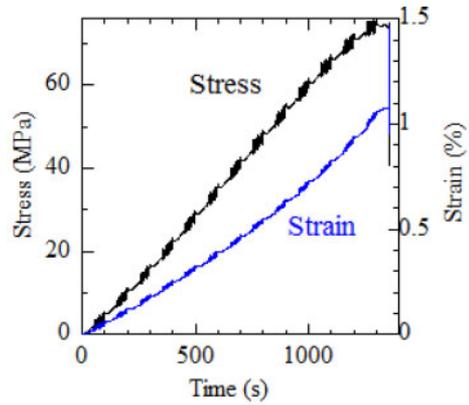$$p = \sum_{j=m}^{n} \{h^j (1-h)^{n-j} \times_n C_j\} \qquad (1)$$

where n = the total number of specimens; h = the probability that a rock specimen fails during cyclic loading (0.5); $_nC_j$ = the number of combination for the case where j specimens are selected from n specimens. Usually the random null hypothesis is rejected when p is smaller than 5%.

Results of rock failure timing and the probability p are shown in Table 1. For the triangular loading test, reverse triangular loading test and small amplitude triangular loading test, many rock specimens failed during constant rate loading. The probability is much larger than 5% and the rock failure timing is statistically considered to be random. These results correspond with the phenomena that rock cliffs do not have to fail during giant earthquakes and some giant earthquakes occur during neap tide other than spring tide.
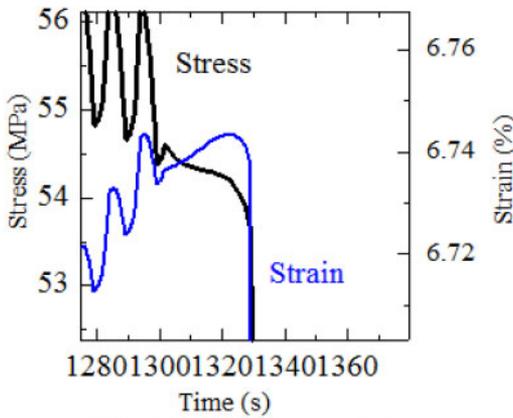
While in the large amplitude triangular loading test ($n = 5$ and $m = 5$), all rocks failed during larger strain
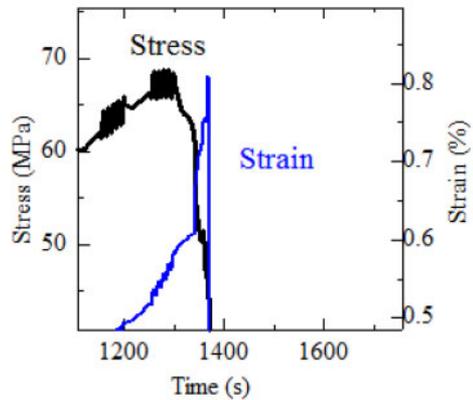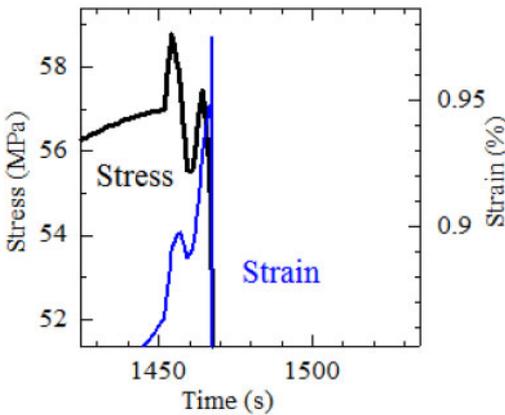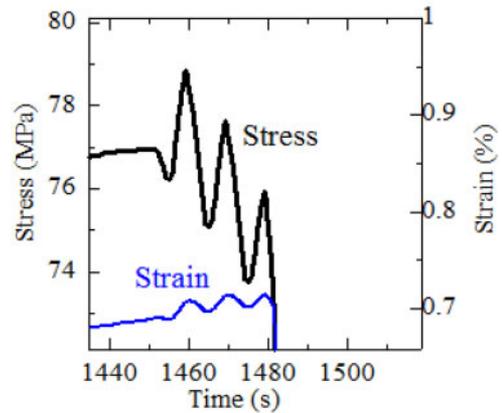
(a) Whole stress and strain.

