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EXPERIMENTAL INVESTIGATION ON DYNAMIC BEHAVIOUR OF FREE-STANDING FRAMES WITH FRICTION

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Abstract

Many existing structures in seismic vulnerable areas require seismic upgrading to prevent the collapse in case of extreme earthquakes. This paper proposes an approach based on the separation of the columns base from the foundation, which allows the superstructure to slide in case of large magnitude ground motions. Such a system can cap the base shear transmitted to the superstructure by means of the friction force between the sliding surface and the column base. To achieve a proper value of friction coefficient graphite lubrication is applied on the sliding surface.

In order to verify the efficiency of the proposed system, a series of shake table test was conducted. The specimen was designed to simulate the features of realistic structures and to take into account the possible influence of overturning moment and superstructure flexibility. Based on the experimental evidence, the lubricated system showed an efficient behaviour. The graphite lubrication reduced the friction coefficient to 0.16 and provided a stable behaviour, despite a large number of loading cycles. When increasing the magnitude of ground motion, the maximum base shear coefficient of the superstructure tended towards an upper limit close to 0.35. The overturning moment showed a negligible influence on the overall response.

Keywords: free-standing; seismic retrofitting; steel-mortar; carbon graphite, friction.

1. Introduction

Although many areas of the world are earthquake prone regions, a large part of the existing buildings does not satisfy the seismic design criteria required by seismic codes. Although the contribution of nonstructural elements, such as infill panels [1], [2], can provide quite a significant benefit in terms of additional stiffness and strength, such structures are yet vulnerable against earthquakes. Thus, the seismic retrofit is a legitimate approach to prevent these structures from collapse.

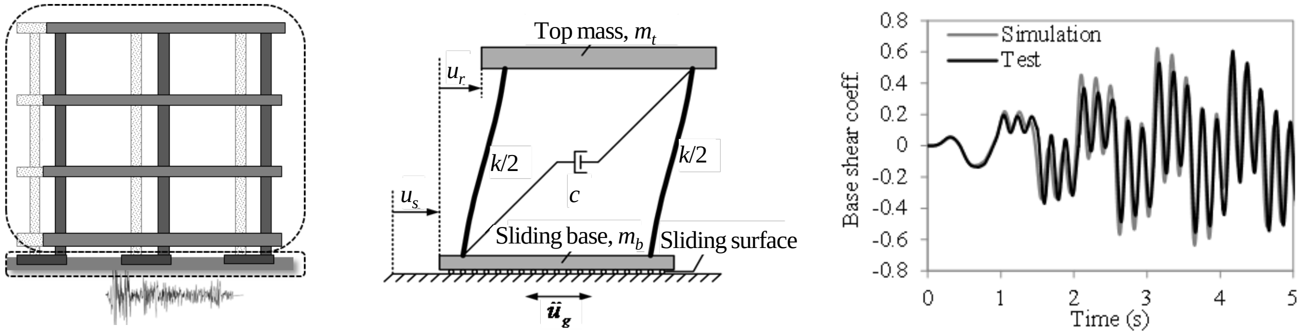
One possible approach for seismic upgrade of these structures is to detach the superstructure from the foundation and to allow the superstructure to slide when extreme earthquakes occur. Thanks to the sliding, the shear forces exerted on the superstructure are reduced, since they are controlled by the friction coefficient of the sliding surface. To prevent the structural collapse, a proper value of the friction coefficient is required. A too large friction coefficient may refrain the structural displacement and force the system to behave as a fixed base system; a too small friction coefficient may cause untimely displacements of the structure. Based on previous experimental studies [3],[4] and theoretical studies[5]-[8], a proper friction coefficient should be approximately equal to 0.2. To achieve such a friction coefficient, it is here proposed a handy and low-cost method, which employs a steel base to slide on a mortar surface lubricated with graphite powder. This approach may appear simplistic, but it has the advantage not to require any special devices or construction works, which make it suitable for extensive retrofit, such as for common residential buildings. Naturally, the main goal of this retrofit technique is the collapse prevention or life safety; thus possible loss of functionalities or residual displacements associated to extremely intense earthquakes should be tolerated.

