TWO-WAYS (BI-DIRECTIONAL) DYNAMIC SHEAR TESTING OF ROCK DISCONTINUITIES

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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.

Key Words : Rock discontinuity, interface, one-way, two-ways, bi-directional, dynamic shear test

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 Earthøs 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. In addition, dynamic tests on mortar samples having discontinuities with ISRM profiles No.0 and No.2¹⁾ are performed. 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^{1,2)}. 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 literature⁴⁻¹⁹. Aydan et al.⁶ 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 classes⁴⁻¹⁹ 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 twoway (bi-directional) cycling shearing with a given cyclic shearing frequency ^{9-11, 15-17} and Yoshida et al. ¹⁷⁻²⁰ described two-way (bidirectional) 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.⁶⁾ develpoed 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.⁴⁾ at University of the Ryukyus was modified to accommodate one-way (uni-directional) dynamic shearing on discontinuities and interfaces²). 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.²⁰⁾ 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 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.



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

However, the consideration of earthquakes on the shear loading of rock discontinuties 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 ²¹⁻²⁴.

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 nonlinear responses during shearing, which is denoted as Pattern 1. Avdan et al.²⁾ suggested a loading pattern illustrated in Figure 5 similar to Shear ILoading 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 2. EW acceleration record at Sakarya station (DAD-ERD, 1999²⁵) by the 1999 Kocaeli earthquake and integrated velocity and displacement responses using the EPS method.







Figure 4. Possible shear loading patterns.



Figure 5. Adopted direct shear loading patterns. 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. In addition, some experiments are carried out on mortar samples having artifical discontinuities with surface profiles Numbered 0 and 1 in the SM of ISRM¹⁾. The discontinuities involve natural cooling joints, schistosity planes and saw-cut surfaces. Some of saw-cut surfaces are polished.

Rock	Location	Туре	Unit Weight	Friction
			(kN/m ³)	Angle (°)
Andesite	Mt. Fuji	Saw-cut	26.1	22.5-24.9
Andesite	Mt. Aso	Cooling	26.6	36.6-41.9
Basalt	Mt. Fuji	Saw-cut	24.1	22.0-23.0
Quartzite	Bay,nd,r	Schistosity	25.1	33.0-39.3
Quartzite	Kumamoto	Schistosity	27.7	35.1-38.9
Diorite	Ishigaki	Saw-cut	26.5	28.8-33.4
Gabro	Unkown	Saw-cut-P	29.8	22.7-23.7
Limestone	Ryukyu	Saw-cut	22.9	27.8-29.6
Limestone	Motobu	Saw-cut	25.3	28.8-31.2
Dolomite	Kita-Daitojima	Saw-cut-P	26.2	17.3-22.0
Granite	Inada	Rough	25.3	32.9-36.3
Granite	Inada	Saw-cut	25.3	24.9-27.0
Granite	Salang	Saw-cut	25.9	37.2-43.2
Mortar	ISRM	Profile 0	20.0	30.1-33.0
Mortar	ISRM	Profile 2	20.0	35.7-35.9

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

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.⁴⁾. 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 displacemenet 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.



Figure 6. A view of two-ways (bi-directional) dynamic testing set-up

In some of experiments, acoustic emissons sensors are used to observe the dynamic shearing response of the sample. Aydan et al.⁶⁾ 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 varions during some of experiments.

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.



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

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 theyir 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 disguished. 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.



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 discontnuity plane with a thin powder after testing.



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

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 the relative displacement - T/N response of the 1st cycle with other cycles. The response is always different for each cycle. Nevertheless, the overall behaviour is close to what was observed in the 1st cycle. Another important feature is that the shear behaviour of disocntinuity plane for cooling joint is not symmetric.

This is thought to be due to the anistotropy of surface morhology of the discontinuity plane²⁷⁾ Figure 12 shows the views of the sheared surfaces of Kumamoto andesite sample. As noted, there is no full contacts on the walls of the discontinuity plane, where thin powder is accumulated.



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

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.