(b) Rock failed during constant loading.

(c) Rock failed during cyclic loading.

Figure 4. Examples of triangular loading test.

(a) Whole stress and strain.

(b) Rock failed during constant loading.

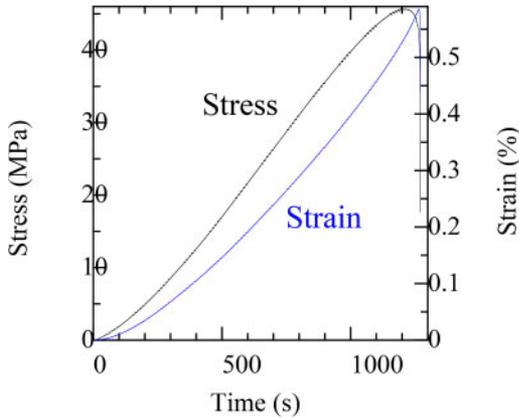(c) Rock failed during cyclic loading.

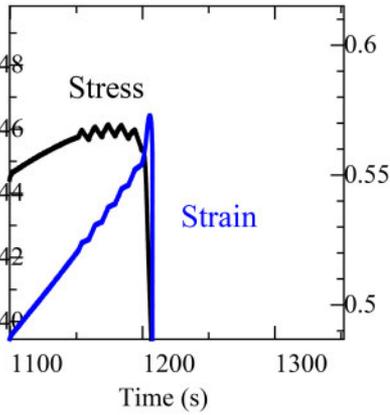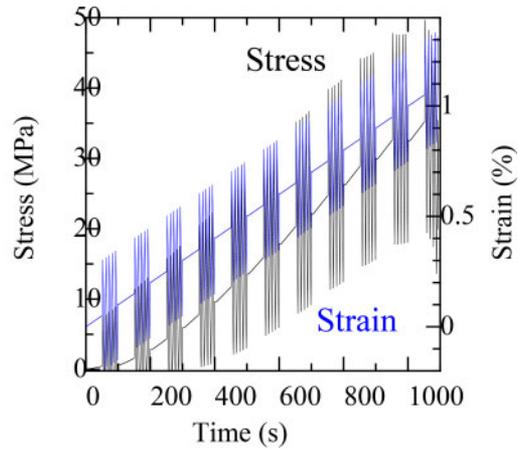Figure 5. Examples of reverse triangular loading test.

(Fig. 8). The probability p was smaller than 5% and the random null hypothesis was rejected. It can be statistically concluded that the specimens failed during larger strain under larger triangular loading.

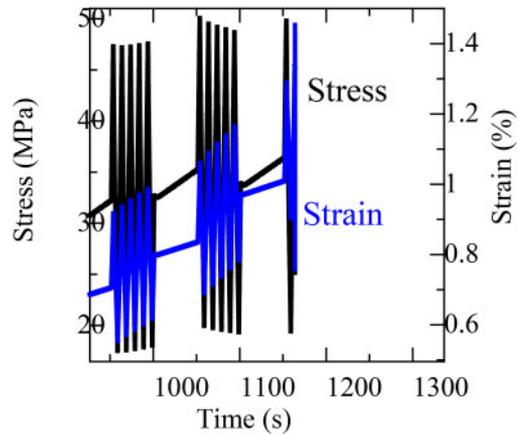## 3 MECHANISM OF THE DIFFERENCE IN FAILURE TIMING

According to Sano (1981), logarithm of rock strength σ_{max} increases linearly with logarithm of strain rate
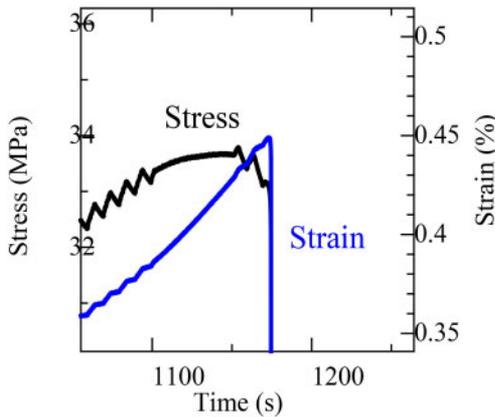
(a) Whole stress and strain.

