

Preliminary experimental verification of current content sliding modelling techniques

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ABSTRACT: Most analytical studies focusing on the sliding of building contents usually make an assumption that the friction force-sliding displacement behaviour is elasto-plastic (e.g. friction coefficient remains constant during sliding). This preliminary study uses experimental data to verify if this assumption is reasonable. Shake table tests of a desk on common flooring materials were conducted to investigate the factors influencing friction behaviour, and to observe the behaviour of the contents under sinusoidal motion. Up to a 15% decrease in friction coefficient was observed with either an 80% increase in mass or a 20 times decrease in relative velocity, indicating that the friction coefficient is dependent on these two parameters. A comparison of the experimental and analytical sliding response of the desk under a single sinusoidal loading pattern on carpet flooring was conducted. Results show that the displacement amplitude of a single sliding excursion and the general sliding trend is well approximated using the elasto-plastic assumption. As such, despite the dependence of friction coefficient on sliding mass and velocity, the elasto-plastic behaviour assumption appears to be reasonable for the sinusoidal loading pattern examined in this paper.

1 INTRODUCTION

It has been observed in past seismic events that movement of building contents can cause serious injury, damage and business disruption. The potential of damage has been highlighted in a shake table experiment of a multi-storey building fitted with office furnishings by Takuya et al. (2008), where large items of furniture (e.g. desks and copying machines) slid several meters at high velocity. Therefore, it is clearly important to consider content sliding when assessing the seismic performance of structures.

While several analytical studies are present in literature (e.g. Younis and Tadjbakhsh (1984), Garcia and Soong (2003), and Lin et al. (2013)), many of these make a common assumption that the friction coefficient remains constant during sliding of the content. This allows sliding to be modelled assuming an elasto-plastic friction force-sliding displacement hysteretic behaviour. While several experimental studies using rigid cubic blocks have shown that the force-displacement trend is generally elasto-plastic in nature (e.g. Aslam et al. (1975) and Nagao et al. (2012)), local oscillations of friction coefficients were observed leading to a large variation of friction coefficients. In addition, Chaudhuri and Hutchinson (2005) showed that the kinetic friction coefficient could potentially be dependent on the relative velocity between the content and floor. Other factors, such as mass and stiffness of the contents, could also influence the sliding behaviour.

In order to provide further experimental evidence to assess kinetic friction coefficients, shake table experiments were conducted at the University of Canterbury using common furniture and flooring materials. Analytical investigations were also conducted and compared with the experimental response to assess the applicability of the elasto-plastic assumption. This paper discusses preliminary findings from this study, and answers to the following questions are sought:

1. Is the static friction coefficient a reasonable estimate of the kinetic friction coefficient, and what parameters affect the friction coefficients?
2. Is the general friction force-sliding displacement trend elasto-plastic in nature?

3. How appropriate is the elasto-plastic assumption when modelling content sliding?

2 EXPERIMENTAL METHODOLOGY

2.1 General setup

The shake table used in this study is 3.5 m long by 2 m wide. Plywood was bolted onto the shake table to protect the surface, and to allow other flooring material to be glued over the top to prevent the flooring material from loosening. Nylon carpet and vinyl flooring were used in these experiments. The layout of the shake table is shown in Figure 1.

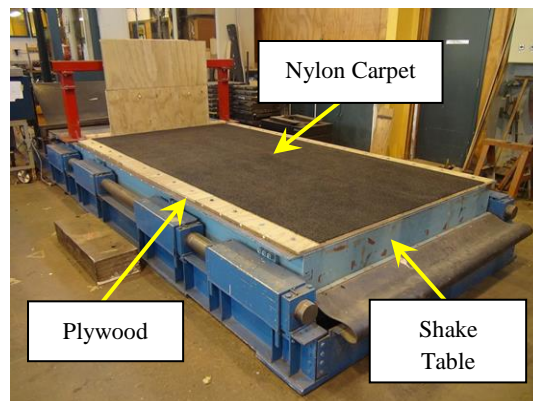


Figure 1. Layout of shake table with nylon carpet flooring (vinyl flooring not shown here)

While a range of furniture items were used in this study, only the results from the desk shown in Figure 2 is discussed in this paper. The desk has a mass of 24.5 kg and has rubber soles at the base of each leg. When subjecting the desk to floor excitation, the desk was orientated such that the direction of excitation is along the longer side of the table to prevent rocking/uplifting effects. Accelerometers were attached at the centre of the desk's top surface and on the shaking table.



