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Two-ways dynamic shear testing of rock discontinuities

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ABSTRACT: Dynamic shearing properties of rock discontinuities are of great importance in many rock engineering applications. Nevertheless, dynamic shear tests on rock discontinuities are very rare. In this study, the authors describe two-ways shearing experiments on various natural rock discontinuities and saw-cut planes. Natural rock discontinuities involve schistosity planes in quartzite, green-schist, cooling planes in andesite, saw-cut planes of Ryukyu limestone, Motobu limestone, andesite and basalt from Mt. Fuji, dolomite from Kita-Daitojima, grano-diorite from Ishigaki and Inada granite. Furthermore, these experimental results are compared with those from static and one-way dynamic shearing experiments and their implications in practice are discussed.

1 INTRODUCTION

Rock dynamics have become one of the most important topics in the field of rock mechanics and rock engineering. The spectrum of rock dynamics is very wide and includes the failure of rocks, rock masses and rock engineering structures such as rock bursting, spalling, popping, collapse, toppling, sliding, blasting, non-destructive testing, geophysical explorations, science and engineering of rocks and impacts of projectiles and meteorites.

Earthquake is an instability problem of Earth's crust and it should be regarded as a subject of rock mechanics. Earthquake is caused by the varying crustal stresses and it is a product of rock fracturing and/or slippage of major discontinuities such as faults and fracture zones. Therefore, the shear response of rock discontinuities has a direct relevance to the mechanism of earthquakes and their source characteristics, and their effect on rock engineering structures.

This study is concerned with two-ways (or bi-directional) dynamic shearing testing of rock discontinuities. However, some discussions are made how to consider the dynamic loading with a reference to actual conditions. Natural rock discontinuities involve schistosity planes in quartzite, green-schist, cooling planes in andesite, saw-cut planes of Ryukyu limestone, Motobu limestone, andesite and basalt from Mt. Fuji, dolomite from Kita-Daitojima, grano-diorite from Ishigaki and Inada granite. These experimental results are also compared with those from static experiments and their implications are discussed.

2 BACKGROUND OF DYNAMIC SHEAR TESTING

Dynamic shearing tests on rock discontinuities and interfaces are recognized as an important item of constitutive modeling of discontinuities and interfaces under dynamic conditions. When structures are constructed on/in rock masses having various kind geological discontinuities and possible ground motion estimations incorporating fault modeling, the determination of their dynamic shearing characteristics are necessary (Aydan 1989; Aydan and Ohta 2011). Furthermore, dynamic conditions may be particularly of great significance in relation to the long-term stability of the structures and during earthquakes as well as in the science of earthquakes due to rate dependency of strength characteristics.

There are very few experimental studies on the dynamic shearing response of rock discontinuities and interfaces in literature (Aydan et al. 1994, 1995, 1996, 2011, 2015, 2016; Celestino and Goodman 1979; Fox et al. 1998; Gillete et al. 1983; Huang et al. 2011; Iwata et al. 2016; Kana et al. 1991, 1996; Okada and Ito). Aydan et al. (2015)have recently shown that dynamic shearing even induces temperature rises along discontinuities and adjacent rock mass. The temperature rise depends on the dynamic shearing rate, normal stress and frictional properties of discontinuities as well as thermal properties of adjacent rocks. The increase of normal stress, dynamic shearing rate and frictional properties results in proportional increase of temperature. Therefore, the heating along discontinuities

would undoubtedly affect the shearing properties of discontinuities and it may also cause the degradation and softening of adjacent rocks.

Although the experimental studies on the rock discontinuities and interfaces are quite few, the dynamic shear testing procedure may be categorized into three classes(Aydan et al. 1994, 1995, 1996, 2011, 2015, 2016; Celestino and Goodman 1979; Fox et al. 1998; Gillete et al. 1983; Huang et al. 2011; Iwata et al. 2016; Kana et al. 1991, 1996) One-way (uni-directional) shearing; b) Two-ways (bi-directional) shearing; c) Shock wave shearing.

While most of dynamic shearing testing devices is limited to two-way (bi-directional) cycling shearing with a given cyclic shearing frequency and Yoshida et al. (2014) described two-way (bi-directional) shearing device capable of handling both cyclic shearing and arbitrary dynamic shearing loading. Dynamic shear loading pattern is based on the scaled wave forms obtained from the acceleration waves of some earthquakes.