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

5.4 Gabro: Polished Saw-cut Plane

Next the dynamic shear behaviour of polished saw-cut plane in

Gabro sample is investigated. 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 be the representation friction angle of planar discontinuities²⁰. 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.



Figure 14. Time-T/N response of a polishd saw-cut plane in Gabro sample Gabro Dead Weight: 381gf+835gf



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 Bay,nd,r quartzite sample

5.5 Bayındır Quartzite: Schistosity Plane

The dynamic shear behaviour of schistosity plane in Bay,nd,r 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 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 can be quite smaller than that at the initial cycle.



Figure 17. Shear response of schistosity plane in Bay,nd,r quartzite sample in the space of relative displacement and T/N.

5.6 Mortar Sample with ISRM Profile of No.2

The final example of two-ways shearing of artificial discontinuity plane in a mortar sample having a surface profile of No.2 in ISRM SM is decsribed. Figure 18 shows the time-T/N response for the discontinuity while the figure 19 compares the relative displacement -T/N response of the 1st cycle with other cycles. The response is always different for each cycle. Furthermore, the shear response is closely influenced by the surface roughness and it is entirely anisotropic²⁷⁾. In other words, the shear behaviour of discontinuity plane does not yield a single dynamic shear resistance.



Figure 18. Time-T/N response of a discontinuity with a ISRM No. 2 profile.



Figure 19. Shear response of a discontinuity with a ISRM No. 2 profile.

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 behaviour of discontinuities are very complex and anisotropic . Furthermore, the degradation of roughness of the discontinuity planes results in further complexity in regard with modelling shear behaviour under dynamic conditions. Nevertheless, the dynamic response at the first full cycle provides a basis for the overall dynamic shear behaviour 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 behaviour of actual discontinuities should be carried out as the next step. As discussed in the introduction, more discussions and experiments are necessay for the selection of appropriate dynamic loading pattern with the consideration possible loading conditions in-situ.

REFERENCES

- 1) Brown, T. (1983). ISRM Suggested Methods (1974-1983), Pergamon Press.
- Aydan, Ö., N. Tokashiki, J. Tomiyama, N. Iwata, K. Adachi, Y. Takahashi (2016). The Development of A Servo-control Testing Machine for Dynamic Shear Testing of Rock Discontinuities and Soft Rocks, EUROCK2016, Ürgüp, 791-796.
- Iwata, N., K. Adachi, Y. Takahashi, Ö. Aydan, N. Tokashiki, F. Miura (2016). Fault rupture simulation of the 2014 Kamishiro Fault Nagano Prefecture Earthquake using 2D and 3D-FEM. EUROCK2016, Ürgüp, 803-808.
- 4) Aydan, Ö., T. Akagi, H. Okuda, T. Kawamoto (1994). The cyclic shear behaviour of interfaces of rock anchors and its effect on the long term behaviour of rock anchors. *Int. Symp. on New Developments in Rock Mechanics and Rock Engineering*, Shenyang, 15-22.
- Aydan, Ö., Komura, S. S. Ebisu, T. Kawamoto (1995). A unified design method for rock anchor foundations of super-high pylons. *The Int. Workshop on Rock Foundation of Large-scaled Structures, ISRM*, Tokyo, 279-284.
- 6) Aydan, Ö. Fuse, T. Ito, T. (2015): An experimental study on thermal response of rock discontinuities during cyclic shearing by Infrared (IR) thermography. Proc. 43rd Symposium on Rock Mechanics, JSCE, 123-128.
- Celestino, T. B. and Goodman, R.E., 1979, Path Dependency of Rough Joints in Bi-directional Shearing, *Proc. 4th. ISRM Congress*, Vol. 1, 91-98.
- Fox, D.J., Kana, D. D. and Hsiung, S. M. (1998). Influence of interface roughness on dynamic shear behavior in jointed rock. Int. J. Rock Mech. Min. Sci. 35(7): 923-940.
- 9) Gillete, D.R., Sture, S., Ko, H.Y., Gould, M.C., Scott, G.A., 1983, Dynamic Behavior of Rock Joints, 24th U.S. Symposium on Rock Mechanics, 163-179.
- Hutson, R.W. and Dowding, C.H. 1990: Joint Asperity Degradation During Cyclic Shear. *nt. J. Rock Mech. Min. Sci. & Geomech. Abstr:* Vol. 27. No. 2, pp. 109-119.
- 11) Jafari, M.K., Pellet, F., Boulon, M., and Hosseini, K.A. (2004).