Figure 2. Desks with rubber soles used in shake table experiment

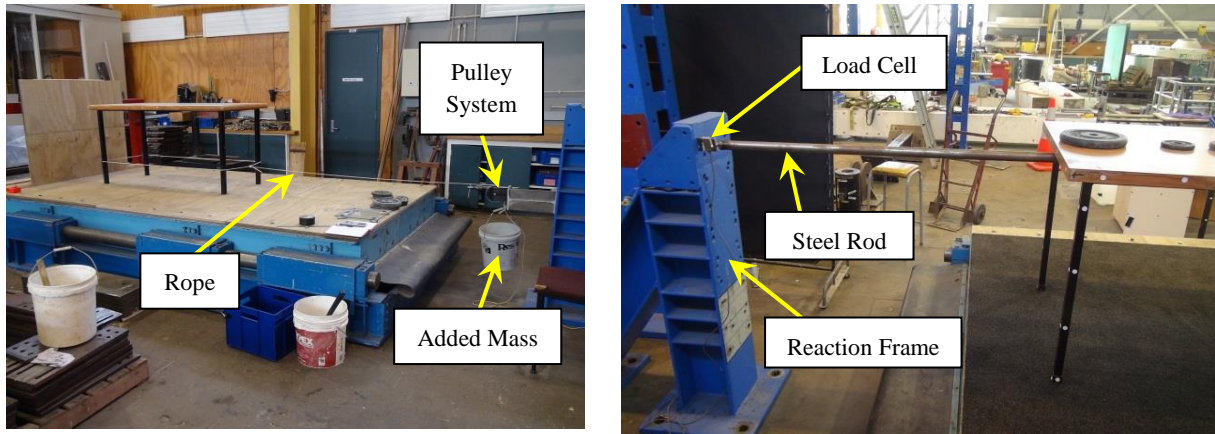
2.2 Determination of friction coefficients

There are two types of friction coefficients commonly referred to in literature; (i) static and (ii) kinetic. The former is related to the force required to initiate sliding of contents when the content is stationary relative to the floor, while the latter is related to the force required to sustain sliding when there is relative movement between the content and the floor. Different experimental setups were used to determine these coefficients.

The static friction coefficient, μ_s , was determined from static pull tests (shown in Figure 3a). A rope was tied around the content on one end, and attached to masses on the other end. A pulley system was used so that the weight of the attached mass equals the horizontal force applied to the content. Sand was slowly added until the content first starts to slide. The total applied mass was then recorded, and the ratio between the applied mass and the mass of the desk gives μ_s . A number of trials were

conducted to obtain a median value of μ_s . This was also repeated with the table facing the opposite direction to minimize directionality effects. The height of the applied horizontal load was initially varied, but it was found that the behaviour was not sensitive to this.

The kinetic friction coefficient, μ_k , was determined by fixing the content to a reaction frame using a steel rod attached to the desk (shown in Figure 3b). A load cell was connected between the steel rod and the reaction frame. The shake table was displaced at a constant rate of displacement (with the exception of the start and end of each test to reach the target or zero velocity) while the desk was held stationary. Five different displacement rates were applied; 0.5, 1.0, 3.0, 5.0 and 10.0 mm/s. In the first two cases, the table was displaced up to 50 mm in each direction, while other cases had up to 100 mm displacement. The limitation of 50 mm was applied in the first two cases to reduce the shake table run time. The load cell records the force required to keep the content stationary. This force divided by the weight of the desk gives μ_k . For both static and kinetic friction tests, additional weights were placed on the table top to observe if there were any dependencies due to increased mass.