In a previous experimental study [4], the behaviour of the lubricated sliding system was tested on an idealized specimen, where the superstructure and lower structure were simulated by two rigid frames connected by rubber bearings. The experimental results showed the stability of friction coefficient provided by the graphite powder and displayed the fundamental dynamic response of a simple 2DOF system. The present study aims at extending the applicability of the lubricated sliding system to more realistic structures, taking into account the possible influence of overturning moment and the flexibility of superstructure on the dynamic response. To this end, a new specimen was designed to be more representative of realistic buildings. It was a one-storey one-bay steel frame and the superstructure consisted of four rigid H-shape columns connected by H-shape flexible beams. Since the structures assumed as the target application of the separated system ranges from medium to low-rise RC or steel structures, the natural frequency of the specimen was designed to be at around 3 Hz. The loading protocol assigned for the shake table test included two sets of inputs. The first set consisted of sinusoidal waves, which aimed at investigating the fundamental dynamic response of the sliding system; the second set included earthquake inputs, to verify the efficiency of the sliding system under non-stationary motions.

2. Basic behaviour of the lubricated free-standing system

The free-standing structure requires the separation of the super-structure from its foundation, to let the superstructure slide in case of strong earthquakes (Fig. 1 a). Due to this disconnection, the sliding system can be simplified with a two degree of freedom (2DOF) system, where the superstructure and the lower structure are modelled by two masses, m_t and m_b respectively, connected by two springs of stiffness $k/2$ and a dashpot of damping c (Fig. 1 b). The friction force develops between the sliding base and the rigid horizontal base, and the static friction force f is equal to μN, where μ is the friction coefficient of the sliding surface, and N is the total normal force ($N = (m_t + m_b)g$).

According to the previous study on sliding systems [8], the fundamental dynamic behaviour of a sliding system is characterized by two phases: the *stick state* and the *sliding state*. The transition from the *stick* to *sliding state* is governed by the friction force. When the dynamic friction force is lower than the static friction force, the sliding does not occur, and the system behaves as a fixed base structure, with natural frequency ω_n and damping ratio ξ. When $f = (m_t+m_b)\mu g$, the structure slides, and the base mass is subjected to a horizontal force that equals the dynamic friction force. For the 2DOF system, as represented in Fig. 1 (b), the governing equations for the *stick state* can be written as follows:



a) b) c)

Fig.1 – (a, b) Basic features of sliding model; (c) Base shear coefficient time history under sinewave 1.5 Hz 4.0 m\s^2

$$m_t\left(\ddot{u}_g+\ddot{u}_s+\ddot{u}_r\right)+c\dot{u}_r+ku_r=0 \tag{1}$$

$$m_b\left(\ddot{u}_g+\ddot{u}_s\right)+m_t\left(\ddot{u}_g+\ddot{u}_s+\ddot{u}_r\right)=f \tag{2}$$

where u_g is the ground displacement, u_s is the sliding displacement, and u_r is the relative displacement between the top mass and the sliding base; $\dot{u}_g$, $\dot{u}_s$ and $\dot{u}_r$ are the corresponding velocities; $\ddot{u}_g$, $\ddot{u}_s$ and $\ddot{u}_r$ are the corresponding accelerations; c is the viscous damping coefficient; k is the lateral stiffness of the superstructure. Eq. (1) represents the dynamic equilibrium of the top mass, while Eq. (2) represents the dynamic equilibrium of the entire system. Substituting the condition of the occurrence of sliding ($f = (m_t+m_b)\mu g$) into Eq. (2), the sliding acceleration is obtained as:

$$\ddot{u}_s=\mu g-\alpha\ddot{u}_r-\ddot{u}_g \tag{3}$$

where g is the gravitational constant. Substituting Equation (3) into Equation (1) and dividing by ($1-\alpha$), the equation of motion for the sliding phase is written in terms of the relative displacement u_r:

$$\ddot{u}_r+2\omega'\xi'\dot{u}_r+\omega'^2u_r=\frac{-\mu g}{1-\alpha} \tag{4}$$