Experimental study of mechanical behavior of rock joints under cyclic loading, Rock Mechanics and Rock Engineering, 37 (1): 3623.

- 12) Kana, D.D., Chowdhury, A.H., Hsiung, S.M., Ahola, P.A., Brady, B.H.G. and Philip, J., 1991, Experimental techniques for dynamic shear testing of natural rock joints, *Proc. 7th. ISRM Congress*, 519-525.
- 13) Kana, D. D., Fox, D. J., Hsiung, S. M. (1996) Interlock/friction model for dynamic shear response in natural jointed rock, *Int. J. Rock Mech. Min. Sci.*, 33, 371-386.
- 14) Krahn, J., and N.R. Morgenstern. 1979. The ultimate frictional resistance of rock discontinuities. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts 16: 127-133.
- 15) Lee, H.S., Park, Y.J., Cho, T.F. and You, K.H., 2001, Influence of asperity degradation on the mechanical behavior of rough rock joints under cyclic shear loading, *Int. J. of Rock Mech. and Min. Sci.*, Vol.38, 967-980.
- 16) Okada, T. Ito, H. Verification of dynamic shear strength estimation procedure for rocks based on laboratory tests (in Japanese). CRIEPI Report, No.09029, 32p.
- 17) Yoshida, J., Yoshinaka, R., Tsubota, Y., Iwakoke, Y. and Nakashima, M., 2013, Development of dynamic test machine for rock discontinuity, *13th Japan Symposium on Rock Mechanics*, 219-224 (in Japanese with English abstract).
- 18) Yoshida, J., Yoshinaka, R. and Sasaki, T., 2014a, Study on dynamic shear strength and deformability of rock discontinuity using dynamic loading test machine, *Proc. 42th Symp., Rock Mech.*, JSCE, 237-242 (in Japanese with English abstract).
- 19) Yoshida, J., Yoshinaka, R., Sasaki, T., Osada, M. (2014b): Study on Dynamic Properties of Rock Discontinuity using Dynamic Direct Shear Test Machine. ARMS8, Sapporo.
- 20) Huang, S., Feng, X.T., Xia, K. (2011). A dynamic punch method to quantify the dynamic shear strength of brittle solids. Rev Sci Instrum., 82(5):053901.
- 21) Aydan Ö. & Ohta Y. 2011. The erratic pattern screening (EPS) method for estimation of co-seismic deformation of ground from acceleration records and its applications. Seventh National Conference on Earthquake Engineering, Istanbul, Turkey, Paper No 66: 1-10 pages.
- 22) Aydan Ö., Ohta Y., Daido M., Kurnsar H. Genis M., Tokashiki N., Ito T. & Amini M. (2011): Chapter 15: Earthquakes as a rock dynamic problem and their effects on rock engineering structures. *Advances in Rock Dynamics and Applications*, Editors Y. Zhou and J. Zhao, CRC Press, Taylor and Francis Group, 341-422.
- Ohta Y., Aydan Ö. 2007. Integration of ground displacement from acceleration records. *JSCE Earthquake Engineering Symposium*, 1046-1051.
- 24) Ohta, Y. and Aydan, Ö. (2010): The dynamic responses of geomaterials during fracturing and slippage. Rock Mechanics and Rock Engineering, Vol.43, No.6, 727-740.
- 25) Earthquake Department of Turkey (formerly Earthquake Research Dept. -ERD) (1999). http://www.deprem.gov.tr/
- 26) KiK-Net (2008): Digital acceleration records of earthquakes since 1998. http://www.kik.bosai.go.jp/.
- 27) Aydan, Ö., Y. Shimizu, T. Kawamoto (1996). The anisotropy of surface morphology and shear strength characteristics of rock discontinuities and its evaluation. *NARMS* '96, 1391-1398.