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Frictional responses of concrete-to-concrete bedding planes under complex loading conditions

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Abstract. Concrete-to-concrete bedding planes (CCBP) are observed from time to time due to the multistep hardening process of the concrete materials. In this paper, a series of direct/cyclic shear tests are performed on CCBP under static and dynamic normal load conditions to study the frictional behavior effect by the shear velocities, normal impact frequencies, horizontal shear frequencies, normal impact force amplitudes, horizontal shear displacement amplitudes and normal load levels. According to the experimental results, apparent friction coefficient k ($k = F_{Shear}/F_{Normal}$) shows different patterns under static and dynamic load conditions at the stable shear stage. k is nearly constant in direct shear tests under constant normal load conditions (DCNL), while it is cyclically changing with nearly constant peak value and valley value for the direct shear tests under dynamic normal load conditions (DDNL), where k increases with decreasing normal force and decreases with increasing normal force. Shear velocity has little influence on peak values of k for the DCNL tests, but increasing shear velocity leads to increasing valley values of k for DDNL tests. It is also found that, the valley values of k ascend with decreasing impact normal force amplitude in DDNL tests. The changing pattern of k for the cyclic shear tests under constant and dynamic normal load conditions (CCNL and CDNL tests) are similar, but the peak value of k is smaller in CDNL tests than that in CCNL tests. Normal load levels, shear displacement amplitudes, vertical impact frequencies, horizontal shear frequencies and normal impact force amplitudes have little influence on the changing pattern of k for the cyclic shear tests. The tests of this study provide useful data in understanding the frictional behavior of the CCBP under distinct loadings, and these findings are very important for analyzing the stability of the jointed geotechnical structures under complicated in situ stress conditions.

Keywords: concrete-to-concrete; dynamic normal force; constant normal force; cyclic/direct shear

1. Introduction

As one of the widely used building materials, reinforced concrete blocks are often encountered in civil and environmental engineering, where the concrete-to-concrete bedding planes (CCBP) are observed from time to time due to the multistep hardening process of the old and new concrete materials (Ceia *et al*. 2016, Waseem and Singh 2017, Cavaco *et al*. 2018). The frictional behavior of CCBP plays a central role in the stability and hazard evaluation of the engineering structures (Liu *et al*. 2012, Liu and Dang 2014, Zhang *et al*. 2016, Waseem and Singh 2017, Cavaco *et al*. 2018). For a better understanding of the frictional characteristic of joints or bedding planes, laboratory shear tests are widely performed in the past decades (Dang *et al*. 2016, 2017, 2018). So far, direct/cyclic shear tests under constant normal load conditions are the most common methods to research the frictional characters of joints or bedding planes. It has been already proved that, the most important factors influencing on the frictional behavior are the surface asperities, shear velocities and normal load levels (Hossain and Yin 2015, Borana *et al*. 2016, Lee *et al*. 2017, Chen *et al*. 2018, Dang *et al*. 2018, Li *et al*. 2018, Shang *et al*. 2018, Samanta *et al*. 2018).

Dynamic excitations like earthquakes are very complicated dynamic movements with simultaneous dynamic impact in different directions in space (Kana *et al*. 1996, Zhou *et al*. 2018, Tao *et al*. 2015, Li *et al*. 2016, Dang *et al*. 2018, Liu *et al*. 2018, Song *et al*. 2018). Stein (1999) reported that the shear stress and normal stress are changed along the surrounding faults or bedding planes during earthquakes. In such cases, the shear movements of the weak surface are subjected to shaking applied vertically, i.e., shearing with complex normal load (static load superimposed dynamic load) conditions happens. In order to understand the frictional characteristics of CCBP under dynamic normal load conditions, several researchers have adopted laboratory test procedures involving step changes or continuous changes in normal stresses. A distinct time shift between peak normal force and peak shear force with peak shear force behind is reported by Dang *et al*. (2017, 2018), where a dynamic shear strength criterion is also suggested for predicting the direct shear strength under cyclic normal load conditions. Konietzky *et al*. (2012) carried out dynamic shear tests under dynamic earthquake