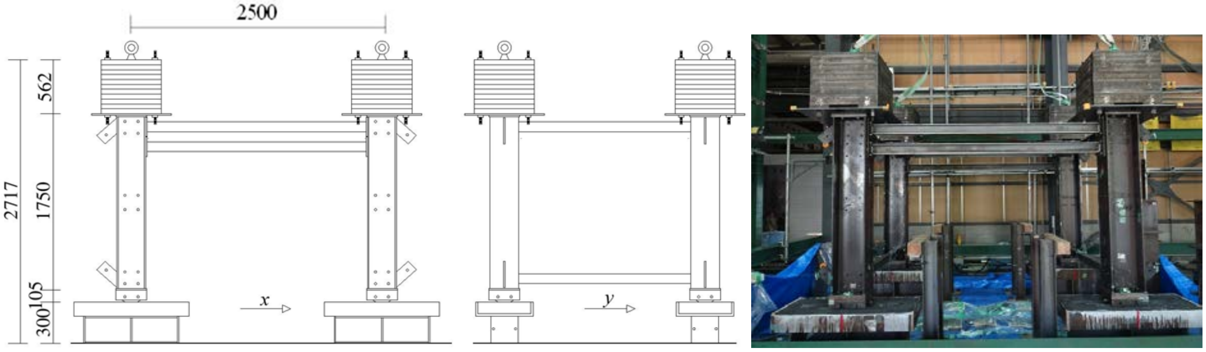
Where:

$$\omega'=\frac{\omega_n}{\sqrt{1-\alpha}}\quad \xi'=\frac{\xi}{\sqrt{1-\alpha}}\quad \alpha=\frac{m_t}{m_t+m_b} \tag{5}$$

Eq. (5) demonstrates that the response characteristics of the sliding structure change with respect to those of the fixed base structure. Due to the slippage, the structure experiences a new “internal” sliding frequency ω’, which is larger that the natural frequency ω_n. This higher frequency causes smaller oscillations shown in the base shear coefficient time history (Fig. 1 (c)) Furthermore, the structure shows a new damping ratio ξ’, larger than ξ. Both the sliding frequency ω’ and the damping ratio ξ’ are related to the frequency and the damping of the structure in the *stick* state by means of the mass ratio α. The mass ratio α is defined as the ratio of the upper mass over the total mass. From previous studies, this parameter is found to play a fundamental role in the dynamic response of the sliding system. In fact, larger mass ratios lead to lower levels of acceleration response.

3. Test program

The application of the lubricated sliding system is mainly concerned with the retrofit of low to medium rise steel or RC buildings, which generally have a natural frequency of around 3 Hz and a ratio of the superstructure mass over the foundation mass close to 0.9. In order to be representative of such structures, the test specimen was designed to achieve the aforementioned target values of frequency and mass ratio, and to take into account the



a) b) c)

Fig. 2 - Test specimen: (a, b) details of the specimen; (c) test set up

possible influence of overturning moment. Effectiveness of the lubricated system applied on this specimen was investigated by means of a series of shake table test.

