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The Effect Of Seismic-like Induced Cyclic Loading On Damage Response Of Sandstone And Granite

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Introduction

- Seismic activities induce a repeated loading–unloading stress on rock mass around mine pillars, roadway tunnels, slopes, and underground waste repositories. Therefore, rock materials are under a combination of static and cyclic stress states.
- The sources of seismic activities could be natural earthquakes, mining-induced seismic events, blasting, or transportation.
- Rock materials behave differently under loading–unloading cycles than under monotonic conditions, depending on the conditions of stress cycles.
- The maximum stress level, loading amplitude, and frequency of stress cycles are those loading conditions which greatly affect the strength response of rocks to cyclic loading.
- Despite all the efforts, there is no unified and agreed understanding of the effect of the cyclic loading conditions and difference in heterogeneity on the fatigue life and damage mechanisms of mineralogically and microstructurally different rocks.

Methodology

- Sandstone and granite/granodiorite rock samples were tested under uniaxial cyclic compression (Fig. 2).
- Tests conducted under different stress paths (next slide) with different loading amplitudes, frequencies and maximum stress levels (Fig. 1).

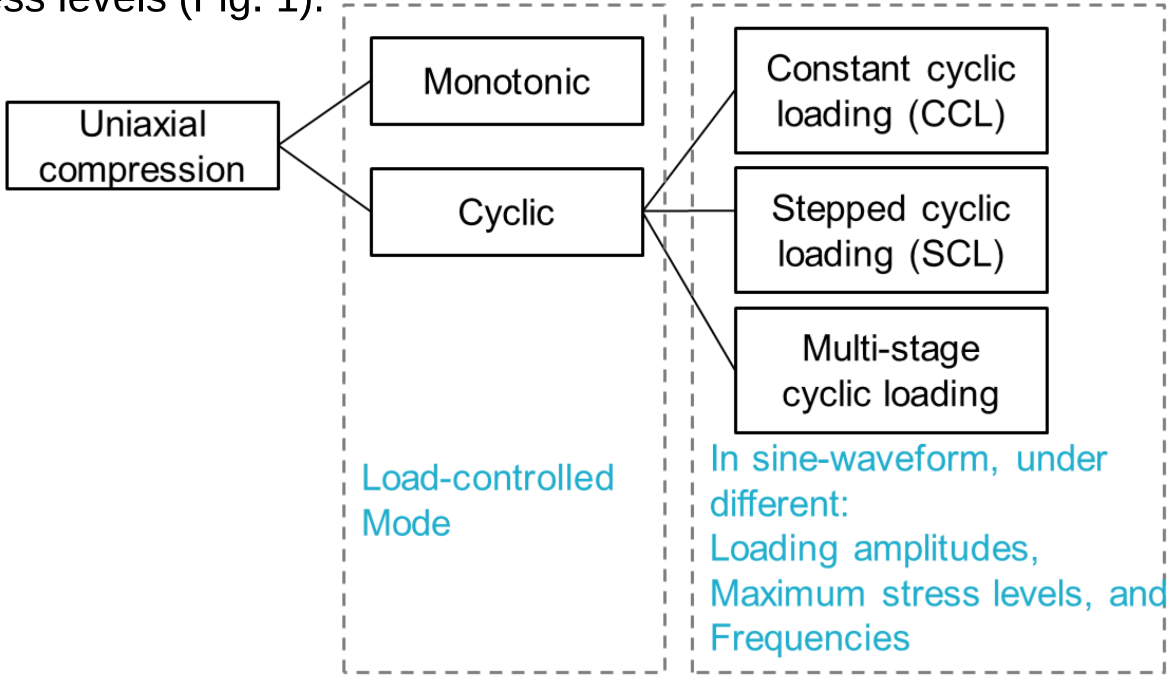
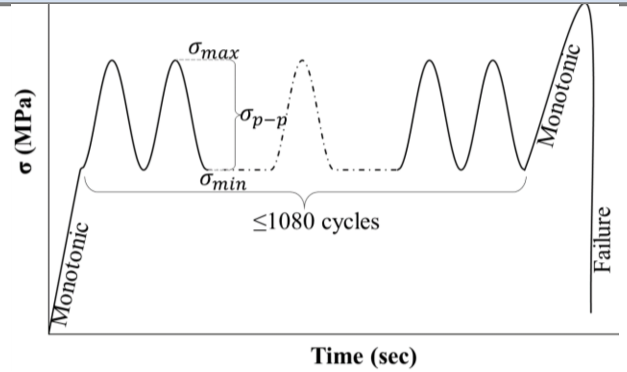