(a) Whole stress and strain.

(b) Rock failed during constant loading.

(b) Rock failed during cyclic loading and larger strain.

Figure 7. Examples of large amplitude triangular loading test.

$\dot{\varepsilon}$ (Fig. 9) and their relationship can be expressed as Equation 2.

$$\sigma_{max} = A\dot{\varepsilon}^{\frac{1}{n+1}}$$ (2)

where A = constant; n = the stress corrosion index. The stress corrosion index n and constant A was evaluated as 63 and 44.8 MPa for Kimachi sandstone through the one specimen method proposed by Hashiba et al (2006). Substituting n, $\dot{\varepsilon}$ and A into Equation 2, theoretical strength increase due to the cyclic loading can be calculated.

For triangular and small amplitude triangular loading tests, actual stress increase (Fig. 11) is similar to theoretical strength increase (Fig. 10). Rock failures were therefore random. A significant difference in neither stress increase nor stress amplitude was

(c) Rock failed during cyclic loading.

Figure 6. Examples of small amplitude triangular loading test.

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Table 2. Average stress increase and average stress amplitude in the last cyclic loading before failure as value ± standard deviation (number of specimens).

Loading pattern	Stress increase (MPa)	Stress amplitude (MPa)
Triangular	1.39 ± 0.09 (18)	1.75 ± 0.37 (18)
Reverse	1.74 ± 0.16 (26)	2.43 ± 0.47 (26)
Large	14.09 ± 1.28 (5)	28.37 ± 3.23 (5)
Small	0.26 ± 0.04 (5)	0.36 ± 0.07 (5)

Figure 10. Theoretical strength increase and actual stress increase due to larger strain rate at the loading part of the cyclic loading. a: small amplitude triangular loading test, b: triangular loading test, c: reverse triangular loading test and d:large amplitude triangular loading test.
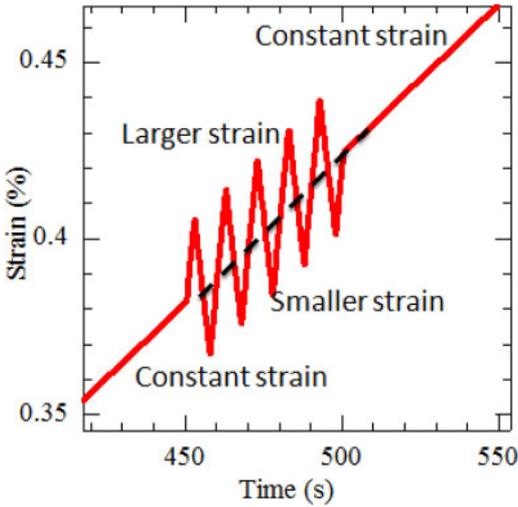