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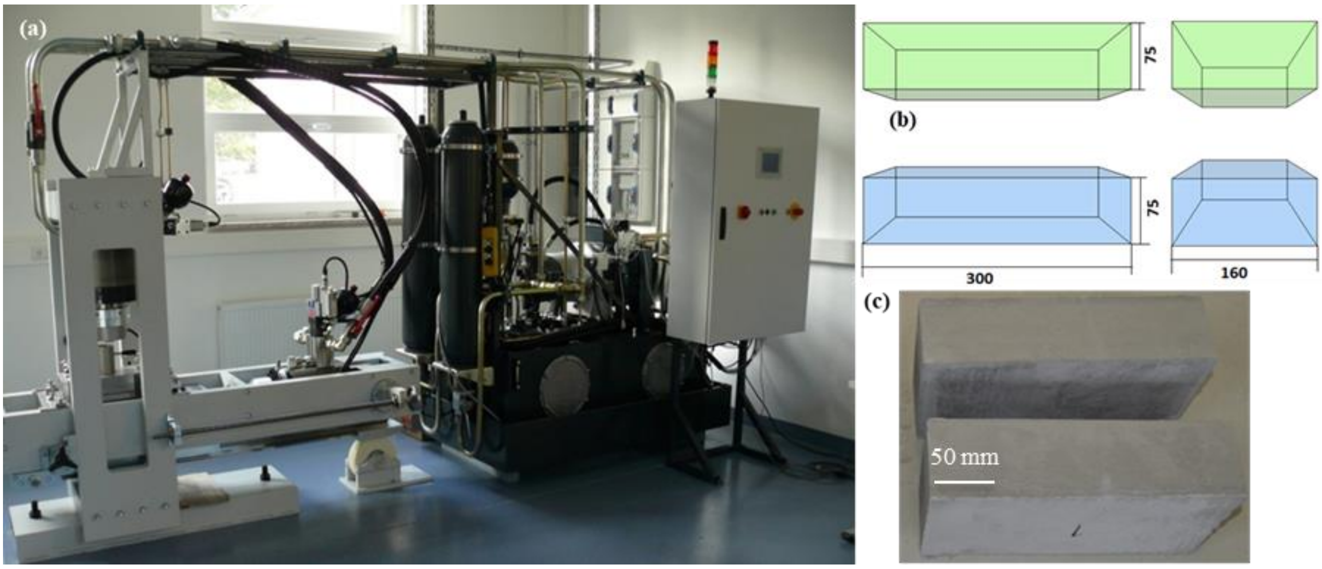

Fig. 1 (a) Shear test apparatus, (b) size of the concrete specimen (unit: mm) and (c) real concrete specimen

signals, where they proved that increasing of shear displacement will weaken the shear strength. Hong and Marion (2005) investigated the frictional behavior of creeping faults on granite to step changes in normal forces. The test results proved that friction coefficient changes with changes in normal stress and slip velocity. Kilgore *et al*. (2012 and 2017) investigated the variation of shear strength and other fault properties with changes in normal stress (between 5 and 7 MPa) using dry initially bare rock surfaces of granite. They identified that changes in rapid normal stress result in gradual, approximately exponential changes in shear stress during fault slip. Molinari and Perfettini (2017) analyzed the frictional responses with changes in shear and normal stresses. They illustrated that an elastic behavior of the plastic contacts is stopped when the instantaneous changes in normal and shear stresses.

Because of the technical limitations of the testing equipment, so far, cyclic shear tests under DNL conditions are seldom reported in relevant researches, especially for the CCBP. However, cyclic frictional behavior of CCBP under DNL conditions is a common phenomenon during earthquakes and blasting. In order to fulfill the blank of the previous studies in this area, the direct/cyclic frictional responses of CCBP under constant and dynamic normal load conditions are investigated in this paper. The static and dynamic friction coefficients are investigated, which can provide a theoretical basis for stability assessment for the concrete-to-concrete structures under complex load conditions.

2. Experimental program

2.1 Test apparatus

The experiments are conducted in a shear box device, GS-1000 (shown in Fig. 1(a)). The GS-1000 shear box device is developed with 16 bit digital records system, where the shear force as well as the normal force is detected by the load cells installed in the cylinders. The shear box device permits servo control of static normal load from 10 kN up to 1000 kN, shear load from -300 kN up to 800 kN, superimposed dynamic normal load up to 500 kN, normal impact frequency and shear frequency up to 40 Hz, shear displacement up to 5 cm, and data can be recorded up to 100 points per second (recording frequency 100 Hz).