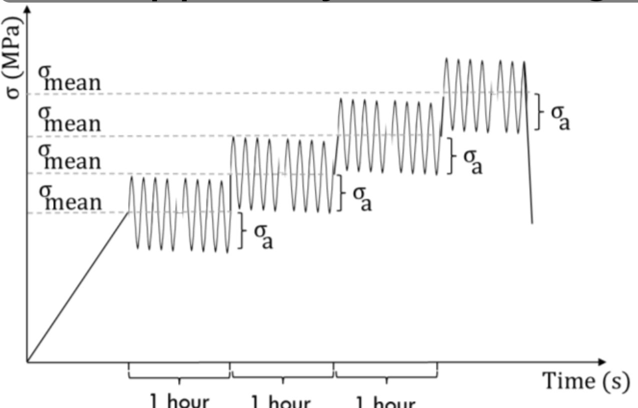
Fig 1. Testing methods implemented in this research

Methodology

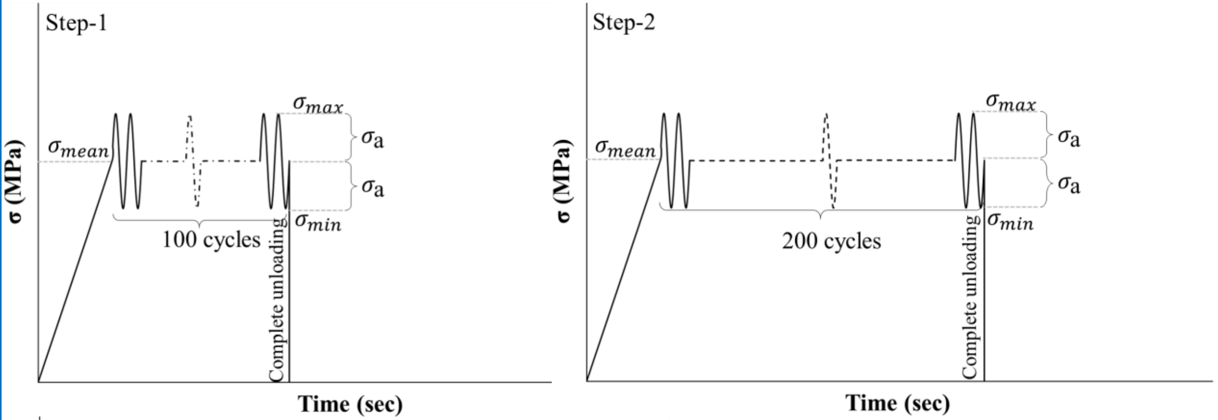
CCL



Stepped Cyclic loading



Multi-stage Cyclic loading



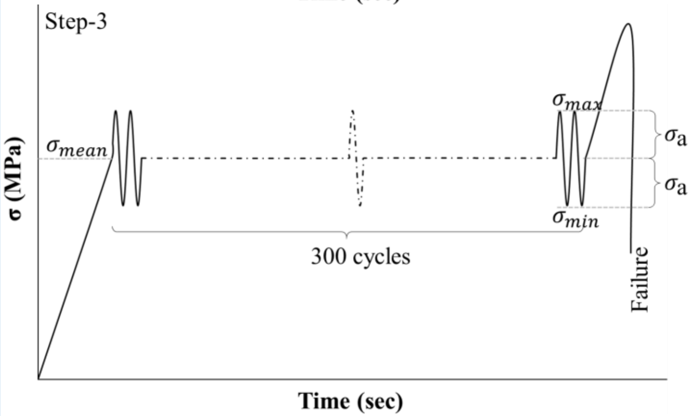


Fig 1. continued from previous slide

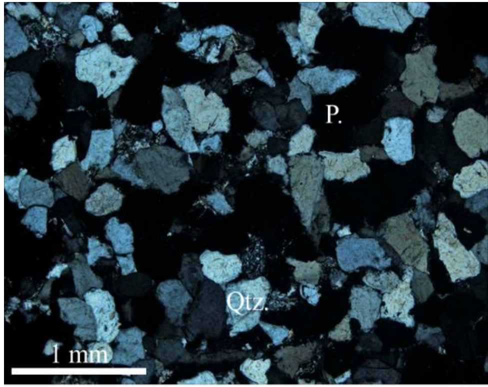
Rock samples

Fig 2. Rock samples tested throughout this study

Rock types

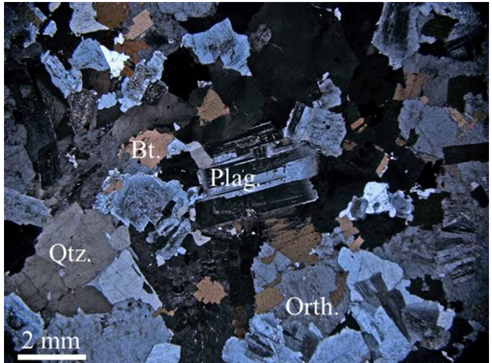
Sandstone

Representative of granular, soft, porous, or ductile rocks



Granite/ Granodiorite

Representative of crystalline, hard, compact, or brittle rocks



Results and discussion

The maximum stress level and fatigue life:

