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Static and Kinetic Coefficients of Friction for Rigid Blocks

by
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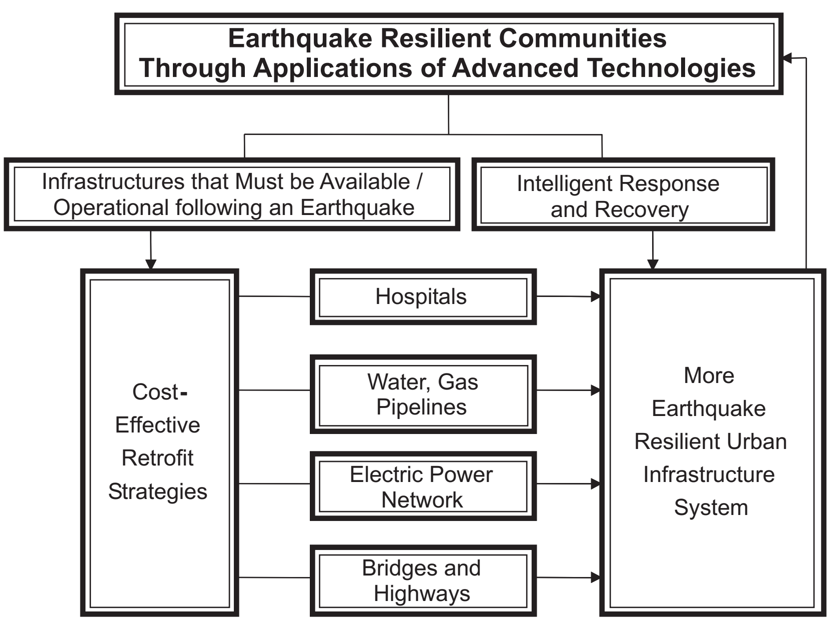
Preface

The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established by the National Science Foundation in 1986, as the National Center for Earthquake Engineering Research (NCEER).

Comprising a consortium of researchers from numerous disciplines and institutions throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

MCEER's NSF-sponsored research objectives are twofold: to increase resilience by developing seismic evaluation and rehabilitation strategies for the post-disaster facilities and systems (hospitals, electrical and water lifelines, and bridges and highways) that society expects to be operational following an earthquake; and to further enhance resilience by developing improved emergency management capabilities to ensure an effective response and recovery following the earthquake (see the figure below).



A cross-program activity focuses on the establishment of an effective experimental and analytical network to facilitate the exchange of information between researchers located in various institutions across the country. These are complemented by, and integrated with, other MCEER activities in education, outreach, technology transfer, and industry partnerships.

The study described in this report is the first phase of research on the seismic performance evaluation of block-type nonstructural components. The analytical work was performed at Cornell University, while the experimental study was conducted at the University at Buffalo. The objective was to characterize the coefficients of friction of three interfaces for rigid blocks with low, medium, and high coefficients of friction. The three interfaces selected for this purpose were Poly-Tetra-Fluoro-Ethylene on steel, wood on steel, and carpet on steel, which represented interfaces with low, moderate, and high coefficients of friction, respectively. Two sets of blocks with different geometry were designed and constructed to model block-type nonstructural components. The static coefficients of friction for the three interfaces were characterized by a series of standard pull and tilt tests. The uncertainties associated with the imperfections in the block-floor interfaces were accounted for by repeated testing. Estimates of the kinetic coefficient of friction were calculated using the maximum responses of the blocks obtained through laboratory experiments and analytical relationships between the maximum responses and the kinetic coefficient of friction. The method explicitly accounted for the uncertainty in experimental errors, imperfections in block-floor interfaces, and the relationship between the kinetic friction coefficient and the loading and block size.

ABSTRACT

The study described in this report is the first phase of research on the seismic performance evaluation of the block-type nonstructural components, supported by the Multidisciplinary Center for Earthquake Engineering Research. The main objective of this study was to characterize the coefficients of friction of three interfaces for rigid blocks with low, medium, and high coefficients of friction. The three interfaces selected for this purpose were Poly-Tetra-Fluoro-Ethylene on steel, wood on steel, and carpet on steel, which were representatives of interfaces with low, moderate, and high coefficients of friction, respectively. Two sets of blocks with different geometry were designed and constructed to model block-type nonstructural components. The block geometries were selected to assure that the blocks would respond to a broad range of uniaxial sinusoidal base excitations by either sticking or sliding. The static coefficients of friction for the three interfaces were characterized by a series of standard pull and tilt tests. The uncertainties associated with the imperfections in the block-floor interfaces were accounted for by repeated testing. Estimates of the kinetic coefficient of friction were calculated using the maximum responses of the blocks obtained through earthquake simulator experiments and analytical relationships between the maximum responses and the kinetic coefficient of friction. The implemented method explicitly accounted for the uncertainty in experimental errors, imperfections in block-floor interfaces, and the relationship between the kinetic friction coefficient and the loading and block size.

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SECTION 1
INTRODUCTION

1.1 Block-Type Nonstructural Components

The seismic performance of building structures depends on the performance of their structural and nonstructural systems. Regardless of the performance of structural systems, a building might lose its functionality just because of the damage to its nonstructural components or critical equipments (Soong and Yao, 2000; Filiatrault et al, 2001). Furthermore, recent studies have shown that the financial consequences of earthquakes result mainly from the poor performance of nonstructural components and systems. Consequently, without consideration of the nonstructural components, performance-based design of buildings seems to be unachievable (Gould, 2003; Kircher, 2003).

A large number of nonstructural components respond to the floor excitation like rigid blocks. These nonstructural components are categorized as block-type nonstructural components. The block-type nonstructural components are either freestanding or restrained (tied to the building floor or wall by bolts, cables, etc.). Most nonstructural components are freestanding by either necessity or choice.

In two dimensions, the response of a restrained block is fully described by two response states: stick and slide. For the two-dimensional response of a freestanding block on the other hand, five different modes are possible: stick, slide, rock, slide-rock, and free flight. Possible response modes for rigid blocks have been identified by many researchers including Ishiyama (1982), Shenton (1996), Pompei et al. (1998), Zhu and Soong (1998), Taniguchi (2002 and 2004), and Garcia and Soong (2003).

Sliding is preferred to rocking for freestanding rigid blocks because high acceleration spikes developed during rocking can damage nonstructural components, energy dissipation during impact is minimal, and rocking might result in overturning, which is often destructive.

Excessive absolute acceleration and relative displacement should be avoided for sliding of a block-type nonstructural component. Excessive absolute acceleration is detrimental for the acceleration-sensitive nonstructural components, and excessive relative displacement during sliding might result in collision of neighboring nonstructural components, or blockage of a doorway required for evacuation after an earthquake.

Several studies have emphasized the influence of the static and kinetic coefficients of friction of the rigid block-floor interface on the response of the block. Shenton (1996) showed that the initial mode of the response is governed by the static coefficient of friction. The initial mode is important because it often remains the predominant mode for the ongoing response.

Garcia and Soong (2003) studied the sliding fragility of rigid blocks and showed that for the case of absolute acceleration limit state, evaluation of the static coefficient of friction is essential for the deterministic fragility assessment. They showed that at a given threshold (absolute acceleration limit), the fragility curves depended only on two parameters: the kinetic coefficient of friction and the vertical peak base acceleration. Garcia and Soong (2003) proved that in presence of high friction, the fragility assessment without consideration of the vertical base acceleration was noticeably un-conservative for both freestanding and restrained rigid blocks.

The analytical and experimental study of Warren and Matzen (2001) showed that a numerical model that included only one of the static and kinetic coefficients of friction was incapable of prediction of sliding block response. They suggested a velocity-dependent kinetic coefficient of friction be used for better prediction of the sliding block response.

1.2 Scope of Study

The study described in this report is the first phase of the research on the block-type nonstructural components supported by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The main objective of this study is to characterize the static and kinetic coefficients of friction of three interfaces for rigid blocks with low, medium, and high coefficients of friction.

The three interfaces selected for this study were 1) Poly-Tetra-Fluoro-Ethylene (PTFE) on steel, 2) wood on steel, and 3) carpet on steel, which were considered likely to result in low, moderate, and high coefficients of friction, respectively.

Two sets of blocks with different geometry were designed and constructed to model block-type nonstructural components. The block geometries were selected to assure that the blocks would respond to a broad range of uniaxial sinusoidal base excitations by either sticking or sliding.

The static coefficients of friction were characterized by series of standard pull and tilt tests. Characterization tests were repeated to generate a sufficient number of data points to account explicitly for the uncertainties associated with imperfections in the block-floor interfaces. At the end of the characterization tests, preliminary estimates of the kinetic coefficients of friction were obtained by series of tilt tests for the wood-steel and carpet-steel interfaces. In these experiments, the acceleration of a block sliding down an inclined surface was measured by an accelerometer attached to the sliding block.