Aydan et al. (2016) developed a shear testing machine to study the shear behaviour of rock discontinuities and interfaces under uniaxial conventional, creep and cyclic loading conditions. The device of Aydan et al. (1994) at University of the Ryukyus was modified to accommodate one-way (uni-directional) dynamic shearing on discontinuities and interfaces. They reported some experimental results on saw-cut discontinuities of limestone, marble and construction joints and interfaces in rockbolts/rockanchors.

In addition some experiments using shock / impact type loading is utilized for determining shear strength characteristics of rocks. Huang et al. (2011) suggested a punch shear device to measure the dynamic shear strength of brittle solids. In this method, a split Hopkinson pressure bar system (SHPB) is used to exert the dynamic load to a thin disc sample by punching. The sample holder also allows the punch head to load the sample directly and in combination with momentum-trap technique in SHPB. However, there is no such test on rock discontinuities and interfaces using a split Hopkinson pressure bar system (SHPB) yet.

3 DYNAMIC SHEAR LOADING

The most critical aspects of dynamic shear loading is how to select shear loading pattern, which is relevant to study actual behaviour of rock discontinuities and interfaces in nature. The cyclic loading patterns due to winds, machine vibrations may be directly related to observations on the induced dynamic loads. Figure 1 shows some example of cyclic shear tests on an interface and its effect of its cyclic shear strength. The direct shear cyclic testing

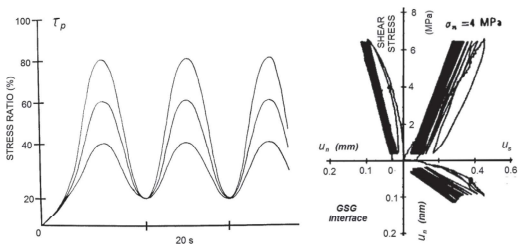

Figure 1. Cyclic shear behaviour of grout-sheath-grout interface in rockanchor systems (from Aydan et al. 1994).

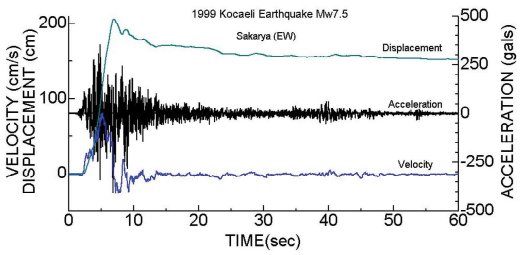

Figure 2. EW acceleration record at Sakarya station (DAD-ERD, 1999) by the 1999 Kocaeli earthquake and integrated velocity and displacement responses using the EPS method.

requires the input information on the anticipated cycle number, the upper and lower shear load levels, frequency or period of cycles and the initial duration to achive the maximum shear load at the start of testing. Once required conditions are input through the touch-panel, the machine can be activated to run a cyclic test. The system enables the users to have several graphic options to see the responses of shear load and shear displacement during testing.

Cyclic shear loads on samples are imposed in steps after a certain number of cycles with a given frequency (period) or linearly with a given frequency (period). Step-wise cyclic shear loading is also known as multi-stage cyclic shear testing.

However, the consideration of earthquakes on the shear loading of rock discontinuities is quite complicated if the actual conditions are taken into account. Direct dynamic shear testing is a relatively new field of experimental research and there are no well-established procedures yet. However, the shear loading procedures must be based on the strong motion records. Strong motions can be in the form of acceleration, velocity or displacement. Figures. 2 and 3 show the accelerations together with integrated velocity and displacement responses for 1999 Kocaeli earthquake and Iwate-Miyagi Intra-plate earthquake using the EPS method (Aydan and Ohta 2011; Aydan 2017).

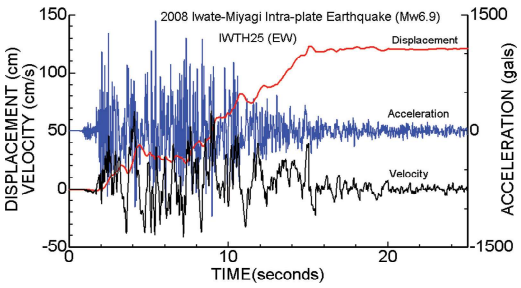

Figure 3. EW acceleration record at IWTH25 station (K-NET, 2008) by the 2008 Iwate-Miyagi earthquake and integrated velocity and displacement responses using the EPS method.