- Generally, all rock types sustain lower number of cycles (fatigue life) at higher maximum stress levels.
- The test results of this research incorporated with a large quantity of data from the literature showed lower fatigue strength threshold of crystalline rocks than that of granular rocks. The fatigue strength threshold is the stress level at which the rock can sustain infinite number of loading cycles without failure.
- This indicates a greater susceptibility of hard and crystalline rocks compared to the soft or granular rocks to cyclic loading.
- This is demonstrated by plotting the stress ratio of the maximum stress level of cyclic loading to monotonic peak strength ($\sigma_{max}/\sigma_{mon}$) against the number of cycles, termed as S–N plot (Fig. 3 and 4).
- Fatigue strength threshold ranges from 0.65 to 0.8 of monotonic peak strength for granite/granodiorite and 0.75 to 0.90 for sandstone.

Results and discussion

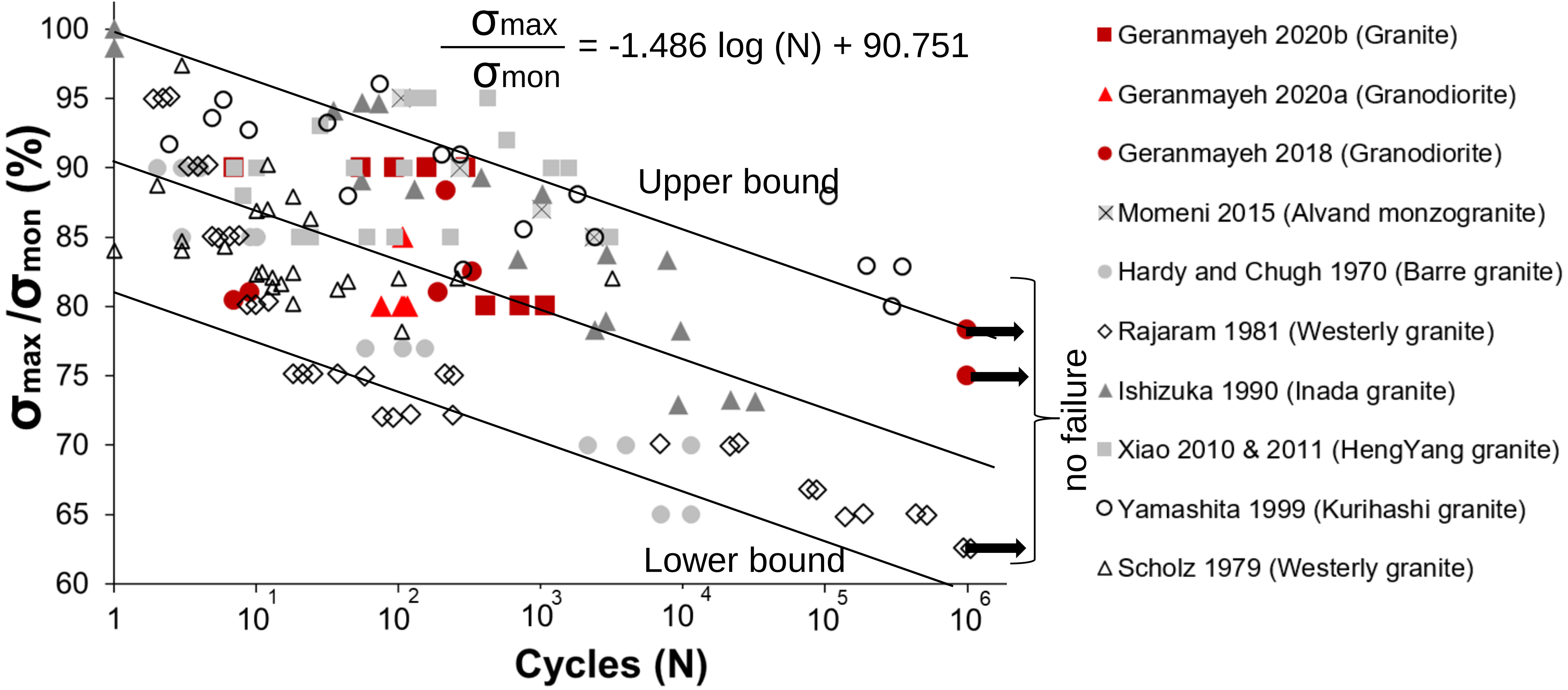


Fig 3. S–N curves for granite/granodiorite as a crystalline rock (modified after Geranmayeh Vaneghi et al. 2020a).