The kinetic coefficients of friction of the three interfaces were established by analysis of the acceleration and displacement response of the blocks throughout series of earthquake simulator experiments with uniaxial sinusoidal input excitation. The implemented method explicitly accounted for the uncertainty in experimental errors, imperfections in block-floor interfaces, and the relationship between the kinetic friction coefficient and the loading and block size.

1.3 Report Organization

This report consists of two major parts. The first part of the report (Sections 2 to 4), which addresses the experimental part of the study was prepared by the authors at University at Buffalo, the State University of New York. The second part of the report (Sections 5 to 8), which presents the analytical part of the study was prepared by the authors at Cornell University.

In Section 2, the design and construction of the blocks are described. Section 3 presents the test plan, instrumentation, and results of the characterizations tests for the static coefficients of friction of the three interfaces and preliminary estimates for the kinetic coefficient of friction of wood-steel and carpet-steel interface. Section 4 describes the earthquake simulator experiments conducted to provide data to establish the kinetic coefficients of friction.

Section 5 describes the dynamic analysis of the block-floor system. The methodology for establishing the kinetic friction coefficient using acceleration and displacement-based approaches is presented in Section 6. The experimental results obtained from earthquake simulator experiments are analyzed in Section 7. The kinetic coefficients of friction are given in Section 8, followed by summary and conclusions in Section 9.

SECTION 2

DESIGN AND CONSTRUCTION OF TEST SPECIMENS

2.1 Test Specimen Design

The block geometry and interface materials were selected to ensure that the blocks would respond to a broad range of uniaxial sinusoidal base excitations by either sliding or sticking modes of response.

For a rigid block subjected to a general tri-directional motion in the x_1, y_1, and z_1 (vertical) directions, the conditions to prevent rocking are given by equations 2-1 through 2-4 (Chong and Soong, 2000):

$$\frac{B}{H} \geq \frac{1}{\frac{g}{|\ddot{x}_1|} - k_{z_1}} \tag{2-1}$$

$$\frac{W}{H} \geq \frac{1}{\frac{g}{|k_{y_1}\ddot{x}_1|} - k_{z_1}} \tag{2-2}$$

$$k_{y_1} = \frac{\ddot{y}_1}{\ddot{x}_1} \tag{2-3}$$

$$k_{z_1} = \frac{\ddot{z}_1}{\ddot{x}_1} \tag{2-4}$$

where:

B = width of the block's base in direction x_1
W = width of the block's base in direction y_1
H = height of the block in direction z_1
g = acceleration due to gravity
$\ddot{x}_1$ = peak base acceleration in direction x_1
$\ddot{y}_1$ = peak base acceleration in direction y_1
$\ddot{z}_1$ = peak base acceleration in direction z_1
k_{y_1} = ratio of the peak base acceleration in direction y_1 to the peak base acceleration in direction x_1
k_{z_1} = ratio of the peak base acceleration in direction z_1 to the peak base acceleration in direction x_1

The condition under which sliding occurs is given by equation 2-5 (Taniguchi, 2002):

$$m_S < \text{Min}\left(\frac{1}{\frac{g}{\text{Max}(|\ddot{x}_1|,|\ddot{y}_1|)} + k_{z_1}}, \frac{B}{H}, \frac{W}{H}\right) \tag{2-5}$$

where:

m_S = static coefficient of friction of the interface

If the base excitation is in the x_1 direction only (this study), equations 2-1 and 2-5 simplify to equations 2-6 and 2-7, respectively:

$$\frac{B}{H} \geq \frac{|\ddot{x}_1|}{g} \tag{2-6}$$

$$m_s < \mathrm{Min}\left(\frac{|\ddot{x}_1|}{g}, \frac{B}{H}\right) \tag{2-7}$$

Equations 2-6 and 2-7 can be combined to form equation 2-8:

$$\frac{B}{H} \geq \frac{|\ddot{x}_1|}{g} > m_s \tag{2-8}$$

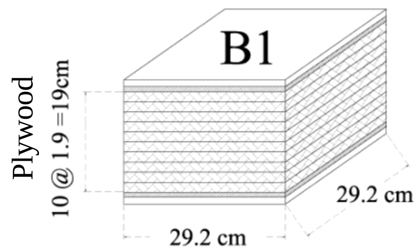
Equation 2-8 summarizes the conditions required for sliding and no-rocking response of a rigid block to a uniaxial base excitation. Width-to-height ratios greater than 0.8 for the blocks would satisfy equation 2-8 over a broad range of input motions and interface materials. Two six-block sets were constructed of different sizes for this study and a potential future study to investigate the influence of block geometry on response. Six nominally identical blocks in each set were deemed sufficient to provide data for statistical analysis accounting explicitly for the randomness associated with the block-floor interfaces.

Three different interfaces PTFE-steel, wood-steel, and carpet-steel were chosen as representative of interfaces with low, moderate, and high coefficients of friction, respectively. The coefficients of friction (both static and kinetic) of the PTFE-steel and wood-steel interfaces were estimated to be between 0.05 to 0.20, and 0.2 to 0.5, respectively and the coefficients of friction (both static and kinetic) of the carpet-steel interface were estimated to be larger than 0.4.

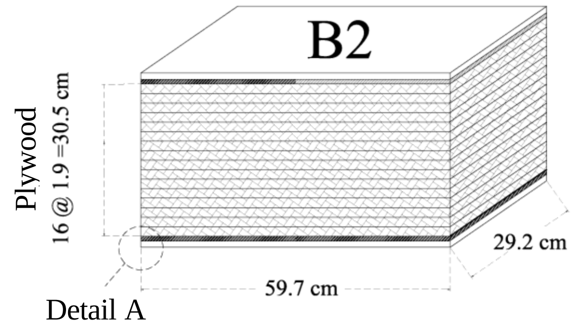
2.2 Test Specimen Construction

The test blocks were constructed by joining multiple layers of plywood with glue and pins. Steel plates were attached to the bottom and top surfaces of each block to act as backing for the interface material. The carpet was glued to the steel. The wood and PTFE surfaces were screwed to the blocks. Figure 2-1 presents some construction details. Figure 2-2 presents photographs taken during and after the construction of the blocks.

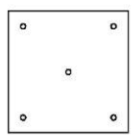
Table 2-1 lists the dimensions and mass of the twelve constructed blocks. Block names have general format of Bij; i indicates the block type and is either 1 or 2. B1j are the smaller of the two sets of blocks. In this report, B1 and B2 are used instead of B1j and B2j when referring to a block set. Since there are six nominally identical blocks of each size, j varies from 1 to 6.



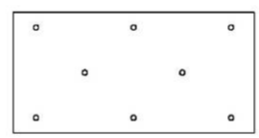
(a) Block type B1



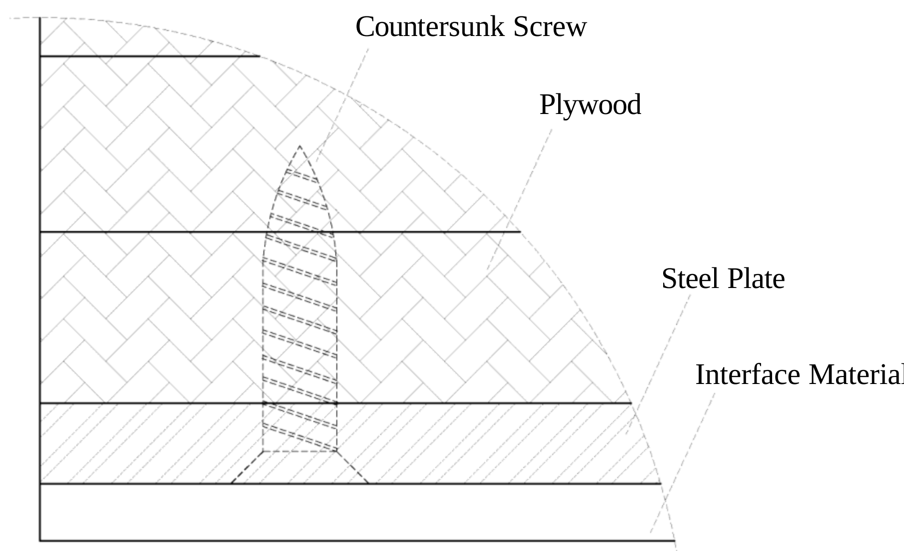
(b) Block type B2



(c) Steel plate $(29.2 \times 29.2 \times 0.47$ cm), attached to the top and bottom of the block type B1



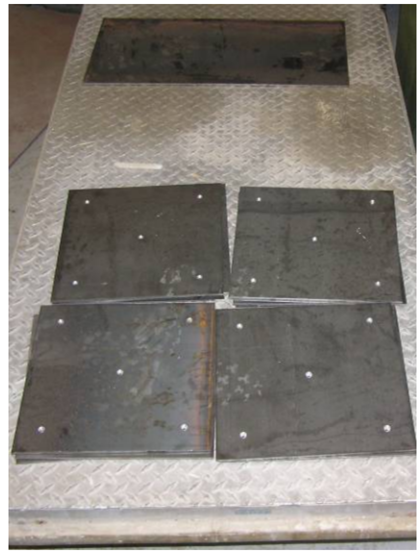
(d) Steel plate $(59.7 \times 29.2 \times 0.47$ cm), attached to the top and bottom of the block type B2