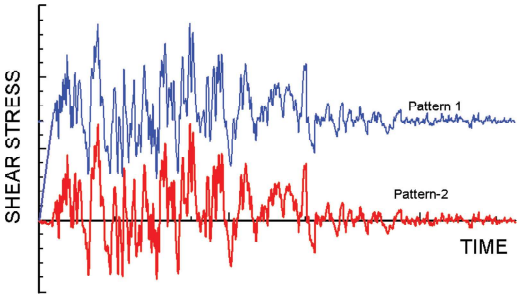

Figure 4. Possible shear loading patterns.

If the shear loading on rock discontinuities due to actual earthquakes is to be considered, the displacement response must be used. As noted from Figures. 2 and 3, the displacements are in the order of meters, none of shear testing device available in the field of rock mechanics and rock engineering can impose such displacement records on the samples. If the acceleration records as illustrated as Pattern 2 in Figure 4 are imposed, the asperities are expected to be sheared at first peak and the shear responses of the samples would be reduced to residual state. It seems that the shearing loading based velocity records might be a potential form for shear loading. The shear loading without reversed shearing would be appropriate in view of the machine capacity as well as the evaluation of linear and non-linear responses during shearing, which is denoted as Pattern 1.

Aydan et al. (2016)suggested a loading pattern illustrated in Figure 5 similar to Shear Loading Pattern 1 as the most appropriate loading pattern in view of actual conditions. However, in this study, two-way shearing on natural and saw discontinuities would be employed in order to see what to expect from Shear Loading Pattern 2.

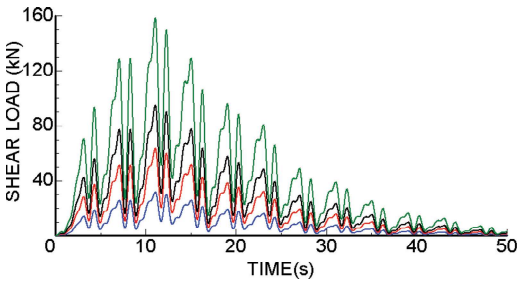

Figure 5. Adopted direct shear loading patterns.

Table 1. A list of discontinuities tested and their static friction angles.

Rock	Location	Type	ϕ (°)
Andesite	Mt. Fuji	Saw-cut	22.5–24.9
Andesite	Mt. Aso	Cooling	36.6–41.9
Basalt	Mt. Fuji	Saw-cut	22.0–23.0
Quartzite	Bayındır	Schistosity	33.0–39.3
Quartzite	Kumamoto	Schistosity	35.1–38.9
Diorite	Ishigaki	Saw-cut	28.8–33.4
Gabro	Unkown	Saw-cut-P	22.7–23.7
Limestone	Ryukyu	Saw-cut	27.8–29.6
Limestone	Motobu	Saw-cut	28.8–31.2
Dolomite	Kita-Daitojima	Saw-cut-P	17.3–22.0
Granite	Inada	Rough	32.9–36.3
Granite	Inada	Saw-cut	24.9–27.0
Granite	Salang	Saw-cut	37.2–43.2
Mortar	ISRM	Profile 0	30.1–33.0
Mortar	ISRM	Profile 2	35.7–35.9

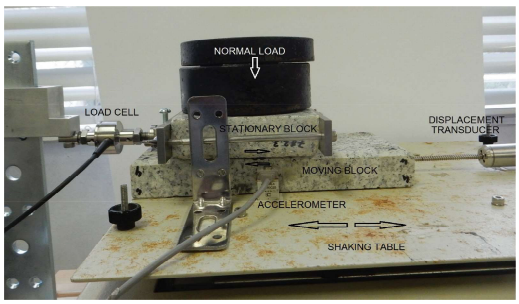

Figure 6. A view of two-ways dynamic testing set-up.

4 TWO-WAY DYNAMIC (BI-DIRECTIONAL) SHEAR TESTS

Discontinuities and their static friction angle determined from tilting test are listed in Table 1. Rocks involve igneous, metamorphic and sedimentary rocks. The discontinuities involve natural cooling joints, schistosity planes and saw-cut surfaces. Some of saw-cut surfaces are polished.

A special set-up of dynamic shear testing device has been developed as illustrated in Figure 6. This system is a modified version of the device used by Aydan et al. (2015). The applied normal load on the samples can be up to 4 kPa due to the horizontal load capacity of the shaking table. The shaking table has a stroke of 30mm and the maximum relative shear displacement can be up to 9 mm/s.