Results and discussion

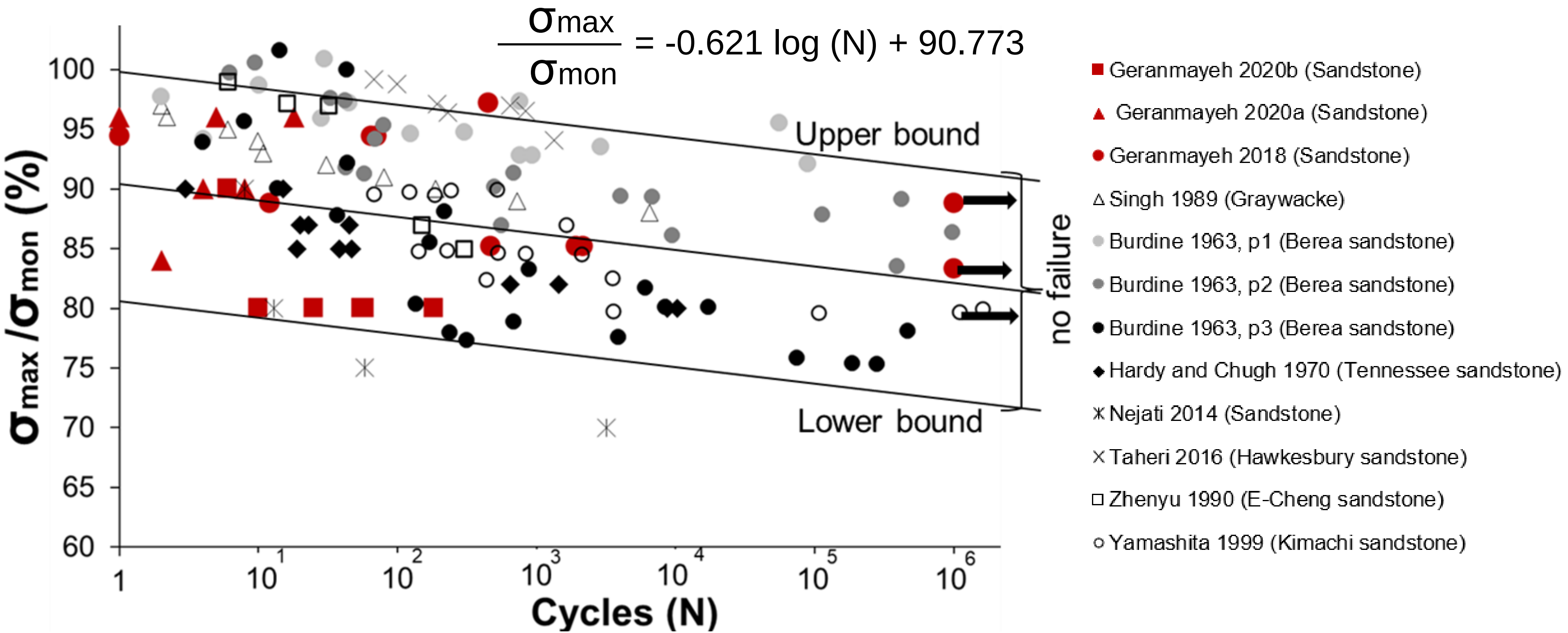


Fig 4. S–N curves for sandstone as a granular rock (modified after Geranmayeh Vaneghi et al. 2020a).

Results and discussion

The effect of loading amplitude:

- The results of this experimental study and data obtained from the literature show a decreasing trend of fatigue life with the loading amplitude, regardless of the test type and other loading conditions.