(a) Setup for static friction coefficients

(b) Setup for kinetic friction coefficient

Figure 3. Friction coefficient tests setup (Note: flooring surface and contents shown in photos may not be that discussed in this paper)

2.3 Sinusoidal loading and video capture

While several sinusoidal loading patterns were used in the experiments, only the content response using the sinusoidal loading pattern shown in Figure 4 is discussed in this paper. This sinusoidal pattern has a frequency of 2 Hz and a peak displacement amplitude of 0.06 m. The displacement amplitude varies linearly for 2 seconds at the start and end of the test to bring the shake table from and back to its initial position.

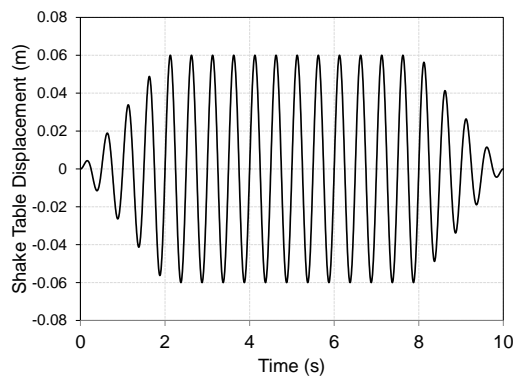


Figure 4. Sinusoidal loading pattern (frequency = 2 Hz, peak displacement amplitude = 0.06 m)

As the desk is unrestrained (i.e. free to move in any direction), a load cell could not be attached to record the sliding force. A Phantom high-speed camera (Miro M310 model) was used to record the displacements at 200 frames per second. The brightness, gain and gamma of the video was adjusted to

create greater contrast between the circular markers (attached to the side of the desks as shown in Figure 2) and the surroundings in order to utilize motion tracking. An example of this is shown in Figure 5. The motion tracking software used in this study was developed by the Hedrick Lab (Hedrick, 2008). This program allows for automatic tracking of multiple markers in a single analysis.



(a) Pre-processed video (markers not clearly defined)

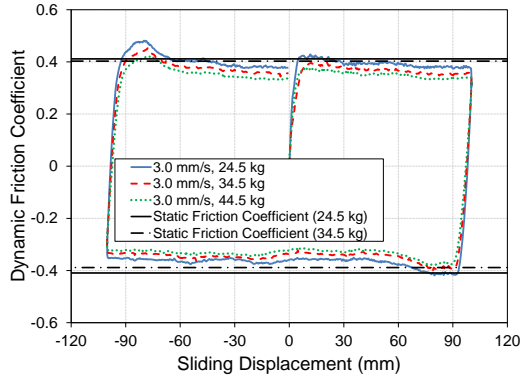
(b) Post-processed video (markers clearly defined)

Figure 5. Comparison of video pre and post-processing

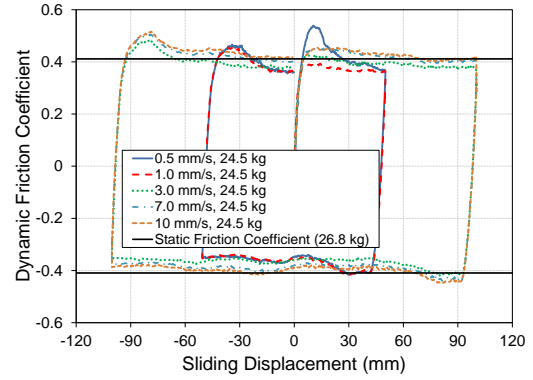
3 FRICTION COEFFICIENTS

The recorded static and kinematic friction coefficients, μ_s and μ_k , against sliding displacement curves for the desk on both carpet and vinyl flooring are shown in Figure 6. Note that different μ_s were recorded in each sliding direction, and is approximately 0.4 for both flooring materials. μ_s does not appear to vary significantly with an increase in mass. However, μ_k tends to decrease with increasing mass (up to a 15% drop with an 80% increase in mass), but increases with increasing relative velocity (up to a 15% increase with a 20 times increase in relative velocity). A possible explanation of the latter is that a larger force is required to satisfy energy equilibrium as more energy is dissipated during sliding in cases of higher velocity (through sound, heat etc). Further data processing is currently underway to identify other reasons for these trends. Generally, the value of μ_s gives a reasonable ballpark figure for μ_k (difference in value usually between +/- 0.05).

