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Effects of shear rate on cyclic behavior of dry stack masonry joint

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HIGHLIGHTS

- Novel dynamic friction test concept is supposed and verified by finite element model.
- Effects of shear rate on cyclic behavior of dry bricks (DB) are studied experimentally.
- A dynamic friction characteristic model with 5 stages of the DB joint is addressed.
- A formula of calculating the dynamic friction coefficient of DB is proposed.
- Stribeck effect is considered in calculating the dynamic friction coefficient of DB.

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ABSTRACT

Dry stack masonry (DSM) constructed without mortar has been suggested for use in reinforced concrete (RC) frame structures. DSM can considerably improve the seismic performance of masonry infill panels and frames. For this type of structure, the characteristics of frictional forces between the bricks are crucial for energy dissipation, but few researchers have studied these forces. In this paper, a novel dynamic loading test concept is proposed. The dynamic friction characteristics of dry bricks were investigated using this concept. A numerical comparison between the novel test and a triplet test was conducted to validate the advantages and stability of the novel test concept. Nine different loading speed tests based on the novel test concept were conducted to study the effects of shear rate on the cyclic behavior of mortarless masonry joints. Investigating dynamic friction hysteretic curves yielded a dynamic friction characteristic model of dry brick joints, comprising five stages: presliding, softening transition, macroslip, hardening transition, and unloading stages. A formula regarding the Stribeck effect on the macroslip stage is proposed to calculate the dynamic friction coefficient, which is of noteworthy importance for use in day-to-day research on the dynamic friction characteristics of dry bricks.

1. Introduction

Reinforced concrete (RC) frame structures with masonry panels are globally known and applied because of their economy and low technology requirements. However, postearthquake investigations have attributed various types of damage inflicted on RC frames to seismic interaction between building frames and masonry infill panels [1,2].

A typical masonry infill panel is designed as a nonstructural element, but it causes an obvious change in the stiffness and energy dissipation of the RC frame. A typical masonry infill has higher stiffness (more rigidity) than a RC frame; hence, the higher stiffness tends to attract higher seismic forces that could damage both panes and frames. During an earthquake, energy dissipation inside infilled panels can improve the seismic behavior of an entire structure, but commonly, energy dissipation in masonry panels is due to the crushing of bricks, which lowers the structure's stiffness and structural integrity. Totoev et al. [3] proposed a novel conceptual system for improving the seismic behavior of framed masonry panels; the frame can be infilled with dry stack masonry (DSM), which can dissipate energy by the relative sliding of bricks.

Lin et al. [4,5] have carried out a series of experiments on DSM-infilled frames; the results indicated that DSM exhibited considerable energy dissipation during cyclic tests and was able to improve the seismic performance of frame structures strongly. In addition, an equivalent model was implemented for evaluating the energy dissipation of DSM to the frame [6], which showed that the energy dissipation of DSM resulted from the friction between bricks. Hence, accurate understanding of the friction between bricks is

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the key for comprehending the shear behavior of DSM and for evaluating the energy dissipation of DSM.

Previous research on the shear behavior of masonry joints focused on traditional masonry built with mortar; DSM has received attention only in recent decades [7–9]. Lourenco et al. [9] conducted a series of cyclic tests under different normal stress levels to investigate the shear strength and hysteretic behavior of dry stack stone. The results indicated that the failure criterion for dry stack stone can be considered as a Mohr-Coulomb failure. The compression stress and shear stress exhibit a linear relationship expressed as follows:

$$\tau = tan\phi \cdot \sigma + c \tag{1}$$

where c represents the cohesion (for DSM, the value of c is zero); σ represents the normal stress of the contact surface; and tan ϕ represents the tangent of the friction angle of the contact surface, which is generally termed the coefficient of friction.

Casapulla et al. [10] studied out-of-plane failure mechanisms using nonstandard limit analysis tools and macro–micro modeling approaches. In his research, a masonry wall was simulated using a rigid, perfectly plastic model with dry contact interfaces governed by the Coulomb failure criterion. The analysis of the complete cycle of evolution of such mechanisms should take into account that the nonlinear transfer behavior of the frictional interfaces may provide the dominant damping mechanism, meaning that (dynamic) friction may also play a crucial role in the vibratory response of the structure. In his latest research [11] the non-linear static field was particularly highlighted by series of tests on the simple overturning both of a three-wall system with weak vertical connections and of the free standing facade. The results indicate the friction can increase more than 100% the loading capacity of the system. However, the influence of loading speed hasn't been investigated quantitatively in his research.