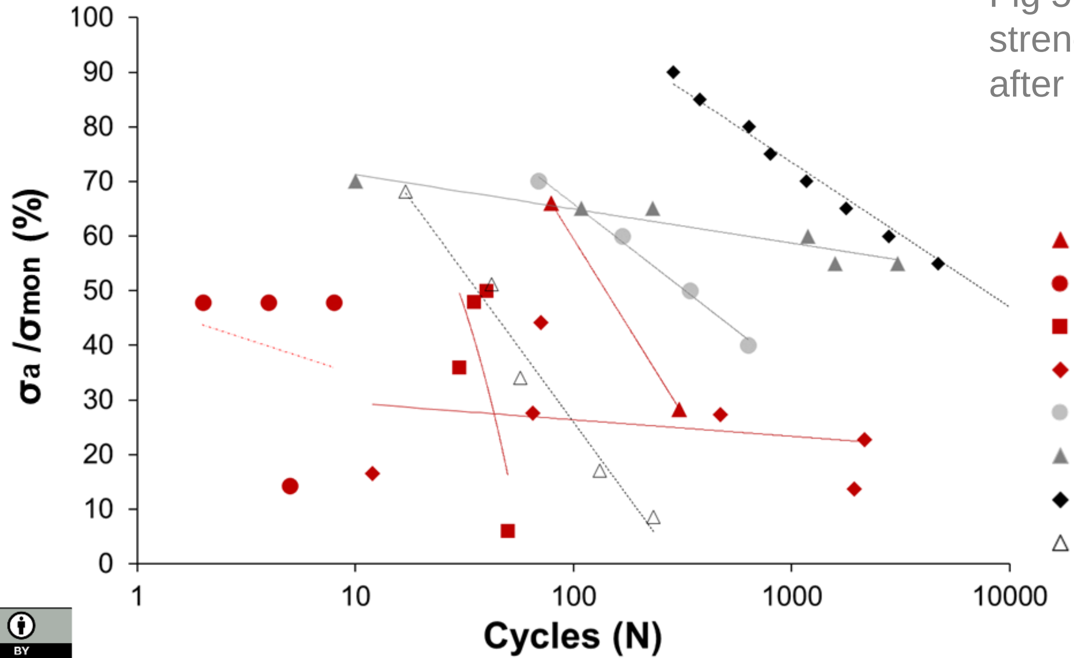


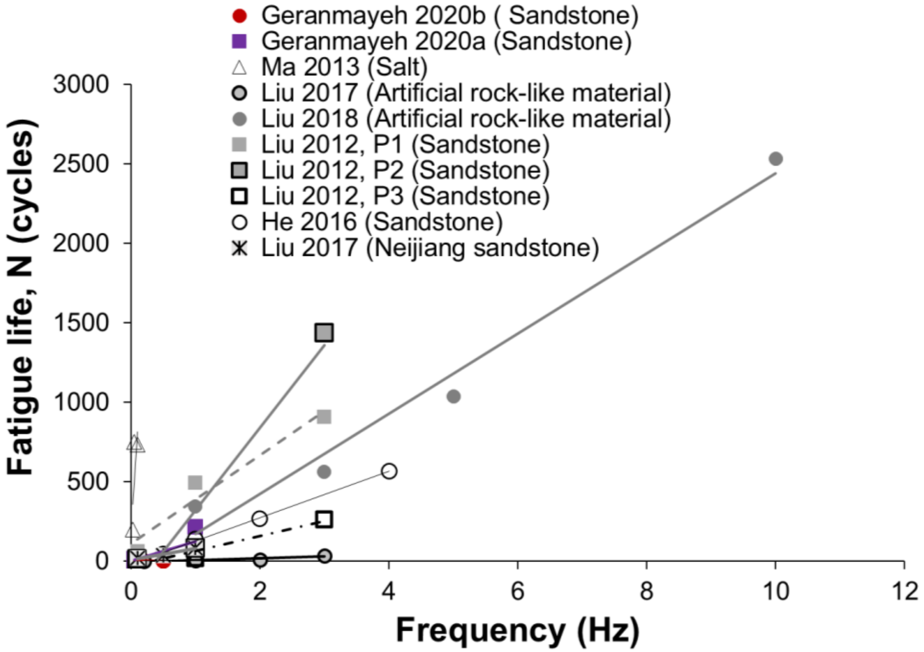
Fig 5. The ratio of stress amplitude to monotonic strength of sandstone and granite rocks (modified after Geranmayeh Vaneghi et al. 2020a).

Results and discussion

The effect of loading frequency:

- The experimental studies, so far, indicate an increasing trend of fatigue life with the loading frequency, regardless of the other cyclic loading conditions and test type. This is more evident at loading frequencies greater than 3 Hz (Fig. 6).
- Fig. 7 shows the data of fatigue life on a semi-logarithmic axis against the loading frequency. The fatigue life for granular rock of sandstone or rocks with similar strength and mineralogy shows a linear relation with the frequency. The fatigue life shows a power relation with frequency for crystalline rock of granite or rocks with similar strength and mineralogy.
- Low-frequency cyclic loading shows a larger damaging effect since both rock types sustained lower loading cycles at lower frequencies.
- The greater damaging effect of low loading frequencies is relatively more noticeable for hard / crystalline rocks, indicating the greater susceptibility of hard rocks to low-frequency cyclic loading.