The dynamic shear testing device was equipped with shear load cell, contact type displacement transducer with a measuring range of 70mm and an accelerometer. monitoring system (WE7000) was used with a sampling interval of 1–10ms. Load, displacement and acceleration can be measured simultaneously. The lower block having a larger size than that of the upper block was fixed to the shaking table while the top block was fixed to a support following the application of the normal load as shown in Figure 6. The top block is stationary while the bottom block moves together with shaking table.

In some of experiments, acoustic emissions sensors are used to observe the dynamic shearing response of the sample. Aydan et al. (2015) also showed that dynamic shearing induces temperature variations in the close vicinity of discontinuity walls. An infra-red camera (Testo 990) was used to measure temperature variations during some of experiments.

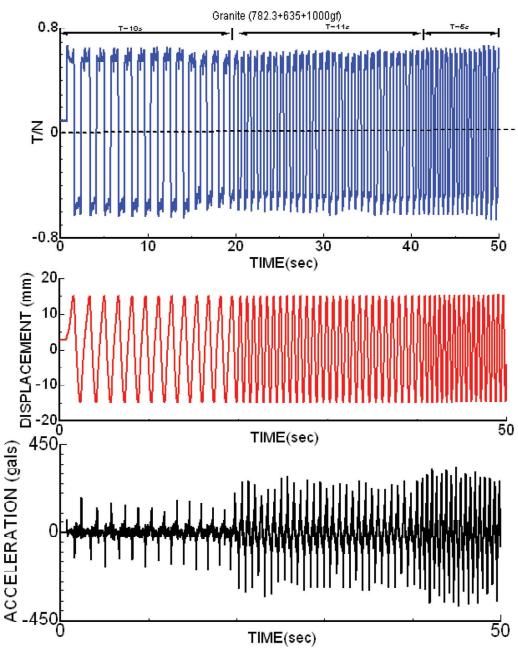

Figure 7. Dynamic shear load, relative displacement and acceleration responses of a rough saw-cut discontinuity in a Inada granite sample.

Figure 7 illustrates an example of experimental results on a rough saw-cut discontinuity plane in a Inada granite sample. As noted from the responses of shear load, relative displacement and acceleration, fairly consistent results are observed. One of important observation is that the softening occurs just after each yielding and the peak strength remains almost constant for a given frequency (or period). The peak and residual shear strength can be inferred from the experimental results. For example, the peak and residual friction angles are 33.6 and 26.6 degrees for results shown in Figure 7. However, the frequency dependency of shear strength is also noted from the plot of the shear load normalized by the normal load.. Another important observation is that the acceleration occur when the shearing stopped and reversed, while it is very small during sliding. This has important implications that the peak strength of discontinuities are influenced by the intrinsic shear resistance and inertia forces acting on the samples.

5 RESULTS

In this section, some of experimental results concerned the overall time-normalized shear resistance (T/N) are described. Furthermore, the variation of shear strength of discontinuities with respect to that at the first cycle of loading would be plotted a in the space of relative shear displacement and T/N and their implications would be discussed.

5.1 *Granite: rough Saw-cut plane*

As time-T/N relation is discussed in Figure 7, we plot the relative displacement-T/N relation as shown in Figure 8. In the same figure, the trajectory of the first cycle is distinguished. It is quite interesting to note that the shear resistance of the discontinuity plane gradually changes after each cycle of shearing. At the end of the experiment, a thin powder is recognized on the discontinuity plane as seen in Figure 9.

5.2 *Kumamoto Andesite (Mt. Aso): cooling joint*

Figure 10 shows the time-T/N response for a cooling plane in Kumamoto andesite. The cycle frequency was gradually increased as seen in the figure. As noted from the figure, shear resistance is not perfectly symmetric. In other words, some inertial effects are apparent in the measured responses.

The peak and residual friction angle in the first stage of dynamic loading are in the order of 40.0–43.3 and 30.5–33.8, respectively. Figure 11 compares

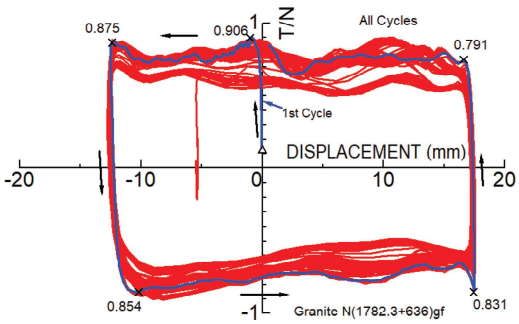

Figure 8. Shear response of a rough saw-cut discontinuity plane in Inada granite sample in the space of relative displacement and T/N.