(e) Detail A

FIGURE 2-1 Block Details

(a) Plywood layers used for the blocks



(b) Steel plates screwed to top and bottom of the blocks

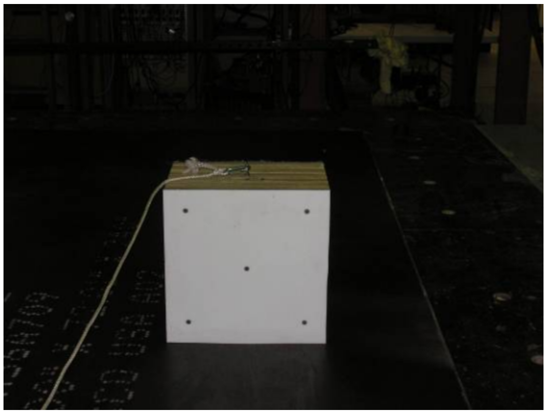
(c) Block type B1, wood surface

(d) Block type B1, carpet surface

(e) Block type B2, wood surface

(f) Block type B2, carpet surface

FIGURE 2-2 Block Construction



(g) Block type B1, PTFE surface

(h) Block type B2, PTFE surface

FIGURE 2-2 (cont'd.) Block Construction

TABLE 2-1 Block Dimensions and Mass

Block Name	**Dimension (cm)**	**Mass (kg)**
B11	29.2 × 29.2 × 20.5	16.1
B12	29.2 × 29.2 × 20.5	15.6
B13	29.2 × 29.2 × 20.5	15.9
B14	29.2 × 29.2 × 20.5	15.6
B15	29.2 × 29.2 × 20.5	15.6
B16	29.2 × 29.2 × 20.5	15.9
B21	59.7 × 29.2 × 32.4	44.9
B22	59.7 × 29.2 × 32.4	44.5
B23	59.7 × 29.2 × 32.4	44.0
B24	59.7 × 29.2 × 32.4	44.0
B25	59.7 × 29.2 × 32.4	44.0
B26	59.7 × 29.2 × 32.4	44.2

SECTION 3

CHARACTERIZATION TESTS:
PULL AND TILT TESTS

3.1 Tilt and Pull Tests to Establish Static Coefficient of Friction

The static coefficient of friction controls the initiation of sliding of a rigid block. Rigid blocks are more likely to experience sticking or rocking rather than sliding if the static coefficient of friction is high (Shenton 1996; Taniguchi, 2002).

A relatively accurate evaluation of the static coefficients of friction between the interface materials and the steel plate was essential to plan for the earthquake simulator experiments and to perform analytical studies throughout this study. A series of tilt and pull tests was conducted to establish the static coefficients of friction of the three interfaces. The pull and tilt tests are straightforward and provide satisfactory results (Chong and Soong, 2000; Konstantinidis and Makris, 2003).

3.1.1 Test Plan and Instrumentation

The pull tests were undertaken by manually applying a horizontal force to the block up to the point at which the block slid (see figure 3-1(a)). The horizontal load was applied at a very slow rate and was measured by a load cell calibrated to measure forces up to 45 kilogram-force (kgf). The load cell used for the pull test series is shown in figure 3-1(b).

The pull tests for the wood-steel and carpet-steel interfaces were repeated twice for each of the twelve blocks. To prevent scoring of the PTFE surfaces of the blocks (see figure 3-1(c)), the characterization tests were conducted for only two of the twelve blocks: B16 and B26. The pull test for each of the two blocks was repeated 10 times.

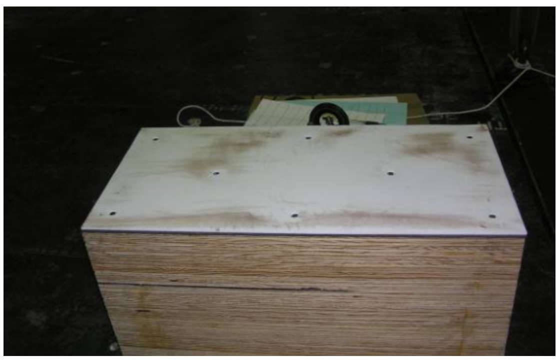
A series of tilt tests was conducted to confirm the values of the static coefficient of friction determined by pull tests. The tilt tests were conducted by lifting one edge of the sliding surface (5.1 cm thick, 152 by 274 cm steel plate) until the block slid (see figure 3-1(d)). The static coefficient of friction, m_s, is related to a, the angle of the surface to the horizontal at the initiation of the sliding:

$$m_s = \tan a \qquad (3\text{-}1)$$

The angle a was measured directly by an inclinometer and calculated indirectly by measuring the height and horizontal distance from the pivot point of the steel plate.

(a) Pull test, block type B2, horizontal force applied manually

(b) Load cell used to measure horizontal force



(c) Showing evidence of scoring of PTFE surface

(d) Tilt test, block type B1, crane used to lift the steel plate

FIGURE 3-1 Tilt and Pull Tests

3.1.2 Test Results

The data generated in each pull test was the horizontal force history measured by the load cell. To calculate the static coefficient of friction, the force at the initiation of sliding was divided by the weight of the block.

Figure 3-2 presents the horizontal force history of the pull test conducted with the carpet surface of block B11. Given the force at the initiation of sliding (7.81 kgf) and block B11 mass (16.08 kg), the static coefficient of friction is calculated as:

$$m_S = \frac{7.81}{16.08} = 0.49 \tag{3-2}$$

The reduction in the horizontal force after initiation of sliding seen in figure 3-2 is attributed to the static coefficient of friction being greater than the kinetic coefficient of friction (Blau, 1996).

The same procedure was implemented to compute the static coefficient of friction of the three interfaces from the pull test results. The measured angle at which each block slid and equation 3-1 were used to compute the static coefficient of friction of the three interfaces from the tilt tests results.

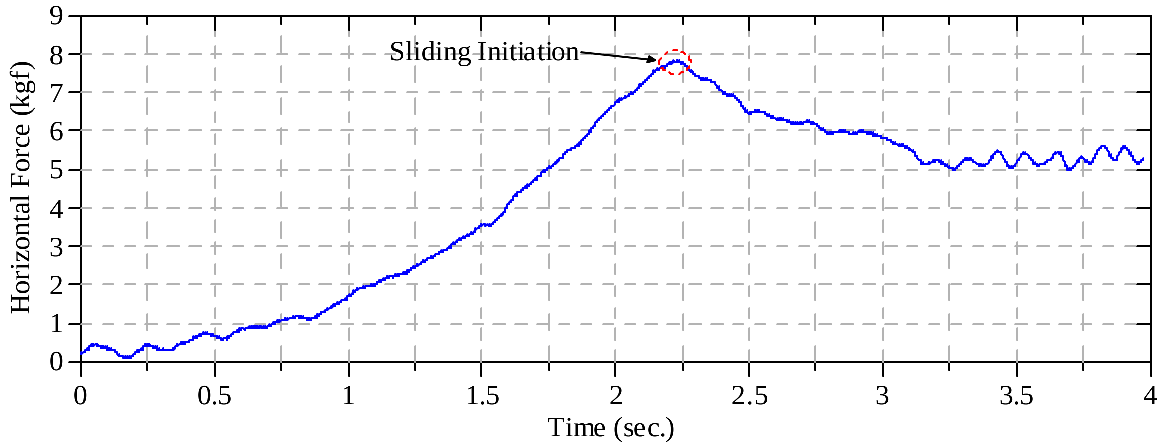


FIGURE 3-2 Pull Test Horizontal Force History, Carpet-Steel Interface, Block B11

Tables 3-1 and 3-2 list the static coefficients of friction of the carpet-steel and wood-steel interfaces of the block types B1 and B2, respectively. Table 3-3 presents the results of the tilt and the pull tests for the static coefficient of friction of the PTFE-steel interface. Tables 3-4, 3-5, and 3-6 summarize the results for the static coefficient of friction of carpet-steel, wood-steel, and PTFE-steel interfaces, respectively. The mean and standard deviation values presented in tables 3-4 through 3-6, are calculated assuming that the static coefficients of friction are Gaussian.