2.2 Materials and specimen preparation

The concrete specimens used in the present research work are made of CEM I 32.5 R cement, glassand and water (the CEM I 32.5 R cement and glassand with a weight ratio of 1:3). The block size of the concrete specimen is 300 mm (length) × 160 mm (width) × 150 mm (/height), where a flat surface (the maximum asperity of the surface is within 0.1 mm) separates the block into two parts and each part with the height of 75 mm (see Fig.1b and c). The samples are cured at a temperature of about 20 over 28 days. At the time of test, the mechanical parameters of the samples are illustrated in Table 1.

2.3 Test setup

The laboratory shear tests setup under static and dynamic normal load conditions are shown in Fig. 2. The frictional behavior is investigated under different normal impact frequency (f_v), horizontal impact frequency (f_h), amplitude of superimposed dynamic normal force (F_d), amplitude of shear displacement (u_{max}) and constant normal force levels. Four group laboratory shear tests are performed:

Group A (Fig. 2(a)): direct shear tests under constant normal load conditions (DCNL). A constant normal load is applied at the upper loading plate, where the constant normal loads are 90 kN and 180 kN, respectively. At the same time, a shear load is applied horizontally to the bottom part of the specimen to provide a shear movement with a fixed velocity, where the shear velocities vary from 1.0 mm/min to 100 mm/min.

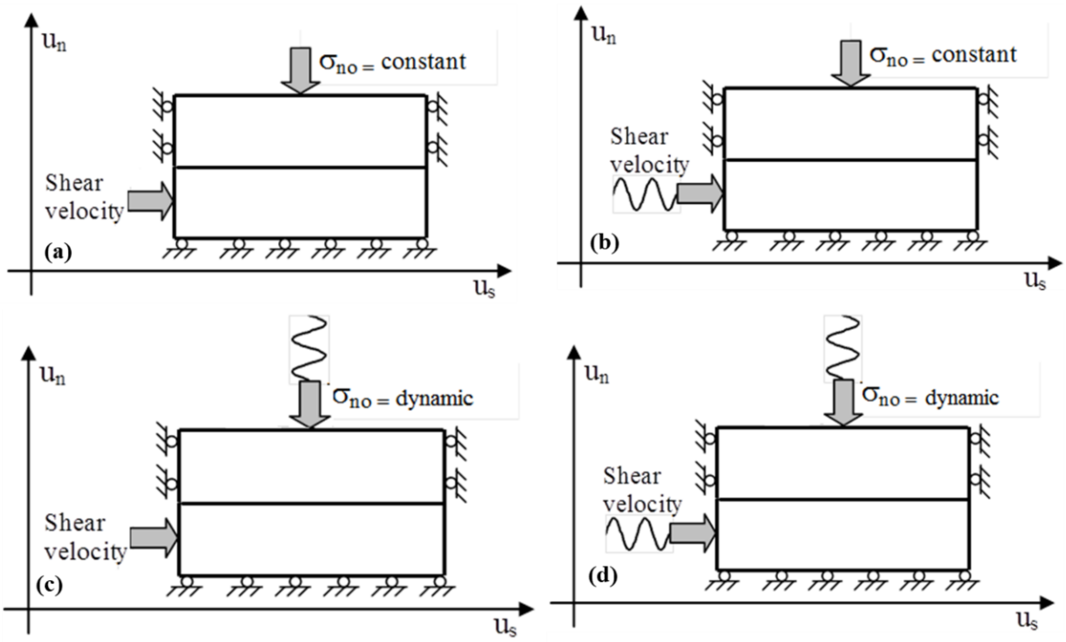

Fig. 2 Sketch map of laboratory tests under static and dynamic normal load conditions: (a) DCNL test, (b) CCNL test, (c) DDNL test and (d) CDNL test

Table 1 Mechanical parameters of concrete specimen

Item	Tensile Strength [MPa]	Uniaxial Compressive Strength [MPa]	Young's modulus [GPa]	Poisson ratio	Cohesion [MPa]	Internal friction angle [°]	Dilation angle [°]	Density [g/cm^3]
Concrete	2.5	19.1	30	0.2	7.2	30	10	2.50

Group B (Fig. 2(b)): cyclic shear tests under constant normal load conditions (CCNL). A constant normal load is applied at the upper loading plate. At the same time, a varied load is applied horizontally to the bottom part of the shear box to provide a sinusoidal excitation of the shear displacement, where the shear displacement is controlled by sinusoidal excitation as described in Eq. (1) All cyclic tests are performed with a horizontal shear frequency f_h of 1.0 Hz. The shear displacement amplitude u_{max} is maintained at approximately ± 2.0 mm, ± 4.0 mm, ± 5.0 mm and ± 8.0 mm, respectively. The constant normal load acting on the sample varies form 30 kN to 360 kN.