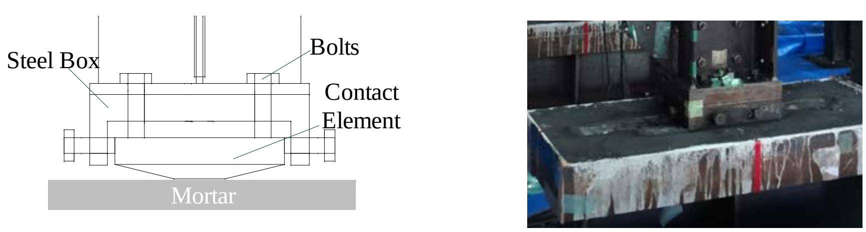
3.1 Test specimen

The specimen was a one-storey and one-bay steel frame, as shown in Fig. 2 (a) and (b). The superstructure consisted of four I-shaped relatively rigid columns with cross section I-300×300×10×15. The columns were connected each other at the top end by flexible I-shaped beams, whose cross section was designed as I-100×80×6×8. With the dimensions adopted above, the natural frequency of the specimen was estimated 3.15 Hz by white-noise excitation. The beams were also flexible enough to ensure an almost equal distribution of gravity forces in columns. Each of the four columns supported on its top a rigid mass of 1,556 kg. The total mass of the specimen was 7,578 kg and the mass ratio α was 0.91. The ratio of the height over the span length was designed to prevent the uplift during all the loading cycles. Thus, according to the height limit for specimens tested on the table, the columns height was assumed 1.75 m and the resulting span length was equal to 2.5 m.

Steel contact elements encased in steel boxes were securely attached underneath each column (Fig. 3(a)). These elements had a plan of 250 mm×250 mm at the upper part and were tapered on each side to a dimension of 75 mm×75 mm at the bottom to yield a good amount of normal stress at the contact area. The bottom surface of the contact element was polished and the mortar surface was lubricated with graphite powder (Fig. 3(b)) to achieve the target friction coefficient, i.e. about 0.2. The specimen was placed on top of the four mortar foundations, which were clamped to the shaking table. Each mortar surface had dimensions 550 mm×1,200 mm, which allowed for approximately ±550 mm of sliding in the *x* direction.

3.2 Loading protocol

The shake table tests were conducted in acceleration control. Uniaxial horizontal accelerations were applied along the *x* direction in Fig. 2 and two sets of input accelerations were chosen. The first set was a sequence of sinusoidal waves. These waves progressively increased to the target acceleration level in the first 3 s, then kept the maximum amplitude for 6 s, and decreased to zero in the last 3 s. Five different loading frequencies were adopted (4.0 Hz, 2.0 Hz, 1.5 Hz, 1.0 Hz and 0.5 Hz) and, for each frequency, tests were repeated with increasing acceleration magnitudes. Among all the frequencies, the lowest acceleration was 0.50 m/s^2 and the largest was



a) b)

Figure 3.Sliding base: (a) cross section of the slider at column base; (b) graphite powder on mortar surface.

10.0 m/s^2. The second set included three earthquake motions: ElCentro, JMA Kobe NS, and JMA Kobe EW. Each record was scaled to various magnitudes, until the sliding displacement reached the upper limit. Table I shows the loading protocols adopted for each test.

Table 1 – Loading protocol

Set 1	**Peak Ground Acceleration (m/s^2)**	**Set 2**	**Peak Ground Acceleration (m/s^2)**
Sin 0.5 Hz	0.5-2.5	El Centro	3.3-11.8
Sin 1.0 Hz	1.0-7.0	JMA Kobe NS	1.6-11.1
Sin 1.5 Hz	1.0-9.0	JMA Kobe EW	3.8-11.5
Sin 2.0 Hz	0.5-8		
Sin 4.0 Hz	0.5-10		

4. Experimental results

The experimental test aimed at (i) investigating the features provided by graphite lubrication subjected to many loading cycles, (ii) analyzing the dynamic response of free-standing system applied to the tall specimen (iii) evaluating the maximum response quantities such as the maximum base shear and maximum displacement.