TABLE 3-1 Static Coefficients of Friction, Wood-Steel and Carpet-Steel Interfaces, Block Type B1

Block Name	Surface	Pull Test		Tilt Test	
B11	Carpet	0.49	0.49	0.49	0.45
	Wood	0.42	0.42	0.36	0.40
B12	Carpet	0.43	0.42	0.47	0.42
	Wood	0.45	0.35	0.36	0.36
B13	Carpet	0.48	0.42	0.41	0.48
	Wood	0.42	0.39	0.34	0.34
B14	Carpet	0.46	0.43	0.46	0.43
	Wood	0.42	0.37	0.38	0.38
B15	Carpet	0.49	0.47	0.44	0.43
	Wood	0.42	0.38	0.38	0.37
B16	Carpet	0.47	0.45	0.51	0.48
	Wood	0.46	0.40	0.38	0.37

TABLE 3-2 Static Coefficients of Friction, Wood-Steel and Carpet-Steel Interfaces, Block Type B2

Block Name	Surface	Pull Test		Tilt Test	
B21	Carpet	0.42	0.43	0.42	0.43
	Wood	0.46	0.49	0.32	0.37
B22	Carpet	0.51	0.48	0.41	0.43
	Wood	0.42	0.49	0.38	0.38
B23	Carpet	0.48	0.47	0.44	0.42
	Wood	0.43	0.38	0.38	0.36
B24	Carpet	0.49	0.48	0.44	0.43
	Wood	0.44	0.42	0.33	0.36
B25	Carpet	0.48	0.42	0.41	0.41
	Wood	0.47	0.46	0.37	0.39
B26	Carpet	0.47	0.45	0.45	0.43
	Wood	0.42	0.36	0.39	0.40

TABLE 3-3 Static Coefficients of Friction, PTFE-Steel Interface, Blocks B16 and B26

Test No.	Block B16		Block B26	
	Pull Test	Tilt Test	Pull Test	Tilt Test
1	0.23	0.23	0.26	0.31
2	0.21	0.26	0.25	0.36
3	0.22	0.34	0.23	0.32
4	0.22	0.35	0.24	0.30
5	0.20	0.33	0.25	0.35
6	0.20	0.29	0.23	0.34
7	0.17	0.26	0.20	0.32
8	0.23	0.32	0.22	0.32
9	0.23	0.35	0.23	0.33
10	0.23	0.23	0.21	0.29

TABLE 3-4 Static Coefficient of Friction, Carpet-Steel Interface[1]

Block Type	m_s												$\bar{m}_{si}$	s_i	$\bar{m}_s$	s
B1	0.49	0.49	0.49	0.45	0.43	0.42	0.47	0.42	0.48	0.42	0.41	0.48	0.46	0.030	0.45	0.030
	0.46	0.43	0.46	0.43	0.49	0.47	0.44	0.43	0.47	0.45	0.51	0.48				
B2	0.42	0.43	0.42	0.43	0.51	0.48	0.41	0.43	0.48	0.47	0.44	0.42	0.45	0.030		
	0.49	0.48	0.44	0.43	0.48	0.42	0.41	0.41	0.47	0.45	0.45	0.43				

1. m_s is the static coefficient of friction; $\bar{m}_{si}$ is the mean and s_i is the standard deviation of the static coefficient of friction obtained in tests with each block type; $\bar{m}_s$ is the mean and s is the standard deviation of the static coefficient of friction obtained in all the tests conducted.

TABLE 3-5 Static Coefficients of Friction, Wood-Steel Interface[1]

Block Type	m_s												$\bar{m}_{si}$	s_i	$\bar{m}_s$	s
B1	0.42	0.42	0.36	0.40	0.45	0.35	0.36	0.36	0.42	0.39	0.34	0.34	0.39	0.030	0.40	0.040
	0.42	0.37	0.38	0.38	0.42	0.38	0.38	0.37	0.46	0.40	0.38	0.37				
B2	0.46	0.49	0.32	0.37	0.42	0.49	0.38	0.38	0.43	0.38	0.38	0.36	0.40	0.050		
	0.44	0.42	0.33	0.36	0.47	0.46	0.37	0.39	0.42	0.36	0.39	0.40				

1. m_s is the static coefficient of friction; $\bar{m}_{si}$ is the mean and s_i is the standard deviation of the static coefficient of friction obtained in tests with each block type; $\bar{m}_s$ is the mean and s is the standard deviation of the static coefficient of friction obtained in all the tests conducted.

TABLE 3-6 Static Coefficients of Friction, PTFE-Steel Interface[1]

Block Type	m_s										$\bar{m}_{si}$	s_i	$\bar{m}_s$	s
B1	0.23	0.21	0.22	0.22	0.20	0.20	0.17	0.23	0.23	0.23	0.26	0.055	0.27	0.054
	0.23	0.26	0.34	0.35	0.33	0.29	0.26	0.32	0.35	0.23				
B2	0.26	0.25	0.23	0.24	0.25	0.23	0.20	0.22	0.23	0.21	0.28	0.052		
	0.31	0.36	0.32	0.30	0.35	0.34	0.32	0.32	0.33	0.29				

1. m_s is the static coefficient of friction; $\bar{m}_{si}$ is the mean and s_i is the standard deviation of the static coefficient of friction obtained in tests with each block type; $\bar{m}_s$ is the mean and s is the standard deviation of the static coefficient of friction obtained in all the tests conducted.

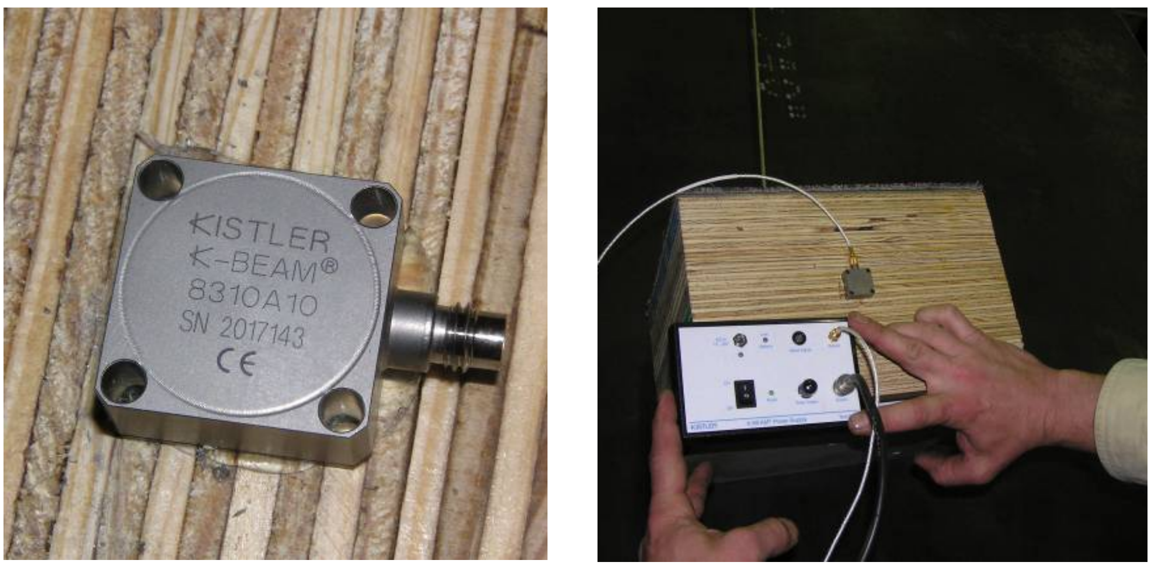
3.2 Tilt Tests for Preliminary Estimation of Kinetic Coefficient of Friction

3.2.1 Test Plan and Instrumentation

Tilt tests were undertaken to provide preliminary estimates of the kinetic coefficients of friction, which were required to predict the maximum displacement of the blocks in the earthquake simulator experiments. The predicted maximum displacement response of the blocks were used to arrange the blocks on the steel plate so that they could slide without hitting each other or sliding off the steel plate during the earthquake simulator experiments.

The acceleration of a block sliding down the inclined steel plate was used to estimate the kinetic coefficient of friction of the wood-steel and carpet-steel interfaces.

The steel plate (the sliding surface) was held at either 30 or 45 degrees to the horizontal. The acceleration of the blocks sliding down the steel plate was measured by an accelerometer. As shown in figure 3-3, the accelerometer was attached to one of the side faces of the sliding block.



(a) Accelerometer (b) Signal conditioning system

FIGURE 3-3 Tilt Tests Instrumentation

The test plan is presented in table 3-7. Because of the heavy weights of the block type B2 and the difficulty in placing them on the sliding surface, only block B26 was used in this series of tilt tests. Tests were repeated 6 times for each of the carpet and wood surfaces of block B26. This series of tilt tests did not include the PTFE-steel interface because the block with PTFE surface would not slide down the inclined surface in a straight line (would rotate whiling sliding down), and repeated testing would damage the PTFE surfaces.