Results and discussion



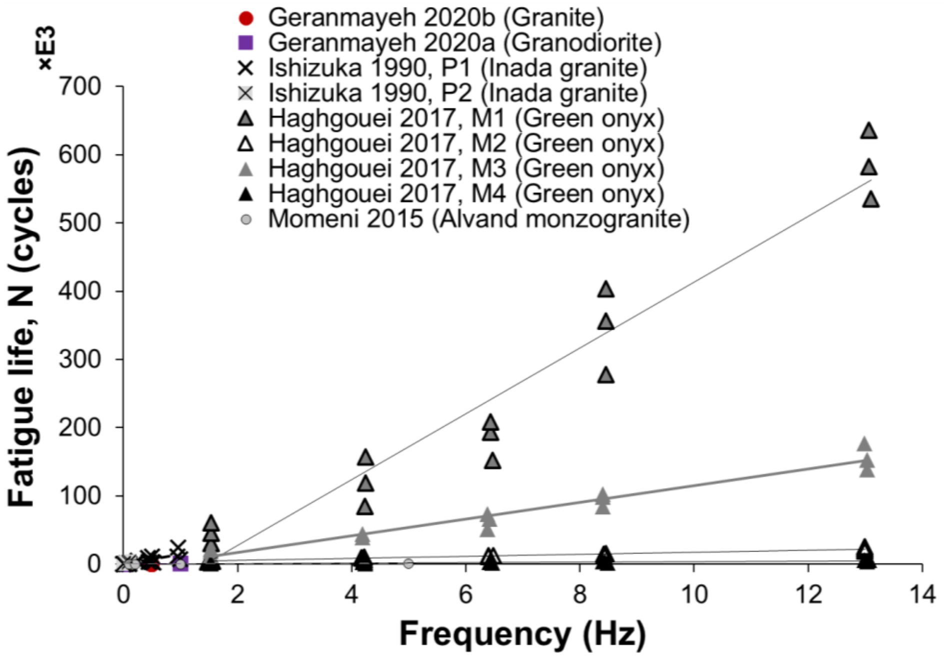
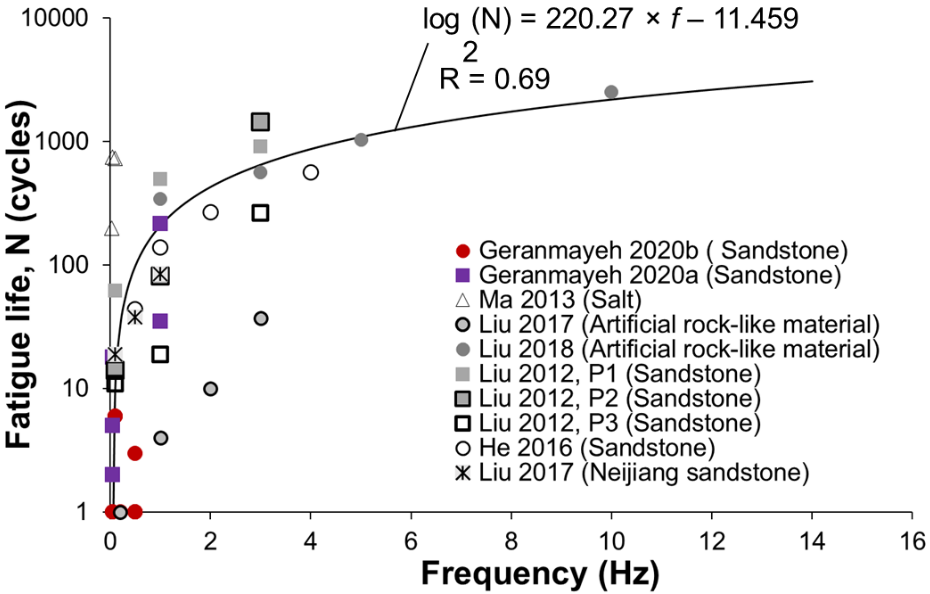


Fig 6. The general trend of fatigue life with loading frequency granular and relatively soft rocks like sandstone and crystalline and hard rocks like granite (reproduced from Geranmayeh et al. 2020b).

Results and discussion



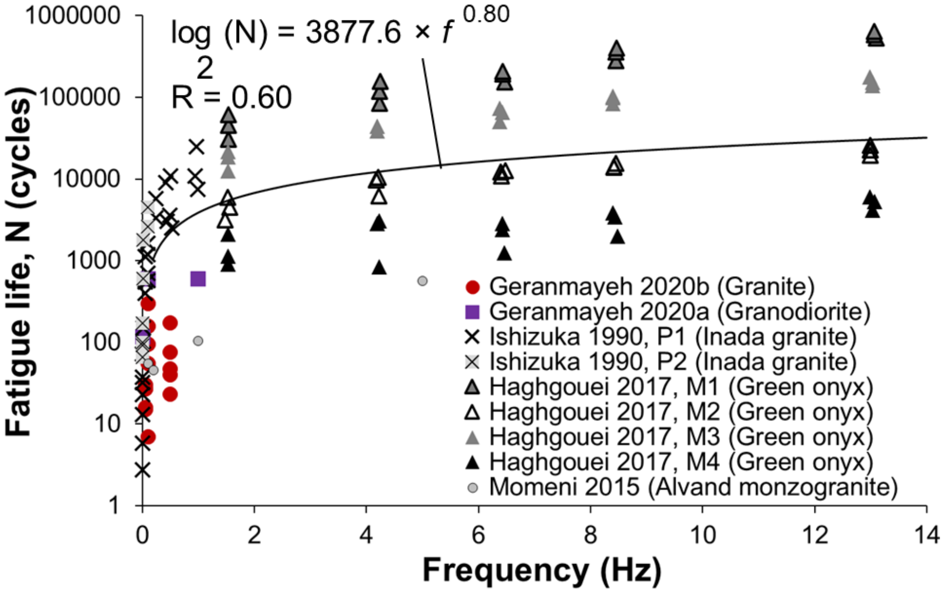


Fig 7. The general trend of fatigue life with loading frequency granular and relatively soft rocks like sandstone and crystalline and hard rocks like granite (reproduced from Geranmayeh Vaneghi et al. 2020b).