Group C (Fig. 2(c)): direct shear tests under dynamic normal load conditions (DDNL). A constant normal load is applied at the upper loading plate, at the same time, a dynamic superimposed normal force is given. The dynamic superimposed normal force is defined by Eq.2. Simultaneously, a shear load is applied horizontally to the bottom part of the specimen to provide a shear movement with a fixed velocity The constant and superimposed dynamic normal force are 90 kN ± 45 kN and 180 kN ± 90 kN, respectively. The maximum shear displacement is 0.5 cm with the f_v of 0.5 Hz. The shear velocities vary from 1.0 mm/min, to 100 mm/min.

Group D (Fig. 2(d)): cyclic shear tests under dynamic normal load conditions (CDNL). A constant normal load is applied at the upper loading plate, at the same time, a dynamic superimposed normal force is given.

Simultaneously, a varied load is applied horizontally to the bottom part of the shear box to provide a sinusoidal excitation of the shear displacement, where the shear displacement is controlled by sinusoidal excitation as described in Eq.1 and the dynamic superimposed normal force is defined by Eq.2. F_s varies from 30 kN to 360 kN. F_d varies from ± 15 kN to ± 180 kN. Both, f_h and f_v vary from 0.25 Hz to 5.0 Hz, u_{max} varies from ± 2.0 mm to ± 8.0 mm.

$$F_{sd} = F_d \sin(2\pi f_v t) \tag{1}$$

$$u_s = u_{\max} \sin(2\pi f_h t) \tag{2}$$

where, F_{sd} is the impact normal force, F_d is the amplitude of superimposed dynamic normal force, f_v is the normal impact frequency, t is the time. u_s is the shear displacement, u_{max} is the amplitude of shear displacement, f_h is the horizontal impact frequency.

3. Results and discussion

The frictional behavior of CCBP under different shear and normal load conditions is illustrated in Figs. 3-8. In DCNL tests, at the stable shear stage, the peak values of the apparent friction coefficient k (k = F_{Shear}/F_{Normal}) are constant under different normal load levels and different shear velocities (shown in Fig. 3(a) and Fig. 4), and peak at an approximate value of 0.8. It should be noticed that, at