TABLE 3-7 Plan of Tilt Tests for Preliminary Estimation of the Kinetic Coefficient of Friction of Wood-Steel and Carpet-Steel Interfaces[1]

Test No.	Block Name	α	Surface	Test No.	Block Name	α	Surface	Test No.	Block Name	α	Surface
1	B11	30	Carpet	13	B11	30	Wood	25	B11	45	Carpet
2	B12	30	Carpet	14	B12	30	Wood	26	B12	45	Carpet
3	B13	30	Carpet	15	B13	30	Wood	27	B13	45	Carpet
4	B14	30	Carpet	16	B14	30	Wood	28	B14	45	Carpet
5	B15	30	Carpet	17	B15	30	Wood	29	B15	45	Carpet
6	B16	30	Carpet	18	B16	30	Wood	30	B16	45	Carpet
7	B26	30	Carpet	19	B26	30	Wood	31	B11	45	Wood
8	B26	30	Carpet	20	B26	30	Wood	32	B12	45	Wood
9	B26	30	Carpet	21	B26	30	Wood	33	B13	45	Wood
10	B26	30	Carpet	22	B26	30	Wood	34	B14	45	Wood
11	B26	30	Carpet	23	B26	30	Wood	35	B15	45	Wood
12	B26	30	Carpet	24	B26	30	Wood	36	B16	45	Wood

1. α is the angle of the sliding surface to the horizontal in degree.

3.2.2 Test Results

If a block sliding down on an inclined surface is subjected only to gravity and friction forces, the sliding acceleration of the block will be constant along its path and will be related to the kinetic coefficient of friction of the block-surface interface as follows:

$$m_k = \tan a - \frac{\ddot{x}_S}{g \cos a} \tag{3-3}$$

where:

m_k = The kinetic coefficient of friction of the interface
$\ddot{x}_S$ = constant acceleration of the block along the sliding path
a = the angle of the sliding surface to the horizontal (either 30 or 45 degrees)
g = acceleration due to gravity

In this series of tilt tests, the constant acceleration was calculated as an average over an interval in which the block experienced almost constant acceleration. A sample of the constant acceleration window is illustrated in figure 3-4 for the carpet-steel interface of block B16 sliding on a 45-degree surface. For this particular test, the kinetic coefficient of friction is calculated as:

$$m_k = \tan(45^\circ) - \frac{0.43}{\cos(45^\circ)} = 0.39 \tag{3-4}$$

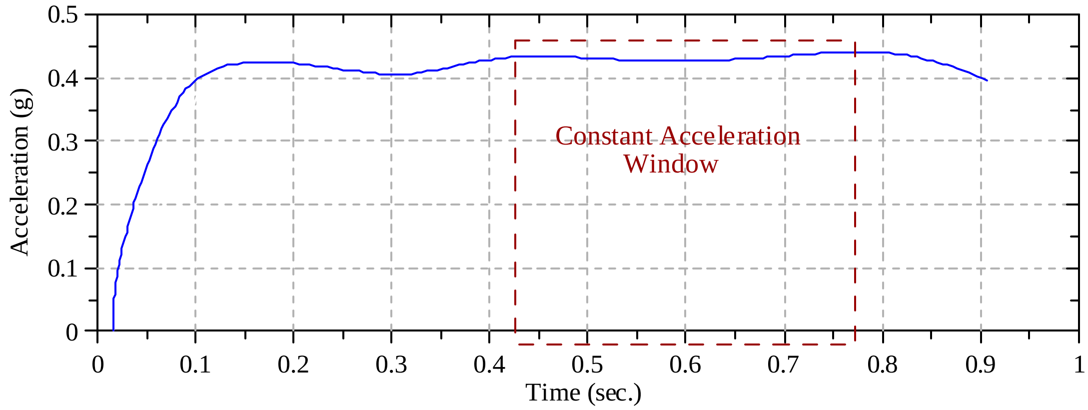


FIGURE 3-4 Sliding Acceleration, Carpet-Steel Interface, 45 Degree Surface, Block B16

Thirty-six tilt tests were conducted but only thirty results are presented here. For the six remaining experiments, it was not possible to define a constant acceleration window in the acceleration history. Consequently, the kinetic coefficient of friction was not calculated for those six experiments. The results of the thirty experiments were sufficient to provide preliminary estimates for the kinetic coefficients of friction and supplemental tests were deemed unnecessary.

Table 3-8 lists the kinetic coefficients of friction estimated for the carpet-steel and wood-steel interfaces. Tables 3-9 and 3-10 collect the results of table 3-8 and present values for the mean and standard deviation of the kinetic coefficients of friction of the wood-steel and carpet-steel interfaces.

TABLE 3-8 Kinetic Coefficients of Friction for Wood-Steel and Carpet-Steel Interfaces[1]

Block Name	Surface	a	m_k	Block Name	Surface	a	m_k
B11	Carpet	30	0.31	B15	Carpet	45	0.37
		45	0.38		Wood	45	0.17
	Wood	30	0.17	B16	Carpet	45	0.40
		45	0.15		Wood	45	0.19
B12	Carpet	30	0.31	B26	Carpet	30	0.31
		45	0.31			30	0.32
	Wood	30	0.17			30	0.32
		45	0.20			30	0.32
B13	Carpet	45	0.33			30	0.33
	Wood	30	0.17			30	0.31
		45	0.12		Wood	30	0.20
B14	Carpet	30	0.31			30	0.21
		45	0.33			30	0.28
	Wood	30	0.19			30	0.28
		45	0.17			30	0.25

1. α is the angle of the sliding surface to the horizontal in degree; m_k is the kinetic coefficient of friction.

TABLE 3-9 Kinetic Coefficients of Friction for the Wood-Steel Interface[1]

Block Type	m_k										$\bar{m}_{ki}$	s_i	$\bar{m}_k$	s
B1	0.17	0.15	0.17	0.20	0.17	0.12	0.19	0.17	0.17	0.19	0.17	0.016	0.20	0.042
B2	0.20	0.21	0.28	0.28	0.25	?	?	?	?	?	0.24	0.038		

1. m_k is the kinetic coefficient of friction; $\bar{m}_{ki}$ is the mean and s_i is the standard deviation of the kinetic coefficient of friction obtained in tests with each block type; $\bar{m}_k$ is the mean and s is the standard deviation of the kinetic coefficient of friction obtained in all the tests conducted.

TABLE 3-10 Kinetic Coefficients of Friction for the Carpet-Steel Interface[1]

Block Type	m_k									$\bar{m}_{ki}$	s_i	$\bar{m}_k$	s
B1	0.31	0.38	0.31	0.31	0.33	0.31	0.33	0.37	0.40	0.34	0.035	0.33	0.029
B2	0.31	0.32	0.32	0.32	0.33	0.31	?	?	?	0.32	0.008		

1. m_k is the kinetic coefficient of friction; $\bar{m}_{ki}$ is the mean and s_i is the standard deviation of the kinetic coefficient of friction obtained in tests with each block type; $\bar{m}_k$ is the mean and s is the standard deviation of the kinetic coefficient of friction obtained in all the tests conducted.

3.3 Remarks

Representative values for the static coefficient of friction were established for three interfaces in this section. The mean static coefficients of friction found to be 0.45 for the carpet-steel, 0.40 for the wood-steel, and 0.27 for the PTFE-steel interfaces. Differences in the coefficients of individual blocks for a given interface are attributed to minor differences in the properties of the materials and change in the material properties due to testing. The coefficient of variation for static coefficients of friction was less than 7% for the carpet-steel interface, 10% for the wood-steel interface, and 20% for the PTFE-steel interface.

The average value of the preliminary estimates of the kinetic coefficients of friction were 0.33 for the carpet-steel and 0.20 for the wood-steel interfaces. The coefficient of variation was less than 10% and 20% for the estimated kinetic coefficients of friction of the carpet-steel and wood-steel interfaces, respectively. It should be noted that the preliminary estimates of the kinetic coefficient of friction for wood-steel and carpet-steel interfaces are 50.00% and 26.67% less than their mean static coefficient of frictions, respectively. These values are greater than the 15% difference commonly found in other studies (Blau, 1996), and are due to the difficulty in defining proper constant acceleration windows in the blocks' acceleration response histories in the estimation procedure.

The kinetic coefficient of friction for the carpet-steel, wood-steel and PTFE-steel interfaces will be estimated using the results of the earthquake simulator tests described in the next section and theoretical considerations described in Section 6.

SECTION 4

EARTHQUAKE SIMULATOR TESTS FOR KINETIC COEFFICIENT OF FRICTION CHARACTERIZATION

4.1 Test Plan

The purpose of the earthquake simulator experiments was to provide data to establish the kinetic coefficients of friction. The displacement and acceleration response of the sliding blocks during the earthquake simulator experiments were to be used to compute the kinetic coefficients of friction (Sections 5 to 7). In these experiments, the six nominally identical blocks were arranged on the steel plate, which was bolted to the earthquake simulator platform. Sinusoidal input motions per figure 4-1 were used for the experiments. To provide result of statistical significance, tests were repeated with different input motions. The amplitude and period of the input motion were varied to generate different input motions. The duration of the sinusoidal histories was set initially at a minimum of 50 cycles.