Results and discussion

Failure mechanisms:

- Rocks loaded under cyclic conditions fail at different modes compared to that of monotonic loading and more fragmentation and powdering of rock grains in failed surfaces was reported to be main indication of fatigue failure (Burdine 1963; Royer-Carfagni and Salvatore 2000; Liu et al. 2017).
- Mineralogy and microstructure play an important role in the failure modes of rocks; however, the cyclic loading conditions also greatly affect the failure modes which has not been well understood.

Fig 8. Examples of typical failure patterns for sandstone and granite/granodiorite samples after cyclic test

Results and discussion

Failure mechanism of Granite / Granodiorite :

- Fail with two shear fractures accompanied by tensile microcracks developed across these planes under monotonic loading. The failure mode under a higher loading frequency is similar to that of monotonic condition.
- Post-cyclic failure (if the failure does not occur during cyclic loading and test continues under monotonic condition approaching failure) is similar to that under monotonic condition but with more tensile fractures.
- The failure under cyclic conditions occurs along single shear plane accompanied by tensile bands (larger quantities of axial tensile microcracks compared to that under monotonic condition create narrow straps of fractured rocks).
- The greater opening and aperture of tensile microcracks (greater dilation and lateral expansion) ins the main indication of failure at higher loading amplitudes.
- Lower loading frequencies cause greater damage on rocks leading to a larger quantities of tensile bands with a greater aperture and length.

Results and discussion

Failure modes of granite / granodiorite

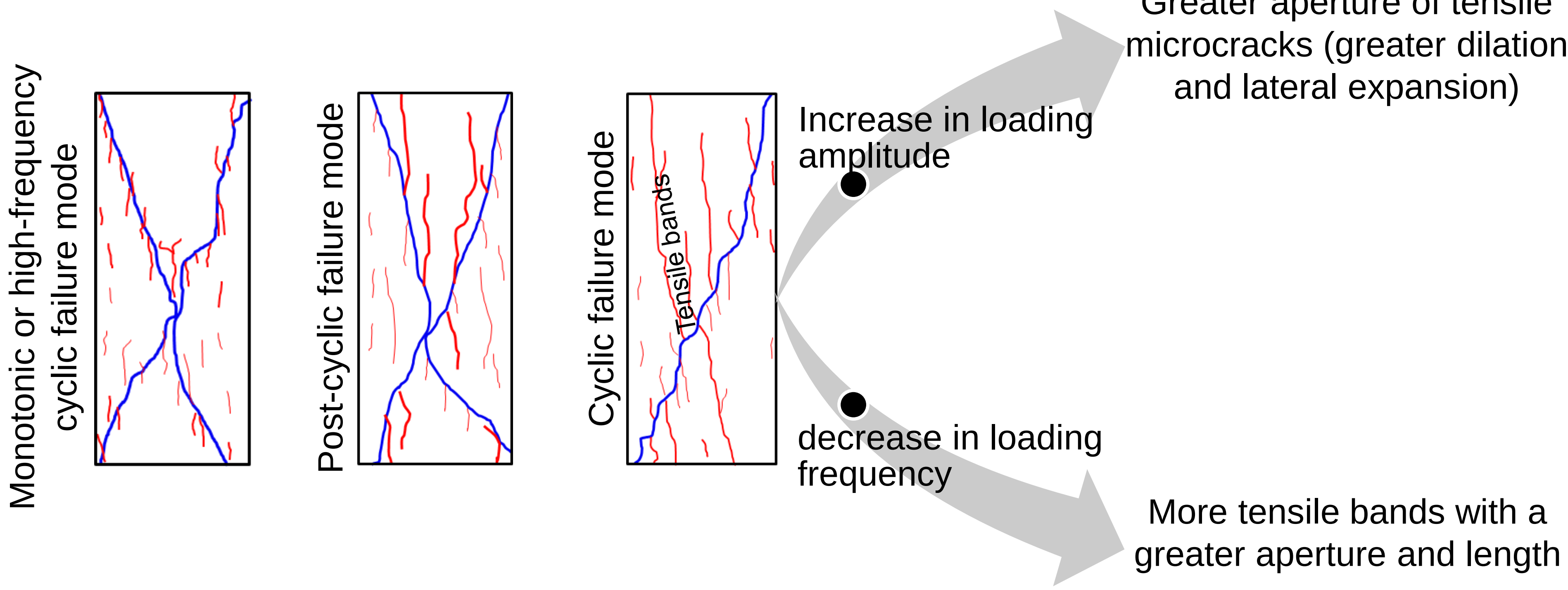


Fig 9. Failure modes of crystalline rocks like granite/granodiorite under uniaxial monotonic and cyclic compression tests; blue line represents shear fracturing and red line is the tensile cracking

Results and discussion

Failure mechanism of Sandstone samples:

- Fail along a single shear plane, accompanied by tensile splitting developed parallel to the loading direction and crossed the shearing plane under monotonic loading. The failure mode under a higher loading frequency and post-cyclic loading is similar to that of monotonic condition.
- While there is no distinguishable difference between failure modes of samples under different loading frequencies, more axial splitting and some premature shear cracks accompany the main shear plane at higher maximum stress levels and loading amplitudes.