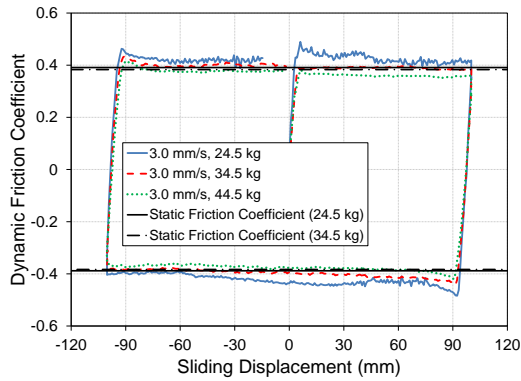
Interestingly, μ_k tends to be lower than μ_s when using carpet (Figures 6a and 6b) but higher when using vinyl flooring (Figures 6c and 6d). In addition, the μ_k curve using carpet flooring is smoother (less local oscillations), which indicates a smoother/less sticky sliding surface. However, there is a noticeable localised increase in the μ_k curve with the carpet flooring which usually occurs at the initiation of sliding. While a localised increase is also observed with vinyl flooring, it is not as prominent as that for carpet. This localised increase may be due to the desk's legs deforming, then releasing energy as they straighten out. Comparisons with other furniture will be examined in future studies to test this hypothesis. Following the localized increase in the curves, μ_k tends to decrease with increasing sliding displacement. On both surfaces the friction coefficient-sliding displacement relationship does appear to be reasonably elasto-plastic in nature.



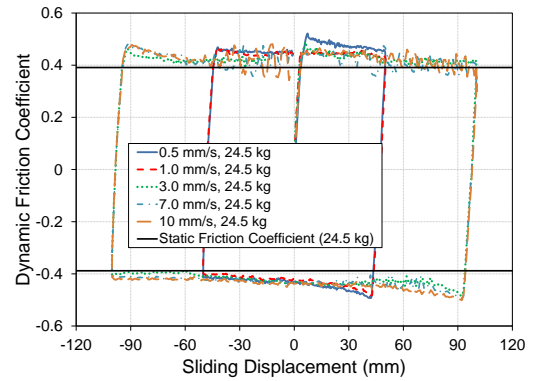
(a) Fixed velocity (3 mm/s), carpet flooring



(b) Fixed mass (24.5 kg), carpet flooring



(c) Fixed velocity (3 mm/s), vinyl flooring



(d) Fixed mass (24.5 kg), vinyl flooring

Figure 6. Friction coefficient-sliding displacement curves

4 KINETIC RESPONSE OF SHAKING TABLE AND CONTENT

The response of the shake table and the desk on carpet flooring under sinusoidal loading is shown in Figure 7. Similar trends were observed for other experiments conducted. The recorded experimental behaviour is similar to that observed in studies (e.g. Aslam et al. (1975) and Lin et al. (2013)), and can be summarized in the following steps:

1. Prior to $t = 1.8$ s, the shake table and contents' response is similar, although some minor sliding was observed. Within this range, the total acceleration of the shake table had not exceeded the friction coefficient of the content.
2. Noticeable separation first occurs at $t = 1.8$ s, as can be seen by the total displacement curves diverging at this point. Between $t = 1.8$ - 2.0 s, the content's total acceleration is reasonably constant. This results in the total content velocity being approximately linear.
3. At $t = 2.0$ s, the total velocity of the content and the shake table is the same (e.g. relative velocity is zero). Reversal of the content's acceleration occurs at this stage. Sliding in the opposite direction occurs once the friction coefficient is exceeded in that direction.
4. Steps (2) and (3) repeat until the friction coefficient is no longer exceeded after the relative velocity once again reaches zero.