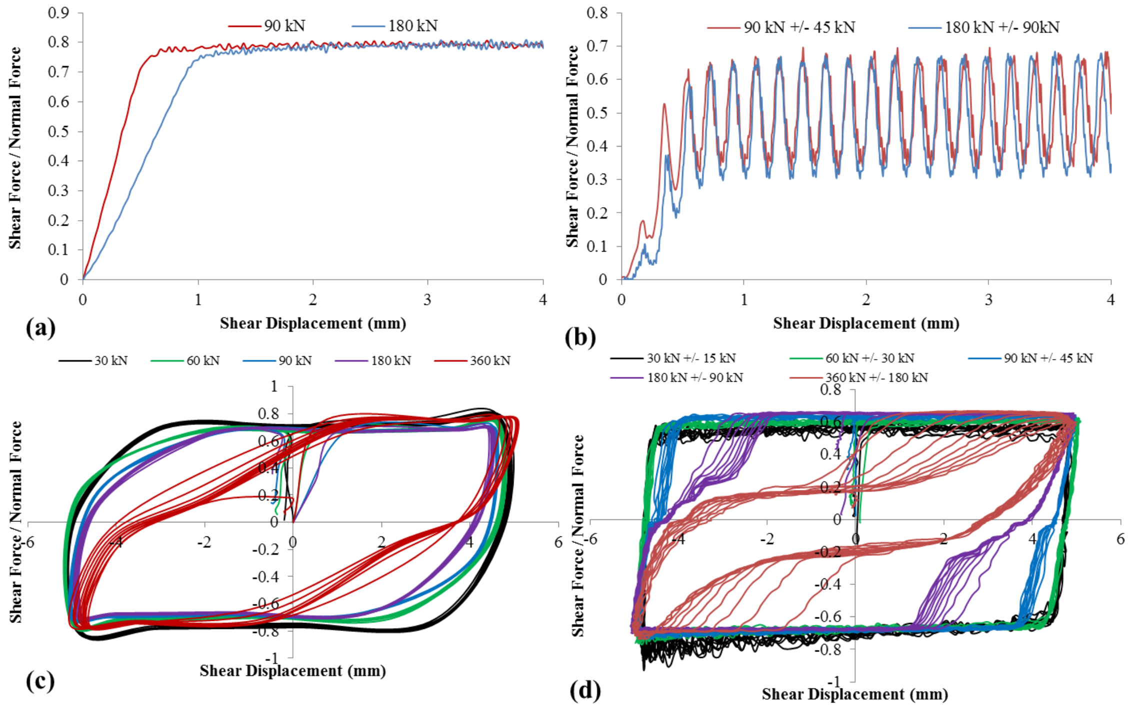

Fig. 3 Ratio between shear force and normal force vs. shear displacement. (a) DCNL test with shear rate of 100 mm/min, (b) DDNL test with shear rate of 3 mm/min, (c) CCNL test at f_h of 1.0 Hz and (d) CDNL test at f_h of 1.0 Hz and f_v of 1.0 Hz

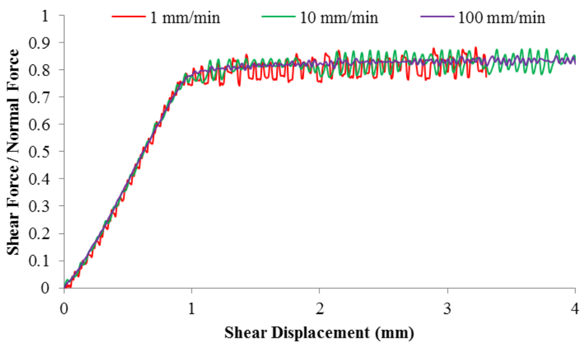

Fig. 4 Ratio between shear force and normal force vs. shear displacement of DCNL test at different shear velocities

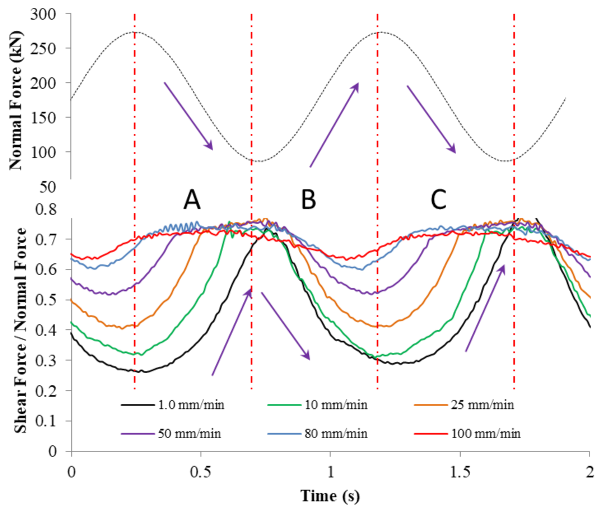

Fig. 5 DCNL test results under normal force of 180 kN +/- 90 kN, f_v of 1.0 Hz at different shear velocities, constant periodic stages are taken and starting time is shifted to zero

low shear velocities (e.g., 1 mm/min, 10 mm/min), the stick-slip behavior is observed, which makes *k* fluctuation at the stable shear stage. At the shear rate of 100 mm/min, when the friction coefficient reaches to the peak value of 0.8, it needs 0.6 mm shear displacement under normal load of 90 kN, while the required shear displacement increases to 1.0 mm under normal load of 180 kN (shown in Fig. 3a). Large shear displacement is required to the peak friction coefficient under large normal load levels, which indicates lager shear stiffness of the CCBP under large normal load levels. Fig. 4 also shows that under the same normal load conditions, shear rate has little influence on the shear displacement reaches to the peak friction coefficient, which also means shear rate has little influence on the shear stiffness of CCBP.