Figure 9. A view of a sheared rough saw-cut discontinuity plane with a thin powder after testing.

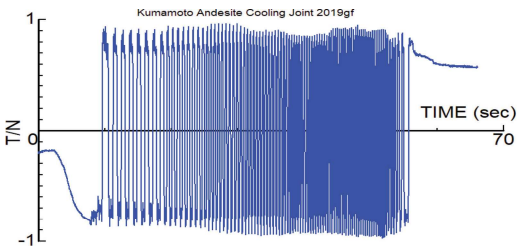

Figure 10. Dynamic shear load response of cooling joint in Kumamoto andesite.

the relative displacement—T/N response of the 1st cycle with other cycles. The response is always different for each cycle. Nevertheless, the overall behavior is close to what was observed in the 1st cycle. Another important feature is that the shear behavior of discontinuity plane for cooling joint is not symmetric. This is thought to be due to the anisotropy of surface morphology of the discontinuity plane (1996). Figure 12 shows the views of the sheared surfaces of Kumamoto andesite sample. As noted,

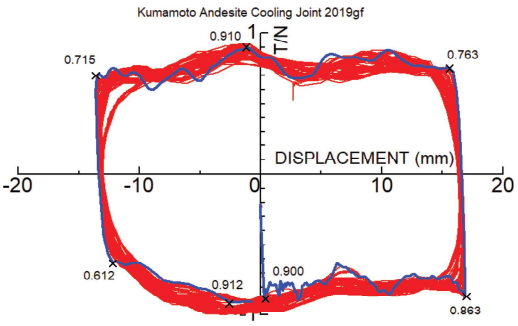

Figure 11. Shear response of a cooling joint in Kumamoto andesite sample in the space of relative displacement and T/N.

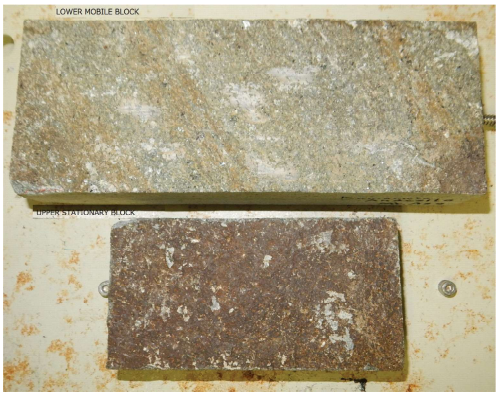

Figure 12. A view of a sheared cooling joint in Kumamoto andesite sample after testing.

there is no full contacts on the walls of the discontinuity plane, where thin powder is accumulated.

5.3 *Mt. Fuji Andesite: Saw-cut plane*

Figure 13 shows the time-T/N response for a saw-cut plane in Mt. Fuji andesite. The cycle frequency was gradually increased as seen in the figure. As noted from the figure, shear resistance is not perfectly symmetric. Furthermore, the shear resistance of the saw-cut plane increases cycle number increases. Initially the smooth surface of the saw-cut plane gradually scratched and the scratching on the saw-cut plane increases the apparent shear resistance of the discontinuity plane.

5.4 *Gabro: polished Saw-cut plane*

Next the dynamic shear behaviour of polished saw-cut plane in Gabro sample is investigated.

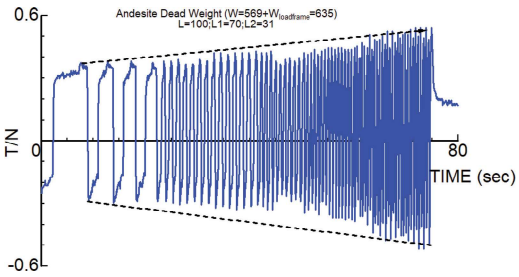

Figure 13. Time-T/N response of a saw-cut plane in Mt. Fuji Andesite.

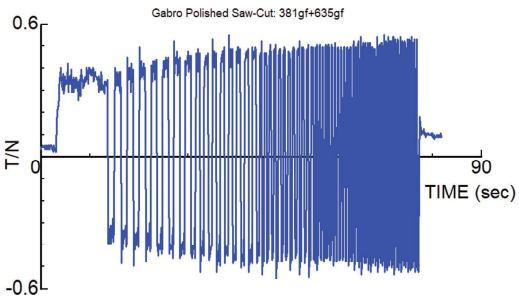

Figure 14. Time-T/N response of a polished saw-cut plane in Gabro sample.