Interestingly, the total content acceleration recorded for the content is approximately 38% higher than the friction coefficient recorded on average. This is possibly due to amplification of acceleration from the flexibility in the desk's legs, or due to vibration at the top surface of the desk. As such the acceleration recorded may not be equal to μ . As with Nagao et al. (2012), the content total acceleration-sliding displacement trend is elasto-plastic in nature, as shown by Figure 8. However, a noticeable variation in acceleration values is observed (about 20% difference between minimum and maximum total acceleration during sliding), which in turn means that there is a large variation in μ .

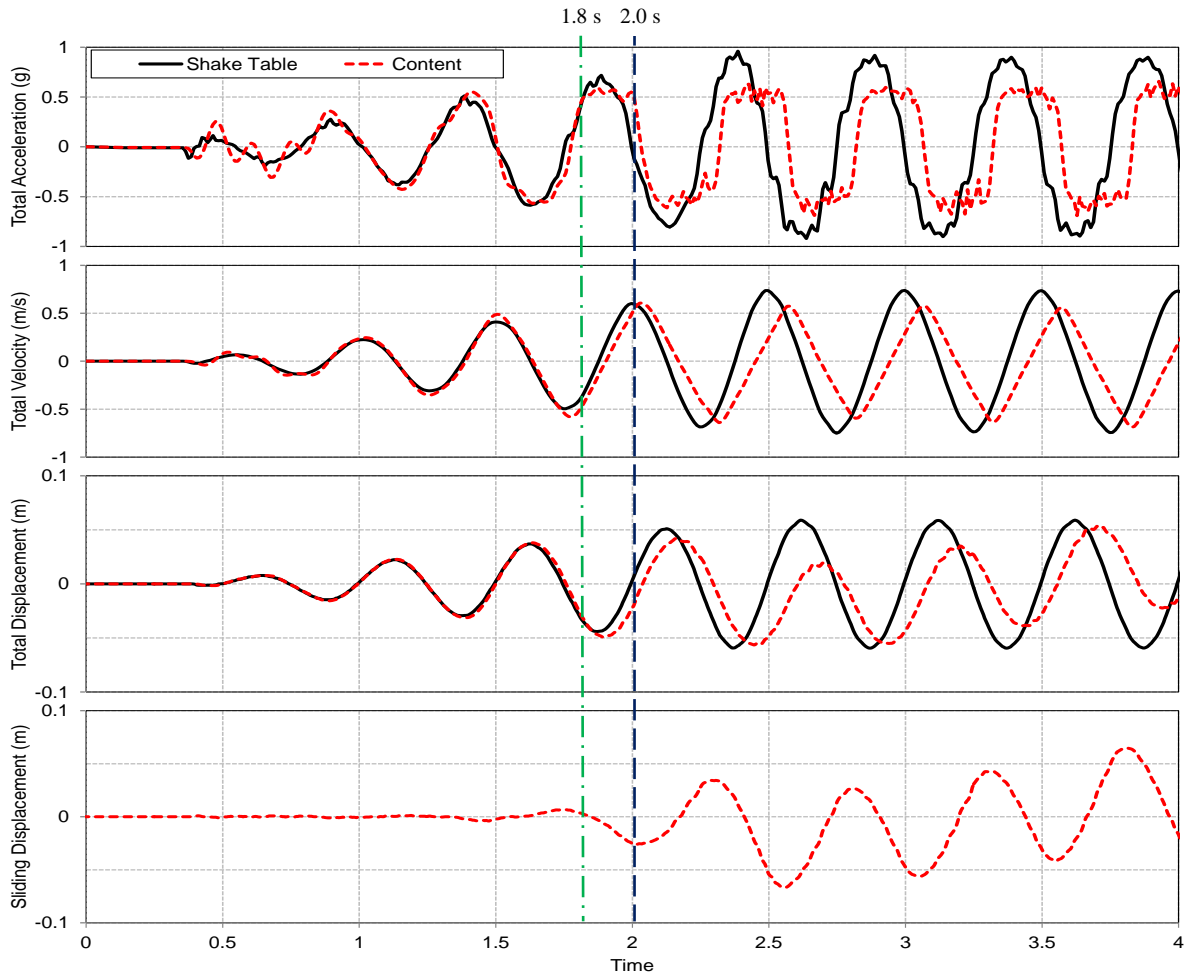


Figure 7. Shake table and desk response on carpet flooring under sinusoidal loading – first 4 seconds