In DDNL tests, the changing pattern of *k* is different comparing with DCNL tests, where *k* is cyclically changing with cyclically changing in normal forces. Fig. 5 and Fig. 6 show that *k* changes immediately when the normal force changes, where *k* increases with decreasing in normal force (shown in Fig. 5 and Fig. 6 area A and C). Conversely, *k* decreases with increasing in normal force (shown in Fig. 5 and Fig. 6 area B) in all cases. The changes of *k* are caused by the shear stiffness of the CCBP. It has already proved that to reach the peak value of k need a certain amount of shear displacement in DDNL tests. This founding is very helpful for people to evaluate the stability of the CCBP under dynamic normal load conditions.

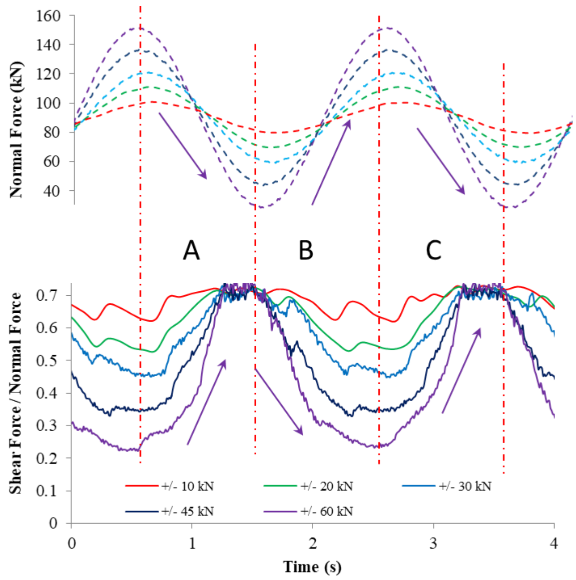

Fig. 6 DCNL test results under static normal load of 90 kN, f_v of 1.0 Hz, shear rate of 3.0 mm/min, different normal impact forces, constant periodic stages are taken and starting time is shifted to zero