Figure 8. Explanation of "larger strain" and "smaller strain".
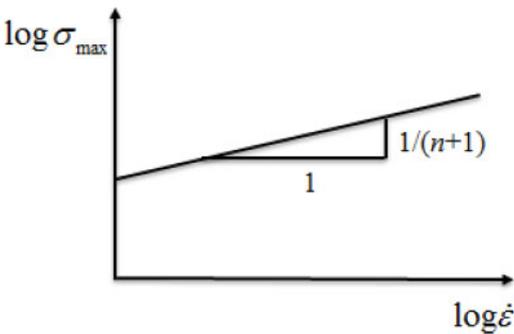
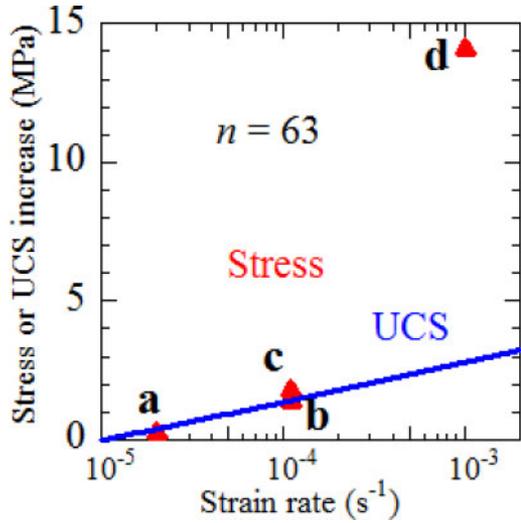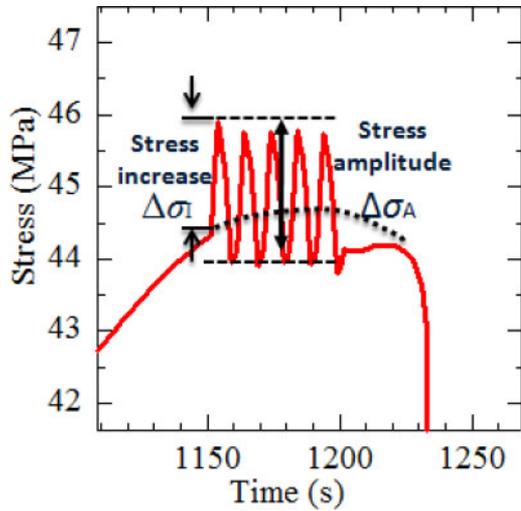

Figure 9. Relationship between rock strength σ_{max} and strain rate $\dot{\varepsilon}$

Figure 11. Stress increase $\Delta\sigma_I$ and stress amplitude $\Delta\sigma_A$.

found among specimens failing during constant rate and cyclic loading (Fig. 12).

Stress increase and stress amplitude in the reverse triangular loading tests were larger than those under triangular loading (Table 2 and Fig. 12). This would be one of the reasons why more rocks failed during cyclic loading in reverse triangular loading tests than triangular loading tests. Not only the larger stress but also

severer fatigue damage due to the larger stress amplitude in reverse triangular loading may facilitate rock failure during the cyclic loading. A significant difference in neither stress increase nor stress amplitude was found among specimens failing during constant rate and cyclic loading again (Fig. 12).

For the large amplitude triangular loading tests, actual stress increase is much larger than the theoretical strength increase (Fig. 9). It is natural that all specimens failed during larger strain (Fig. 8).
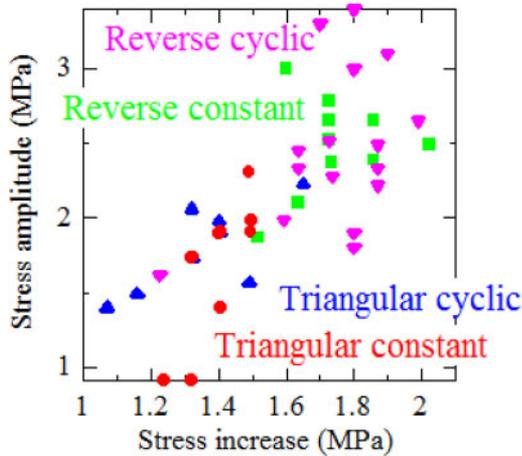
Figure 12. Stress increase and stress amplitude (Fig. 10) for the triangular and the reverse triangular loading tests.

4 CONCLUSIONS

Series of uniaxial compression tests combining constant strain rate and four patterns of cyclic loading were carried out on Kimachi sandstone to clarify the timing of rock failure. It was found that rock failure timing was random in triangular, reverse triangular and small amplitude triangular loading tests and all rocks failed during larger strain in large amplitude triangular loading tests. The results suggest that rock specimens did not have to fail under larger strain when the stress amplitude was smaller than a certain value and gave us clues to explain why rocks do not always fail under larger stress. The mechanism behind the experimental results was explained based on strain rate-dependent rock strength and fatigue damage. Examination should be carried out either on other rock types or under triaxial compression for the next step.

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