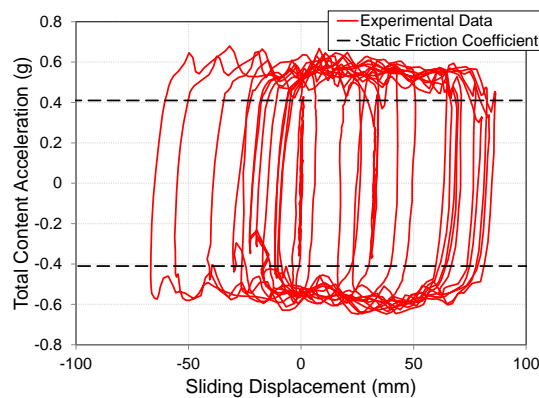


Figure 8. Total content acceleration-sliding displacement behaviour under sinusoidal loading

5 APPLICABILITY OF ELASTO-PLASTIC ASSUMPTION IN MODELLING OF SLIDING

A simple elasto-plastic content sliding model was created on Matlab (The MathsWorks Inc, 2012) and the recorded shake table total acceleration history when subjected to the sinusoidal excitation in Figure 4 was used as the input floor motion. The Newmark Constant Acceleration integration scheme was implemented to solve the equations of motion for both the floor and content. The following three friction coefficient cases listed were examined, the comparisons of which are shown in Figure 9.

1. $\mu = 0.4$ (static friction coefficient from friction tests).

2. $\mu = 0.5$ (peak friction coefficient observed during friction tests).
3. $\mu = 0.54$ (average friction coefficient recorded from sinusoidal loading test).