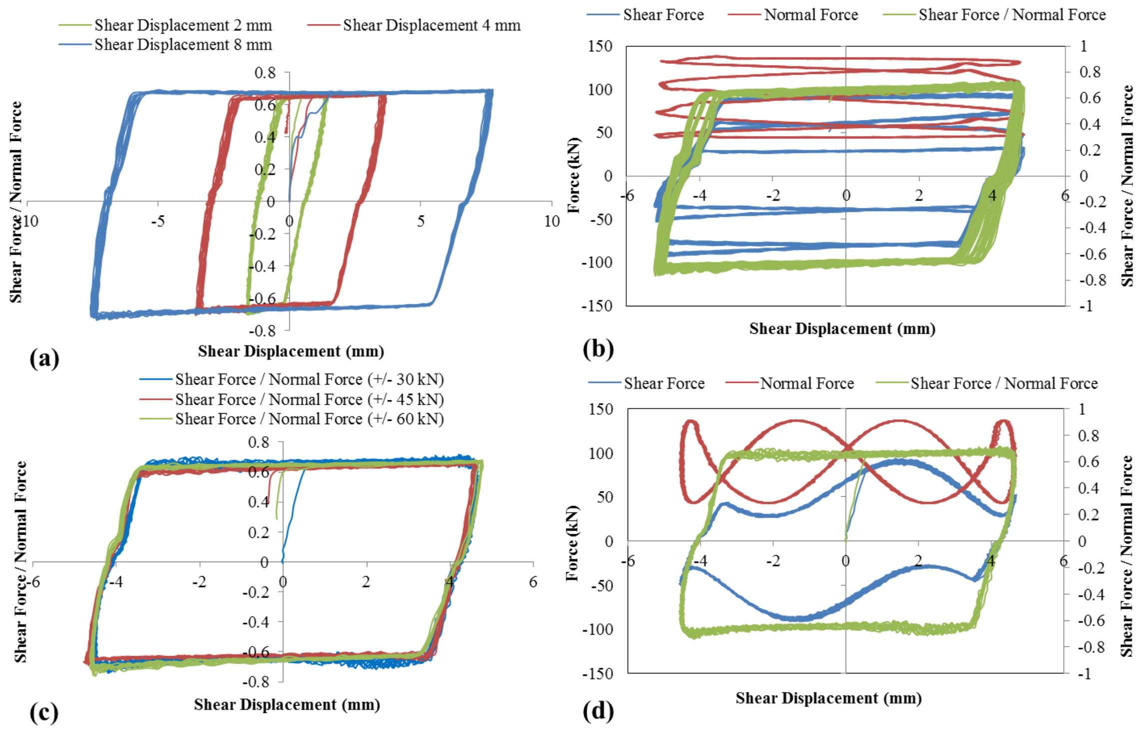

Fig. 7 Ratio between shear force and normal force vs. shear displacement of CDNL tests: (a) constant normal force 90 kN, dynamic normal force +/-45 kN, f_h 1.0 Hz, f_v 1.0 Hz, u_{max} 2 mm, 4 mm, 8 mm, (b) constant normal force 90 kN, dynamic normal force +/-45 kN, f_h 1.0 Hz, f_v 0.25 Hz, u_{max} 5 mm, (c) constant normal force 90 kN, dynamic normal force +/-30 kN, +/-45 kN, +/-60 kN , f_h 1.0 Hz, f_v 1.0 Hz, u_{max} 5 mm and (d) normal force 90 kN +/-45 kN, f_h 0.25 Hz, f_v 1.0 Hz u_{max} 5 mm

In the previous studies (Crawford and Curran 1981), shear velocity can increase or decrease the friction coefficient according to the mechanical parameters of the material. In general, for harder materials, the friction coefficient is proved to decrease with increasing in shear velocity. Conversely, the friction coefficient of softer materials increases with increasing shear velocity. Under dynamic normal load conditions, the changing pattern of friction coefficient is very different comparing with that under CNL conditions for the CCBP. Decreasing the shear velocity leads to a decrease in the valley values of k and the peak values of k keep approximately constant (shown in Fig. 5). However, k keeps constant at different velocities under CNL conditions (shown in Fig. 4). Fig. 6 shows that the changing pattern of k is also influenced by the impact normal force amplitude, where large impact normal force

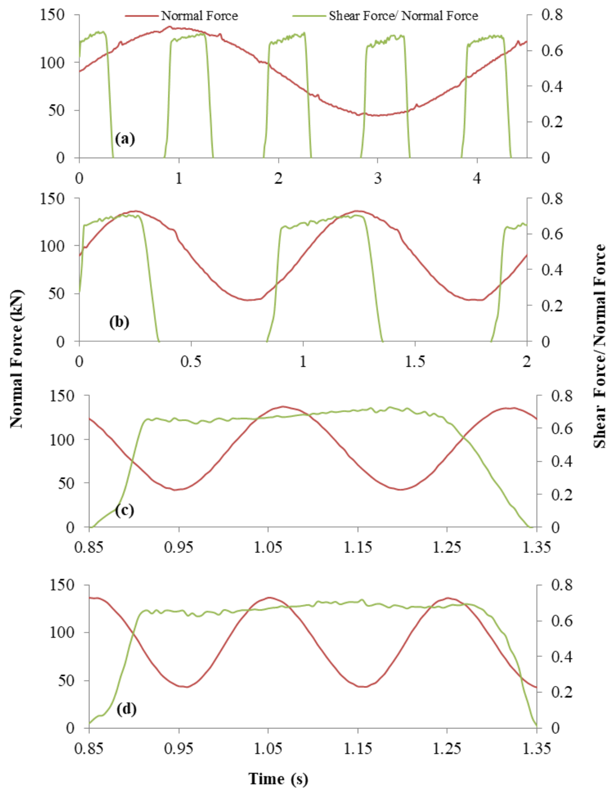

Fig. 8 Normal force and apparent friction coefficient vs. time under different f_h and f_v in the forward shear direction. (a) f_h =1.0 Hz, f_v = 0.25 Hz, (b) f_h =1.0 Hz, f_v = 1.0 Hz, (c) f_h =1.0 Hz, f_v = 4.0 Hz and (d) f_h =1.0 Hz, f_v = 5.0 Hz, only the positive values of shear force / normal force are plotted

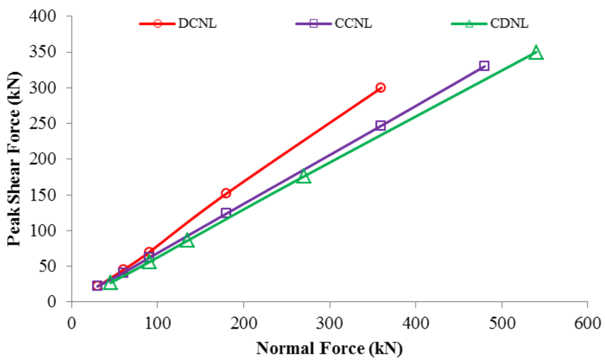

Fig. 9 Peak shear force vs. normal force under different boundary conditions

amplitude leads to a decrease in the valley values of k, and the peak values of k keep approximately constant.