4.1 Investigation on the friction coefficient

The test results were examined in terms of the friction coefficient, since this is the main parameter governing the sliding response. For the sake of simplicity, the specimen was regarded as a 2DOF system and the friction coefficient μ was estimated as follows:

$$\mu = \frac{m_t a_t + m_b a_b}{(m_t + m_b) g} \tag{4}$$

where m_t, a_t, m_b, and a_b, are the masses and acceleration responses of the superstructure and lower structure, respectively. Figure 4 (a) displays an example relationship between the friction coefficient thus evaluated and the sliding velocity for the specimen subjected to Elcentro scaled at PGA equal to 5.16 m/s^2. When the structure does not slide, i.e. when the sliding velocity is close to zero, the static friction coefficient μ_s is evaluated and it has a value close to 0.2. When the structure starts to slide, i.e. when the velocity is not zero, the dynamic friction coefficient μ_d is determined. This latter is the parameter that controls the maximum response quantities of the sliding structure. The observed average value of μ_d is 0.17, and it shows a weak dependence from the velocity. In fact the COV is equal to 0.016.

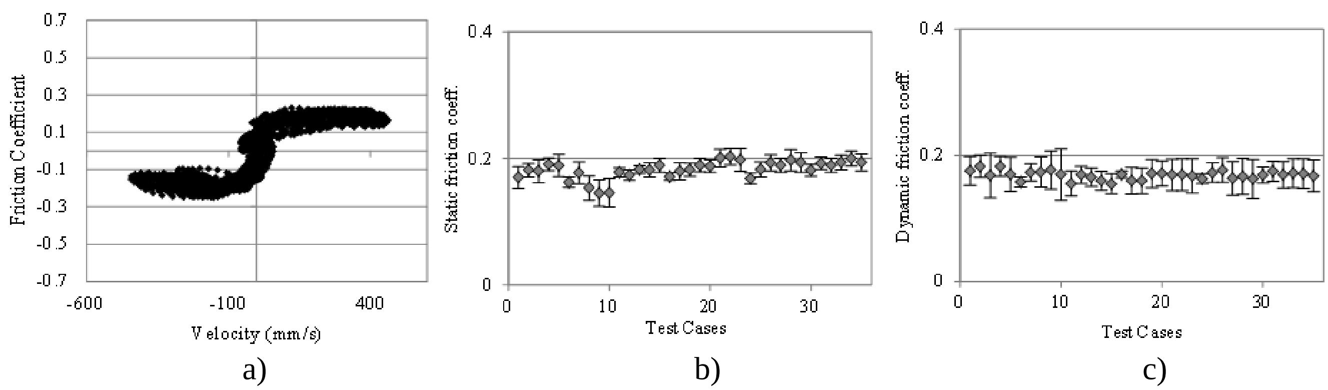


Figure 4. (a) Friction coefficient vs. sliding velocity relationship under sinusoidal 1Hz 2.0 m\s^2; Evaluation of the dispersion of the static and dynamic friction coefficients: (b) static friction coefficient (c) dynamic friction coefficient

To investigate the stability of the friction coefficient and the durability of graphite lubrication throught all the 35 loading cases, the mean and dispersion of the static (Fig. 4(b)) and dynamic (Fig. 4(c)) friction coefficients were evalauted for all tests. Fig. 4 (b) and (c) show the loading case for the abscissa, and the mean (diamond) and standard deviation (bar) for the ordinate. The results demonstrate that graphite lubrication provided a very stable behaviour in both the non-sliding and sliding states. The average static friction coefficient was equal to 0.18, with COV equal to 0.078; the average value of dynamic friction coefficient was 0.17, with COV equal to 0.039. Most notably, even after 450 sliding cycles, the graphite powder remained effective, and its properties remained nearly unchanged. Furthermore, although this specimen showed significant overturning moment, the static and dynamic friction coefficient kept very stable values.