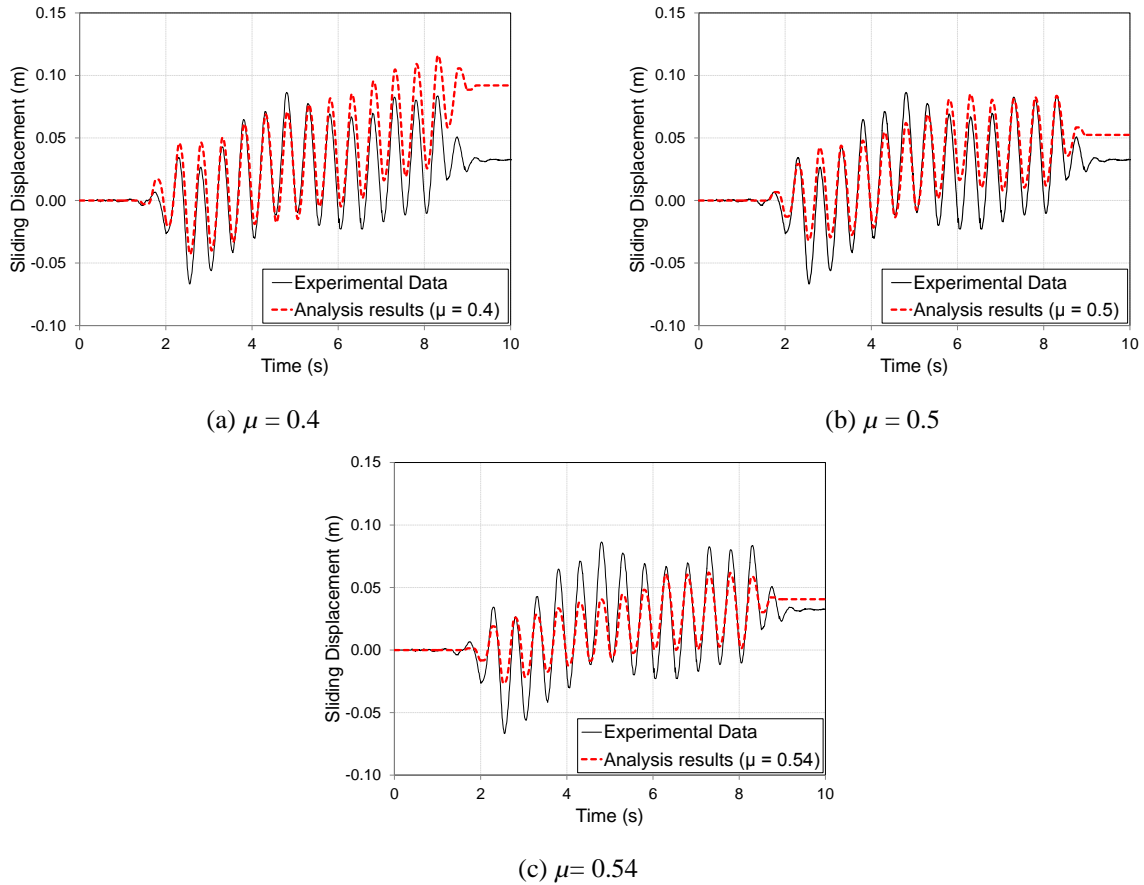


Figure 9. Comparison of experiment and analytical sliding displacement history (carpet flooring)

The $\mu = 0.4$ case (Figure 9a) was the best at predicting the sliding displacement amplitude of each excursion (within $\pm 10\%$). However, the maximum sliding displacement was overestimated by 33%, which was the poorest prediction out of all three cases. It can be seen that the analytical curve follows the experimental curve closely till the 6.0 s mark. After this point, the experimental data showed that the desk had a tendency to slide more towards the negative direction. This effect was not captured by the analysis, which resulted in the large maximum displacement observed.

The $\mu = 0.5$ case (Figure 9b) was the closest match in terms of maximum sliding displacement (underestimated by 1.5%) and general trend (average sliding displacement tapers off at 6.0 s rather than continuously increasing). However, the amplitude for each excursion was underestimated by approximately 25%.

The $\mu = 0.54$ case (Figure 9c) had the worst prediction in terms of the maximum sliding excursion amplitude (underestimated by 50%). While the prediction of the maximum sliding displacement was underestimated by 27%, the residual sliding displacement was the closest out of all cases considered. However, it can be seen that the overall trend was the worst fit of all three cases, especially in the first six seconds. This shows that the high total content acceleration values recorded in Figure 8 was most likely an amplification of μ .

Overall, the elasto-plastic friction force-sliding displacement assumption is able to predict reasonably accurately the displacement amplitude of each sliding excursion, provided an appropriate value of μ was used (μ_s in this case). While it is unlikely that the elasto-plastic assumption can be used to accurately predict the complete sliding response history, it can still predict the general trend well for the case examined in this paper.

6 CONCLUSIONS

This paper summarizes shake table tests of a desk on common flooring materials that were conducted to investigate the factors influencing friction behaviour, and to observe the behaviour of the contents under sinusoidal motion. The findings of this paper are as follows:

1. The static friction coefficient reasonably estimates the kinetic friction coefficient (difference in value between +/- 0.05). The kinetic friction coefficients are dependent on the content mass and relative velocity. A decrease of up to 15% was observed with either an 80% increase in mass or a 20 times decrease in relative velocity.
2. Generally experimental results show that the average friction force-sliding displacement relationship is approximately elasto-plastic. However, local oscillations in the hysteresis curve were observed both in friction tests and under sinusoidal loading tests, leading to a 20% variation in friction coefficients. A localized increase was observed in the friction force-sliding displacement relationships, particularly for carpet flooring, after which the friction coefficient tends to decrease with increasing sliding displacement.
3. Comparisons between the sliding displacement history from experiment and analysis showed that the elasto-plastic assumption captures the displacement amplitude of a single excursion within +/- 10% error, provided that a friction coefficient value close to μ_s was used. However, the maximum total sliding displacement was over-predicted, though the general sliding displacement trend was reasonably well captured.

7 ACKNOWLEDGMENTS

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