Overall, values of k are changing within the range between 0.2 and 0.7 at the stable shear stage in DDNL tests. Decreasing the shear velocity or increasing the impact normal force amplitude leads to a decrease in the valley values of k, but the peak values of k keep approximately constant. The peak value of k is smaller compared with that in DCNL tests.

In CCNL tests, k changes to positive or negative values along with the changing of shear direction. The peak values of k are constant at both the forward and backward shear directions (shown in Fig. 3(c)), where the constant value is about 0.75 in the forward shear direction and -0.75 in the backward shear direction. The plateau level of k becomes smaller with increasing in normal forces, which is caused by two reasons: progressive damage and shear stiffness of the CCBP. The peak value of k is also smaller than that in DCNL tests. Besides, shear displacement amplitude has little influence on the changing pattern of k.

In CDNL tests, the general changing pattern of k is similar to that in CCNL tests, and k is nearly constant at the stable shearing stage. This is very different comparing with the DDNL tests (as mentioned above, the apparent friction coefficient k is cyclically changing with the varying impact normal forces). As shown in Fig. 8, even changes in normal force, the apparent friction coefficient k is nearly constant instead of the cyclically changing with the changes of normal forces at the stable shear stage. It indicates that changes in shear direction meet changes in normal forces triggers a distinct changing pattern of the apparent friction coefficient k. In CNDL tests, shear velocity changes at different point of the shear displacement. It might be caused by the changes in shear velocities encountering changes in normal forces, which leads a special change of the apparent friction coefficient k. The physical reasons of this behavior need further investigations. CDNL test results under different horizontal shear displacement amplitudes, different normal impact frequencies, different horizontal shear frequencies and different vertical impact force amplitudes are shown in Fig. 7. It can be seen that, k is less influenced by the shear displacement amplitudes; vertical frequencies, horizontal impact frequencies, and impact normal force amplitudes. The peak values of k are nearly identical (about 0.7). It should also be noticed that, when the normal forces over 180 kN +/- 90 kN, progressive damage of the contact surface is clearly observed (shown in Fig. 3(d)).

Fig. 9 shows that, peak shear force has a linear relation with normal force under DCNL, CCNL and CDNL conditions. The peak shear force is lager under DCNL conditions than that under CCNL and CDNL conditions, which indicates the reduction effect of dynamic load on the friction coefficient. The peak shear force under DDNL conditions is not constant, which is influenced by the shear velocity and impact normal force amplitude, where the plot is not provided in the present paper.

4. Conclusions

This paper presents the experimental investigations of the frictional characteristic of CCBP under static and dynamic load conditions, where DCNL, DDNL, CCNL and CDNL tests are performed using the GS-1000 shear box device. Normal load levels and shear velocities have little influence on the apparent friction coefficient under DCNL conditions. The apparent friction coefficient is cyclically changing with the cyclic normal force with the constant peak and valley values under DDNL conditions, where due to the shear stiffness of CCBP apparent friction coefficient decreases with increasing normal forces and increases with decreasing normal forces. Increasing impact normal force amplitude or decreasing shear velocity leads to decreasing of the valley value of the apparent friction coefficient, while the peak values are unaffected. The changing pattern of the apparent friction coefficient in the CCNL tests and CDNL tests are nearly the same, but the peak value is smaller under CDNL conditions than that under CCNL conditions. Normal load levels, shear displacement amplitudes, vertical impact frequencies, horizontal shear frequencies, and normal impact force amplitudes have little influence on the apparent friction coefficient under CDNL conditions. Within all the four test groups, the peak value of the apparent friction coefficient is larger under static conditions than that under dynamic load conditions. It should be mentioned that fatigue life and roughness of CCBP are not taken into account in the presented research work, where further investigations are needed in the future.

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