Elvin et al. [12] conducted a shake table test of a full-scale DSM wall and found that the shear behavior of dry stack brick could be analyzed as a friction damper and that the energy dissipation in the wall was affected by ground motions. Zhou et al. [13] systematically discussed the factors influencing the performance of a friction damper, noting that the coefficient of friction was mostly affected by factors such as the loading cycle, loading type, and sliding speed. Therefore, the mechanical behavior of a DSM wall is affected by the friction between the bricks, which is affected by the loading type.

Casapulla et al. [14] conducted research on the shear behavior of dry-jointed blocks subjected to shear, torsion, and bending moments; however, this study applied only monotonic testing with a constant rate of 10 mm/min for all the load cases. The test results showed that the behavior of a DSM joint was Mohr–Coulomb failure with a constant friction factor for each load case. Safiee et al. [15], Franzoni et al. [16], and Lourenco et al. [17] have performed other tests and achieved similar results. However, all the aforementioned tests were under quasistatic loading, which ignored the influence of shear rate.

According to a survey of the literature, one of the most pivotal factors leading to the damage and failure of structures is velocity-dependent loading, which may be caused by events such as earthquakes and explosions [18–20]. Hence, the influence of shear rate must be considered.

Although the influence of shear rate has been ignored in the surveyed research on the shear behavior of masonry, it has been mentioned in research on other materials [21–28]. Experiments on steel surfaces [25], cement surfaces [26], granite joint samples [27], and sandstone rock joints [28] have shown that the friction force between joints decreased with increasing velocity. By contrast, a velocity-hardening behavior has been found for sandstone rock joints [28], concrete surfaces [28,29], and syenite rock joints [28].

The described studies have reported that the influence of shear rate could be reflected by the Stribeck effect, in which a friction force is a function of velocity (for motion of constant velocity), and the behavior of the system shows a nonlinear transition from stick to slip. According to Stribeck curve theory [30], the coefficient of friction varies as the shear rate changes, and the material is the key factor that affects the coefficient of friction.

For different load cases, the Stribeck effect has different formulations [31]. A more common formula, shown in Eq. (2), has been used in prior publications [32,33], and it was adopted in this research:

$$f(v) = f_c + (f_s - f_c)e^{\left[-(v/v_2)^{\delta}\right]} \tag{2}$$

where f_c represents the Coulomb sliding friction (Newton), which is friction after full slipping; f_s represents the static friction (Newton), also known as the breakaway force, which is the force when bricks start to slip; v represents the sliding velocity (mm/s), which can be measured during the test; v_s represents the Stribeck velocity (mm/s); and δ represents a constant value for the shape of the Stribeck curve. The coefficients of Eq. (2) (f_c, f_s, v_s, δ) can be calculated by parameter fitting according to experimental results, which is described in detail in Section 4.4.

The objective of this research was to improve the knowledge about dry-joint masonry under cyclic shear loading, especially the understanding of influence of loading speed, which is critical for seismic actions. Hence, a novel test stage was devised, and it was verified using a finite element model. Dynamic testing on this novel test stage showed notable advantages over the triplet test method. The testing equipment was able to provide a large sliding displacement, which is a necessary condition of dynamic testing. Dynamic friction testing was conducted at nine different loading speeds. Moreover, the loading–displacement curves and typical hysteretic loop were investigated. Finally, a formula considering the Stribeck effect was proposed, and the corresponding parameters were determined according to the experimental results.

2. Novel dynamic loading methodology

2.1. Novel dynamic loading concept

To study the shear behavior of masonry structures, several test methods have been proposed in previous studies [5,9], among which the triplet test was adopted as the standard test in Europe,

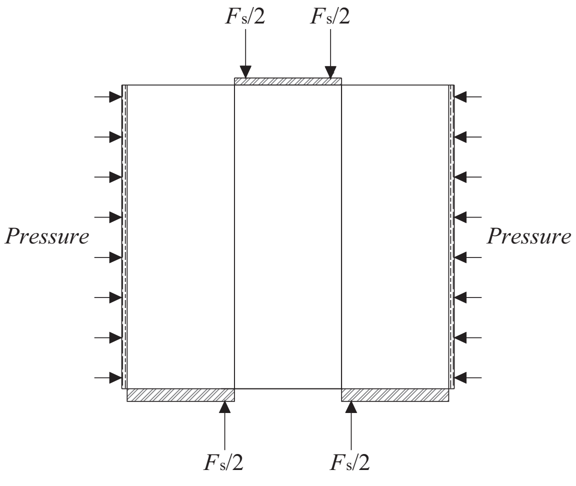

Fig. 1. Sketch of the triplet test.