4.2 Response time history

The response of sliding system against earthquake ground motion is presented. Fig. 5 shows the time history of base shear coefficient for the specimen subjected to JMA Kobe NS (PGA = 8.26 m/s^2, PGD=117.4mm). The time histories of normalized displacement, defined as the base displacement over the maximum ground displacement, is presented as well. Under the applied input, the specimen slided and the base shear coefficient reached the maximum value of 0.31, as shown in Fig. 5(a). According to the associated numerical analyses, if the specimen were fixed at the column base and responded elastically, the maximum base shear coefficient would have reached a value of 0.91. This indicates that the application of graphite lubrication allowed the reduction of maximum base shear coefficient by 66%. The base displacement reached a maximum value of 0.38 m, corresponding to 3.28 times the peak ground displacement. After this peak value, the structure slided briefly and reached the final displacement, which was around the 60% of the maximum displacement, as shown in Fig. 5 (b). Furthemore, the four columns displaced indipendently and by almost the same amount, with a differential displacement lower than 0.5% of column height. These results show that the friction coefficient provided by graphite lubrication could properly trigger the sliding of the structure, leading to a significant reduction of the maximum base shear.

In order to investigate the influence of overturning moment, Fig. 5(c) shows the experimental time history of axial force N normalized by the gravity load N_g in two columns belonging to the same plane. Due to the overturning moment, the ratio N/N_g oscillates around the value of unity. The maximum variation observed in the axial force was 35% relative to the axial force exerted by gravity loads. However, since the axial force never decreased to zero, the columns were always in touch with the foundation and the uplift did not occur.

4.3 Maximum response quantities

Fig. 6 shows the test results in terms of maximum base shear coefficient versus increasing peak ground acceleration (PGA), for the sinusoidal input motions (Fig. 6 (a)) and for the earthquake motions (Fig. 6 (b)). In both cases, the experiment shows that the maximum base shear coefficient increases with larger input acceleration, but the rate of increase reduces progressively for larger magnitudes. Differently from the fixed base structures, larger input magnitudes do not lead to an indefinitely larger base shear coefficient. Existence of this uppermost value is confirmed by the experimental results, which show that the maximum base shear coefficient

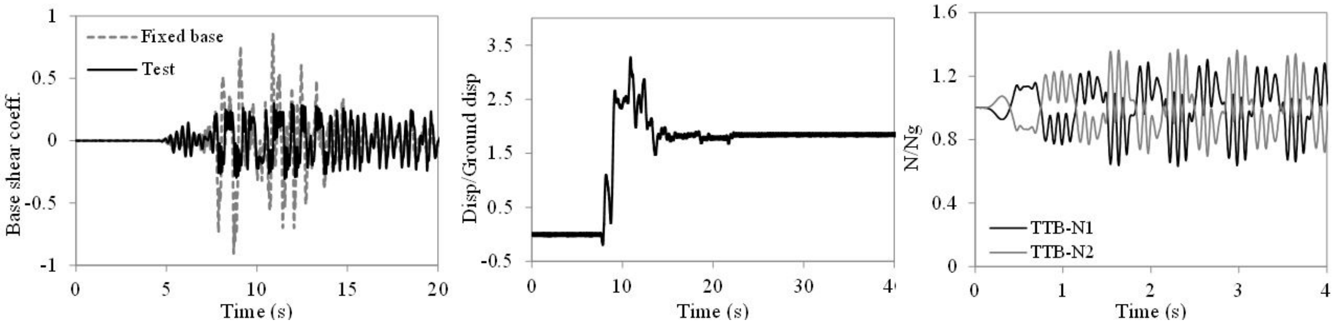
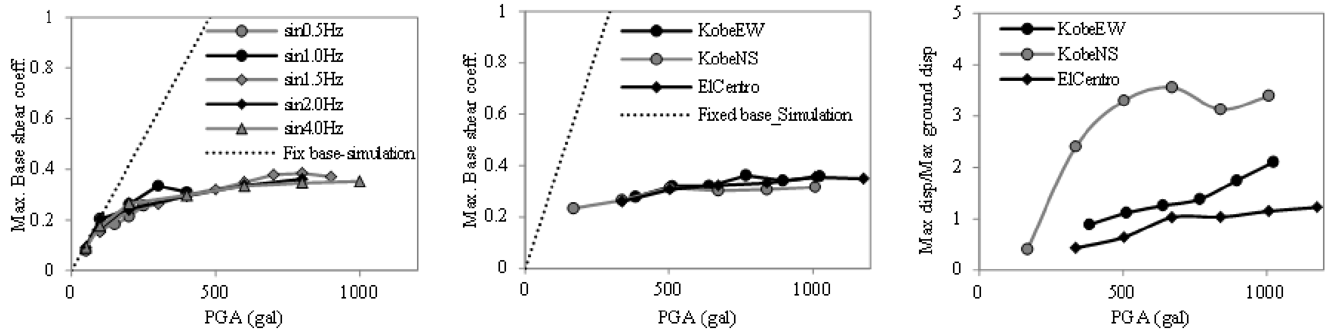