Results and discussion

Failure modes of sandstone

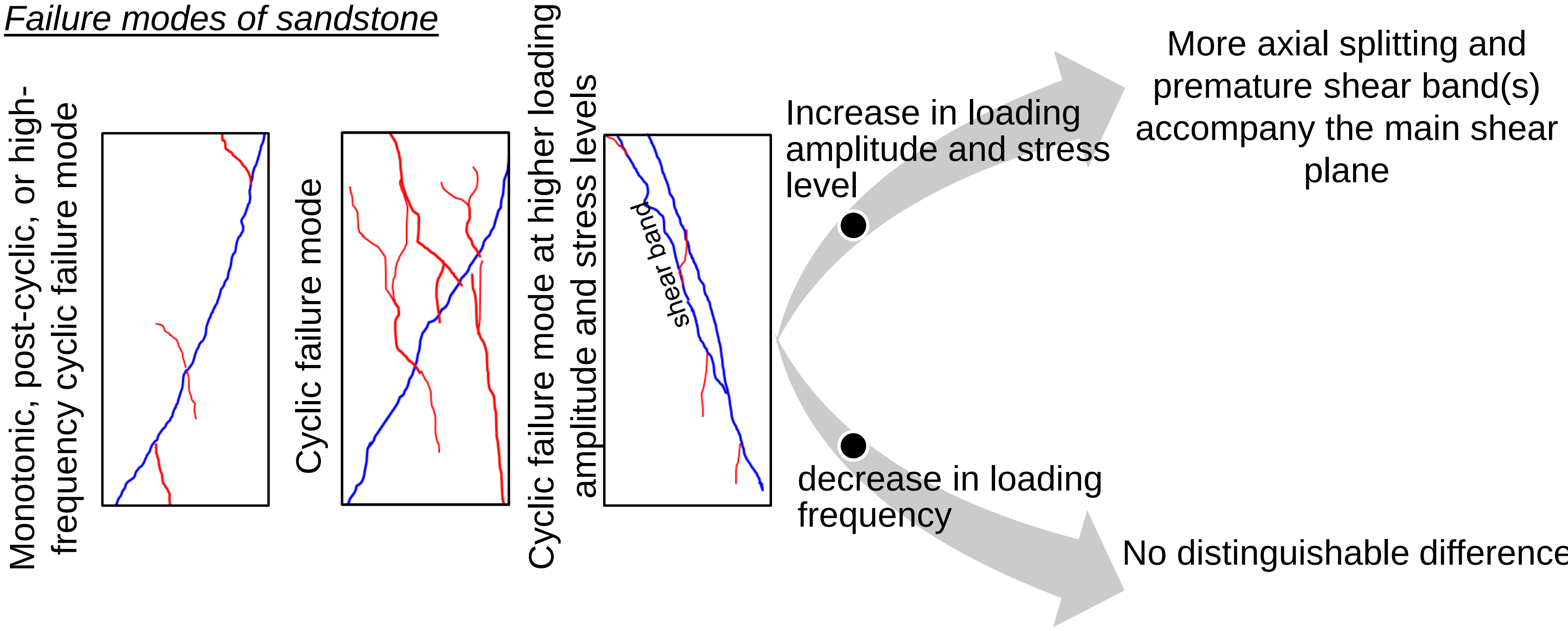


Fig 10. Failure modes of granular rocks like sandstone under uniaxial monotonic and cyclic compression tests; blue line represents shear fracturing and red line is the tensile cracking

Conclusions

- The fatigue strength threshold of hard or crystalline rocks is less than that of granular or soft rocks indicating the greater damage effect of cyclic loading to the crystalline / hard rocks.
- The results of this experimental research are consistent with the literature confirming that the higher loading amplitude has a diverse effect on the fatigue life of rocks.
- Both rocks show a greater susceptibility to the low-frequency cyclic loading. This is more evident for crystalline or hard rocks.
- The failure modes of rocks samples under cyclic loading conditions is greatly affected not only by the microstructure and mineralogy but also by the cyclic loading conditions. More tensile fractures is the main sign of fatigue failure. The higher the loading amplitude and stress level, the bigger extension and opening of tensile fractures which finally creates tensile bands crossing the shear plane in crystalline rocks and other shear bands merged with the main shearing plane in granular sandstone.

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Questions?

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