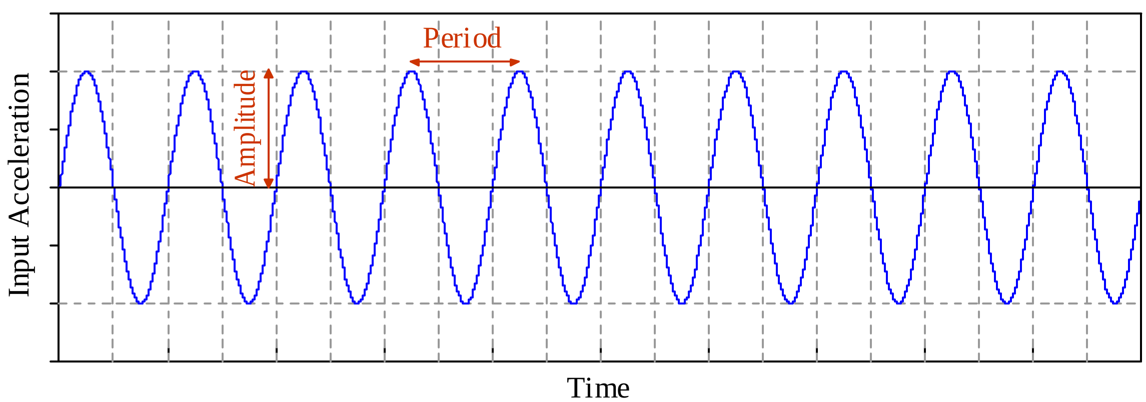


FIGURE 4-1 Parameters Generating Different Sinusoidal Input Motions

The amplitudes of the sinusoidal input motion were selected so that blocks experienced both sliding and sticking modes of response. Table 4-1 lists the amplitudes of the sinusoidal input motions. For each interface, one amplitude was selected for the sticking mode. For the sliding mode, two amplitudes were selected for the PTFE-steel interface and three amplitudes for the wood-steel and carpet-steel interfaces. The period of the sine waves was set to 0.75, 0.50, or 0.10 second. Input motions with long period and large amplitude would exceed the velocity and displacement capacity of the earthquake simulator. Therefore, for the amplitudes larger than 0.6*g* only short periods (0.5 and 0.1 sec.) were used. Table 4-2 presents the target test plan for 50 experiments with sinusoidal input motions.

TABLE 4-1 Sinusoidal Input Motion Amplitudes (*g*)

	Expected Block Response Mode	
Interface	Sticking	Sliding
Carpet-Steel	0.3	0.6, 0.8, 1.0
Wood-Steel	0.2	0.6, 0.8, 1.0
PTFE-Steel	0.2	0.6, 1.0

TABLE 4-2 Earthquake Simulator Test Plan

Test No.	Block Type	Interface	Sine Wave Characteristics	
			Amplitude (g)	Period (sec)
1	B1	Wood-Steel $(m_s \approx 0.40)$	0.2	0.75
2	B1		0.2	0.50
3	B1		0.2	0.10
4	B1		0.6	0.75
5	B1		0.6	0.50
6	B1		0.6	0.10
7	B1		0.8	0.50
8	B1		0.8	0.10
9	B1		1.0	0.10
10	B1	Carpet-Steel $(m_s \approx 0.45)$	0.3	0.75
11	B1		0.3	0.50
12	B1		0.3	0.10
13	B1		0.6	0.75
14	B1		0.6	0.50
15	B1		0.6	0.10
16	B1		0.8	0.50
17	B1		0.8	0.10
18	B1		1.0	0.10
19	B1	PTFE-Steel $(m_s \approx 0.27)$	0.2	0.75
20	B1		0.2	0.50
21	B1		0.2	0.10
22	B1		0.6	0.75
23	B1		0.6	0.50
24	B1		0.6	0.10
25	B1		1.0	0.10

TABLE 4-2 (cont'd.) Earthquake Simulator Test Plan

Test No.	Block Type	Interface	Sine Wave Characteristics	
			Amplitude (g)	Period (sec)
26	B2	Wood-Steel ($m_s \approx 0.40$)	0.2	0.75
27	B2		0.2	0.50
28	B2		0.2	0.10
29	B2		0.6	0.75
30	B2		0.6	0.50
31	B2		0.6	0.10
32	B2		0.8	0.50
33	B2		0.8	0.10
34	B2		1.0	0.10
35	B2	Carpet-Steel ($m_s \approx 0.45$)	0.3	0.75
36	B2		0.3	0.50
37	B2		0.3	0.10
38	B2		0.6	0.75
39	B2		0.6	0.50
40	B2		0.6	0.10
41	B2		0.8	0.50
42	B2		0.8	0.10
43	B2		1.0	0.10
44	B2	PTFE-Steel ($m_s \approx 0.27$)	0.2	0.75
45	B2		0.2	0.50
46	B2		0.2	0.10
47	B2		0.6	0.75
48	B2		0.6	0.50
49	B2		0.6	0.10
50	B2		1.0	0.10

4.2 Earthquake Simulator and Instrumentation

The earthquake simulator used for the experiments, shown in figure 4-2, is located in the laboratory of Department of Civil, Structural, and Environmental Engineering at University at Buffalo, the State University of New York. The simulator has five controlled degrees of freedom. Only the transverse translational movement is restrained. The simulator has a useful frequency range of up to 50 Hz.

The simulator itself is 3.66 by 3.66 m in plan. However, a reinforced concrete platform installed on the simulator increases the useful testing area to 6.10 by 3.66 m. The performance envelope of the simulator in the horizontal direction at a payload less than 196 kN is $\pm$ 15.24 cm for displacement, 76.2 cm/sec for velocity, and 1.15g for acceleration. In the vertical direction, for a payload less than 489.3 kN, the performance envelope is $\pm$ 7.62 cm for displacement, 50.8 cm/sec for velocity, and 2.30*g* for acceleration.

FIGURE 4-2 Earthquake Simulator

In each experiment, the dsplacement and acceleration of the simulator and the blocks were measured. A part view of the instrumentation and the arrangement of the blocks on the steel plate are shown in figures 4-3 and 4-4.

The displacement of the blocks was measured by a Krypton coordinate measurement machine (CMM). The CMM camera traces the displacement of light-emitting diodes (LEDs) moving in its field of view (see http://nees.buffalo.edu/docs/labmanual/html/chapter%203.htm for details). The CMM camera is shown in figure 4-5. Two LEDs were used to describe the displacement of each block (see figure 4-6). To measure the displacement of the sliding surface, three LEDs were attached to the steel plate. As shown in figure 4-7, a displacement transducer was used to measure the actual displacement of the simulator, which could be different from the motion input to the simulator. Accelerometers were attached to the north face of each block (see figure 4-8) and to the earthquake simulator (see figure 4-7). The instrumentation for the tests with block type B1 and B2 is shown in figures 4-9 and 4-10, respectively. Table 4-2, associated with figures 4-9 and 4-10, lists all the instrumentation used in the earthquake simulator experiments.