Figure 14 shows the time-T/N response for a polished saw-cut plane in Gabro sample. The cycle frequency was gradually increased as seen in the figure. As noted from the figure, shear resistance gradually increases as a function of cycle number. While the initial yielding friction angle is about 23.7 degrees, the peak friction angle increased up to 28.6 degrees. In other words, scratching on the polished surface due to hardness difference of minerals constituting discontinuity walls results in the increase of polished plane. In other words, the polished surface would not be the representative friction angle of planar discontinuities (Aydan et l. 2016). The trajectories of shear resistance shown in Figure 15 clearly confirms this statement. When the response at the first cycle is compared with those at following cycles, the shear strength of the plane increases. In other words, the yielding surface dilates as the cycle number increases.

5.5 *Bayındır quartzite: schistosity plane*

The dynamic shear behavior of schistosity plane in Bayındır quartzite sample as a natural discontinuity plane is investigated. Figure 16 shows the time-T/N response for a schistosity plane. The cycle frequency was gradually increased as seen in the figure after the first cycle with a period of 15 seconds. As noted from the figure, shear resistance gradually increases as a function of cycle number. While the initial yielding friction angle is about 24.9 degrees, the peak friction angle was increased up to 39.5 degrees. In other words, scratching on the schistosity plane due to quartzite mineral results in the increase of friction angle. The trajectories of shear resistance shown in Figure 17 clearly confirms this

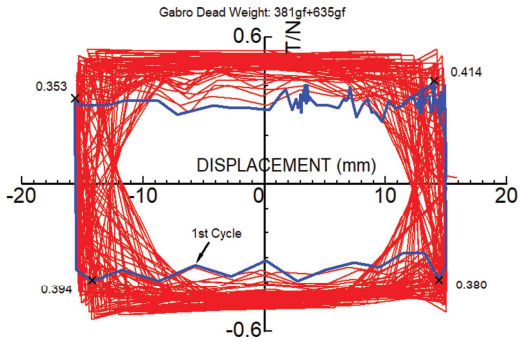

Figure 15. Shear response of a polished saw-cut plane in Gabro sample in the space of relative displacement and T/N.

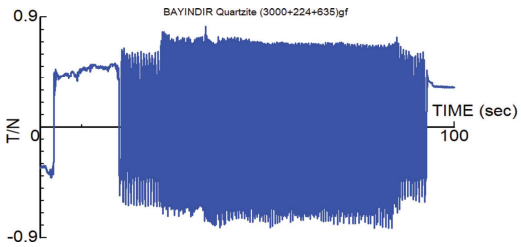

Figure 16. Time-T/N response of a schistosity plane in Bayındır quartzite sample.

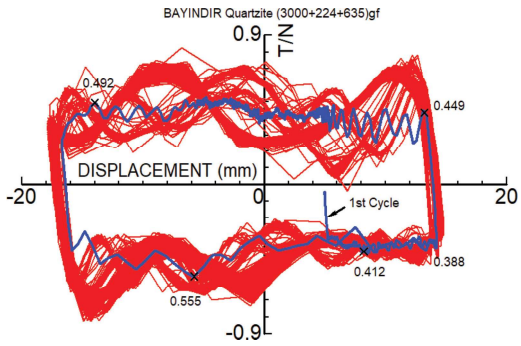

Figure 17. Shear response of schistosity plane in Bayındır quartzite sample in the space of relative displacement and T/N.

statement. However, responses in post-peak stages are quite wavy. When the response at the first cycle is compared with those at the following cycles, the post-yielding strength may be quite smaller than that at the initial cycle in some circumstances.

6 CONCLUSIONS

The authors presented the results of two-ways (bi-directional) dynamic shear tests on natural, saw-cut and artificial discontinuities. The experiments clearly showed that the dynamic shear behavior of discontinuities are very complex and anisotropic. Furthermore, the degradation of roughness of the discontinuity planes results in further complexity in regard with modeling shear behavior under dynamic conditions. Nevertheless, the dynamic response at the first full cycle provides a basis for the overall dynamic shear behavior of discontinuities. and interfaces. Unpolished saw-cut planes of rocks should be used for evaluating their shear responses under dynamic conditions in first step. Then, the dynamic shear behavior of actual discontinuities should be carried out as the next step. As discussed in the introduction, more discussions and experiments are necessary for the selection of appropriate dynamic loading pattern with the consideration possible loading conditions in-situ.

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