Figure 5. Time history responses: (a) base shear coefficient; (b) sliding displacement ratio; (c) axial force ratio



a) b) c)

Figure 6. Max base shear coefficient versus increasing PGA: (a) under sinusoidal inputs (b) under earthquake motions. (c) Max displacement over peak ground displacement versus increasing PGA under earthquake motions

of the sliding structure has as an asymptotic tendency towards a limit value, for both the sinusoidal inputs and earthquake motions. Most notably, in both cases the upper limit is approximately equal to 0.35. Furthermore, although various inputs were applied, with different frequency contents and peak ground accelerations, the maximum base shear coefficient did not show significant dependency on the input characteristics.

Since the most realistic case is represented by the application of earthquake inputs, Fig. 6 (c) shows the maximum sliding displacement normalized by the peak ground displacement ratio for increasing PGA. The maximum value of the displacement ratio varies from 1.2 to 3.4 and this variability reflects the different features of inputs considered. However, although peak ground accelerations larger than 10 m/s^2 were applied, the absolute values of the sliding displacements ranged from 250 mm to 490 mm, which is not necessarily so large. However, extremely large ground motions could lead to excessive sliding displacements. Thus, to prevent such undesirable behavior, introduction of stoppers or recentering systems may be needed and this is topic for future investigation.

5. Conclusions

To prevent extensive damage in building structures in case of extremely strong earthquakes, this paper presents a handy and low-cost seismic retrofit method. The proposed approach requires the separation of the column bases from the foundation to allow the superstructure to slide in case of large ground motions. Such structures have the attractive feature to cap the shear forces transmitted to the superstructure by means of the friction force developed between the sliding surfaces. In order to properly limit the shear forces, graphite powder is spread on the sliding surface.

Previous studies investigated the basic behaviour of lubricated sliding system using a rigid short specimen. This paper shows a new series of shake table test, which was conducted to investigate the efficiency of lubricated free-standing system for more realistic structures. The new specimen was designed to take into account the possible influence of overturning moment and the flexibility of the superstructure.

Based on the experimental results, the lubricated sliding system showed an efficient behaviour. Despite 450 loading cycles were applied and the base displacement ranged from 6 to 470 mm, the graphite lubrication provided very stable behaviour and reduced the dynamic friction coefficient to an average value of 0.17 with a standard deviation not greater than 0.05. Thanks to this, sliding was properly triggered, and the columns presented almost equal displacements. The base shear of the superstructure was reduced to more than 60% compared to the corresponding fixed base system and the overturning moment did not show a significant influence on the overall behaviour. Most notably, although different inputs with increasing peak ground accelerations were applied, the lubricated free-standing system provided an upper limit to the maximum base shear coefficient approximately equal to 0.35. This value did not show an obvious dependence on the input characteristics.

The present study is an initial investigation into the fundamental features of this separated system. Further tasks of the research will regard a continuous study on a methodology to evaluate the feasibility of the proposed approach as a seismic retrofit technique for the collapse prevention of existing structures. In particular, the aspects to be investigated are the applicability of the base-shear capping system in terms of (i) preliminary strength diagnosis of the existing structure, (ii) quantification and generalization of maximum base shear coefficient, (iii) limitation and control of the maximum sliding displacement and (iv) realization of technological construction details.

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