FIGURE 4-3 Arrangement of Blocks Type B1 on the Steel Plate

FIGURE 4-4 Arrangement of Blocks Type B2 on the Steel Plate

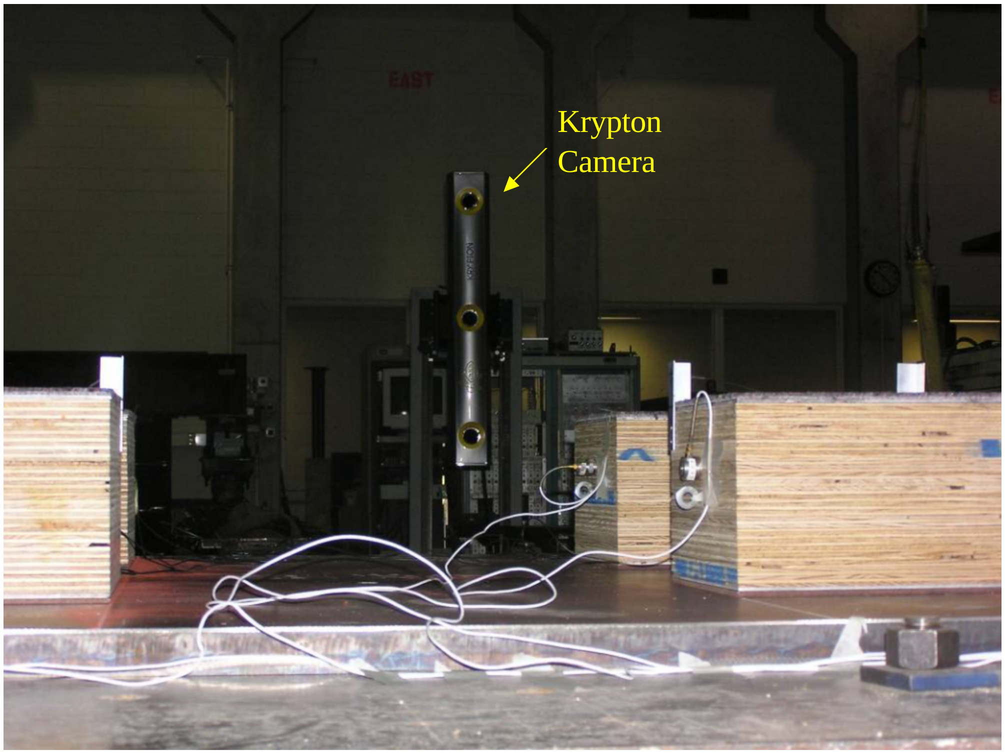


FIGURE 4-5 Coordinate Measurement Machine

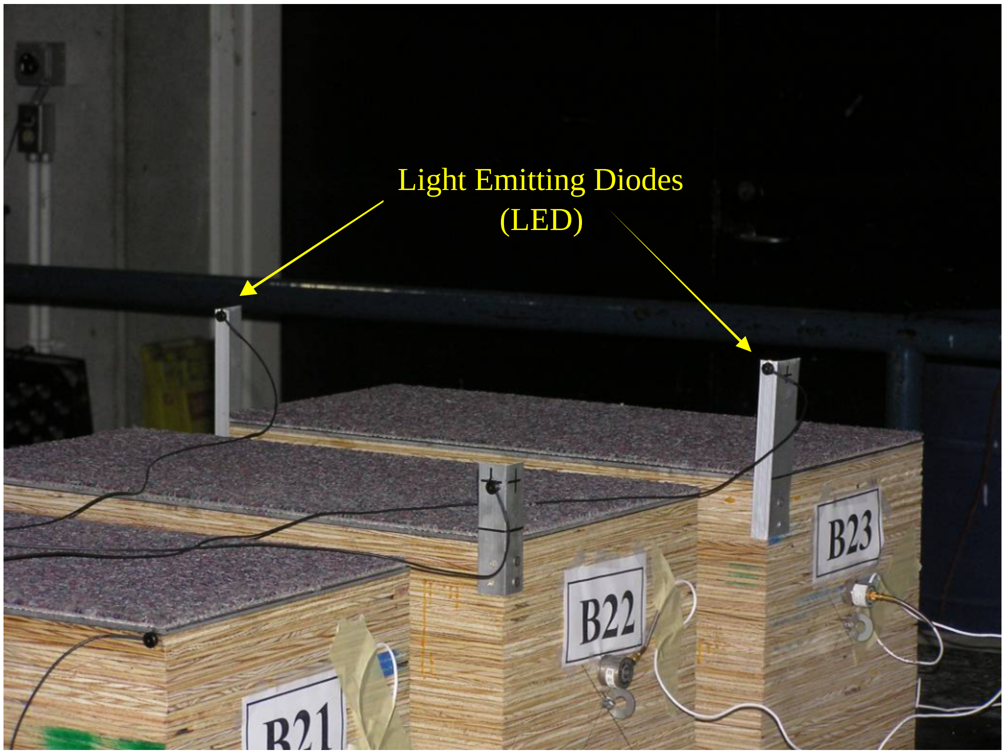


FIGURE 4-6 Two LEDs Attached to Each Block to Measure Displacement

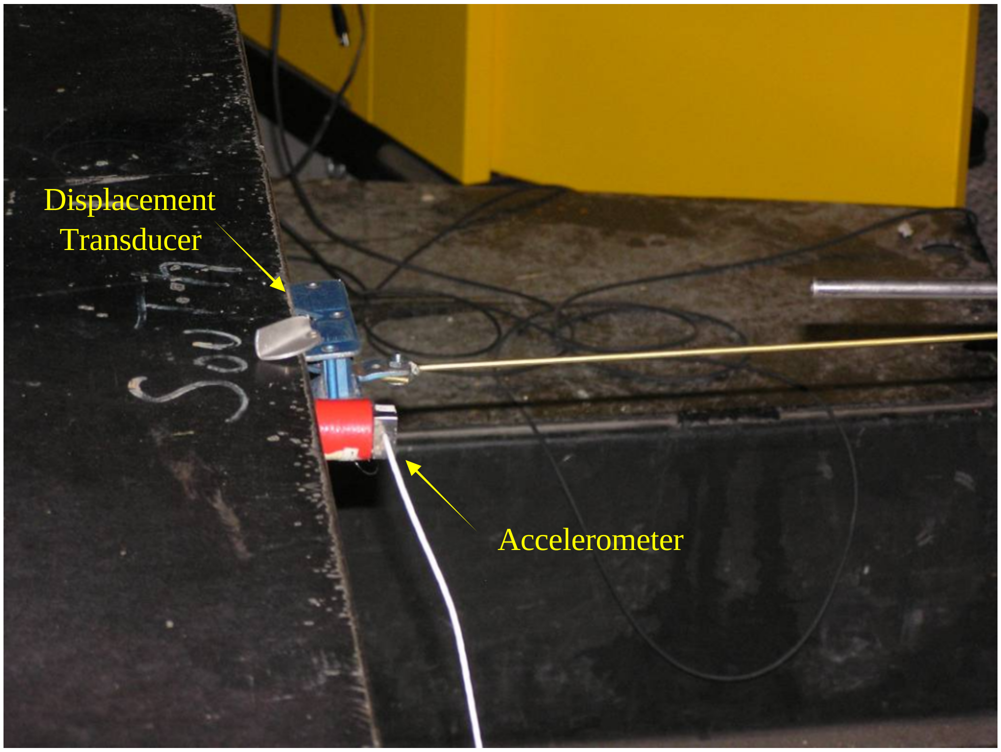


FIGURE 4-7 Displacement Transducer and Accelerometer Used to Measure the Simulator Platform Response

FIGURE 4-8 Accelerometer Attached to the Block

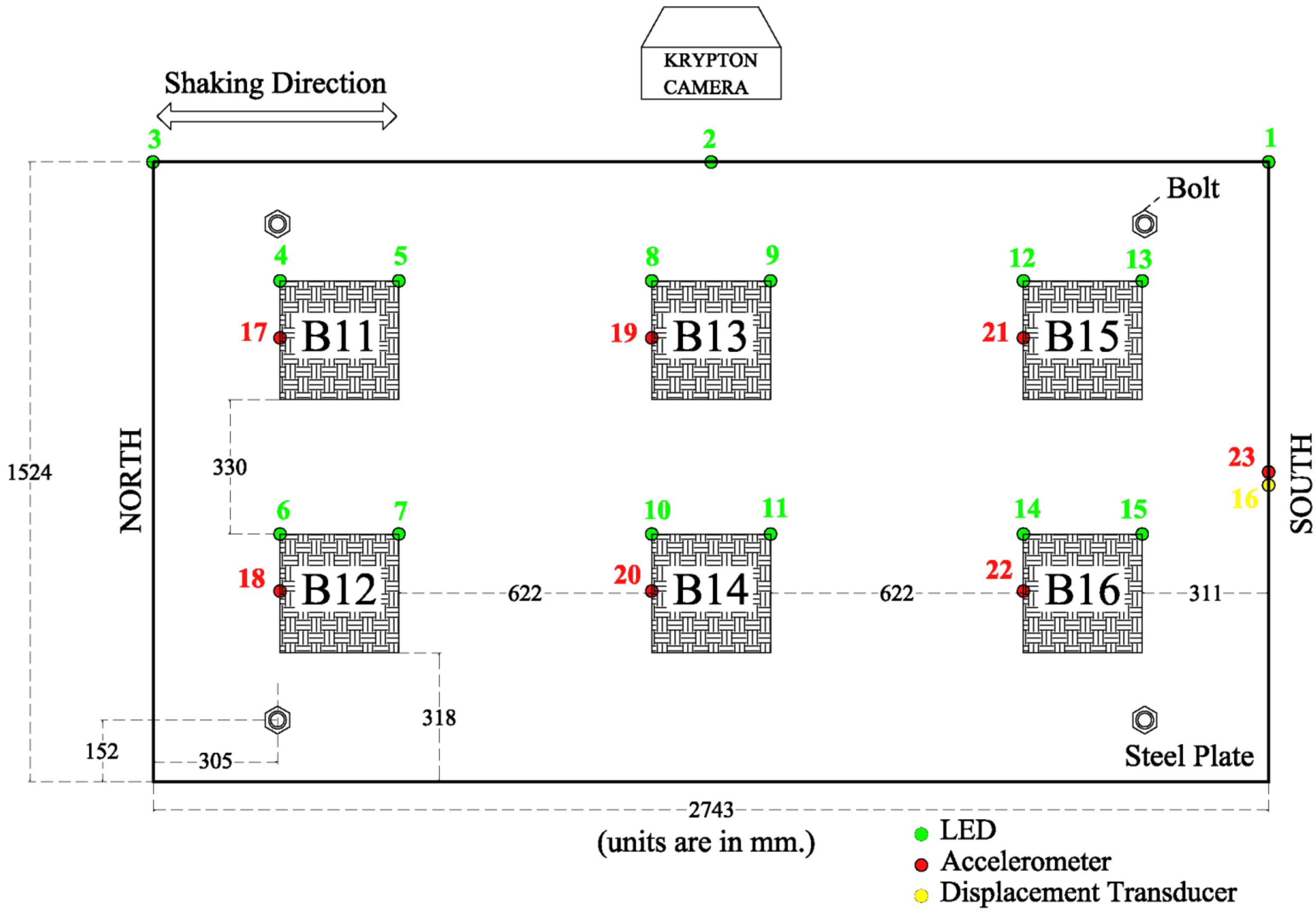


FIGURE 4-9 Instrumentation for Tests with Block Type B1

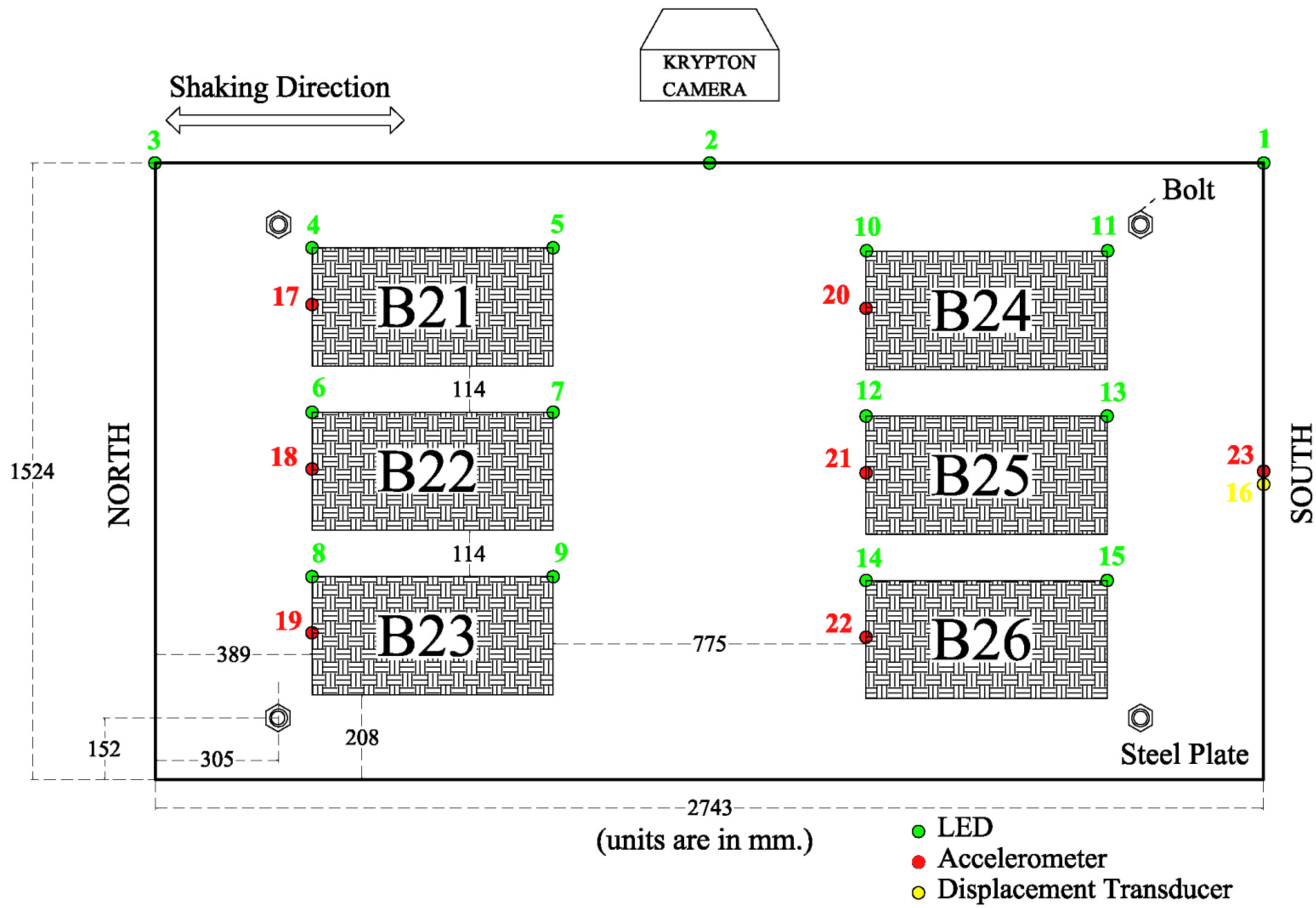


FIGURE 4-10 Instrumentation for Tests with Block Type B2

TABLE 4-3 Instrumentation List

No.	Measured Parameter	Type / Location
1	Steel Plate Displacement	LED / South-east corner of the steel plate
2	Steel Plate Displacement	LED / Middle of the east edge of the steel plate
3	Steel Plate Displacement	LED / North-east corner of the steel plate
4	Block Displacement	LED / North-east-top corner of the block B11 or B22
5	Block Displacement	LED / South-east-top corner of the block B11 or B21
6	Block Displacement	LED / North-east-top corner of the block B12 or B22
7	Block Displacement	LED / South-east-top corner of the block B12 or B22
8	Block Displacement	LED / North-east-top corner of the block B13 or B23
9	Block Displacement	LED / South-east-top corner of the block B13 or B23
10	Block Displacement	LED / North-east-top corner of the block B14 or B24
11	Block Displacement	LED / South-east-top corner of the block B14 or B24
12	Block Displacement	LED / North-east-top corner of the block B15 or B25
13	Block Displacement	LED / South-east-top corner of the block B15 or B25
14	Block Displacement	LED / North-east-top corner of the block B16 or B26
15	Block Displacement	LED / South-east-top corner of the block B16 or B26
16	Shake Table Displacement	Displacement transducer / South edge of the simulator
17	Block Acceleration	Accelerometer / North face of block B11 or B21
18	Block Acceleration	Accelerometer / North face of block B12 or B22
19	Block Acceleration	Accelerometer / North face of block B13 or B23
20	Block Acceleration	Accelerometer / North face of block B14 or B24
21	Block Acceleration	Accelerometer / North face of block B15 or B25
22	Block Acceleration	Accelerometer / North face of block B16 or B26
23	Shake Table Acceleration	Accelerometer / South edge of the simulator

4.3 Remarks

In some of the earthquake simulator tests, blocks slid and rotated around their vertical axis. This type of response can be attributed to a non-uniform frictional force per unit area across the contact surface. Figure 4-11 shows the combined response of the blocks and their positions at the end of an earthquake simulator experiment for small blocks sliding on a wood surface. The blocks response in such experiments could not be used to calculate the kinetic coefficients of friction.

FIGURE 4-11 Combination of Sliding and Rotation Response in Some Tests

SECTION 5
DYNAMIC ANALYSIS OF BLOCK-TABLE SYSTEM

Consider a freestanding rigid block of mass m, which can represent a sliding nonstructural component, sitting on a shake table. Let $z(t)$ and $y(t)$ be the displacement of the shake table and of the block relative to an absolute frame whose origin corresponds to the vertical position of the block centroid, respectively, μ_s and μ_k be the static and kinetic coefficients of friction between the block and the surface of the shake table, respectively, and g be the acceleration of the gravity as shown in figure 5-1. Denote the displacement of the block relative to the shake table by $x(t)$,

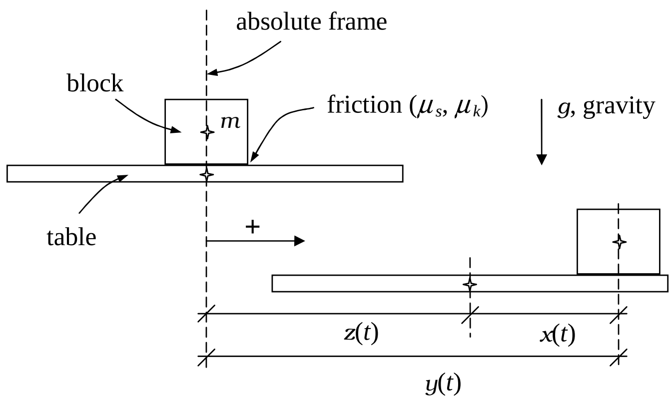


FIGURE 5-1 System of Sliding Block and Shaking Table

so that $y(t) = z(t) + x(t)$. The displacements $y(t)$ and $x(t)$ are referred as the total displacement response of the block and the relative displacement response of the block, respectively, throughout the report.

5.1 Equation of Motion

The equation of motion of the block results from its free body diagram in figure 5-2, illustrating

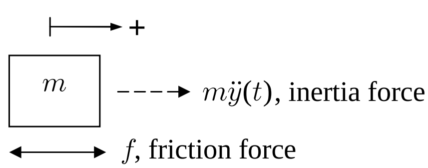


FIGURE 5-2 Free Body Diagram of the Block

only the horizontal forces. At any time t, the only external horizontal force acting on the block is the force of kinetic friction f. The force of kinetic friction f changes its sign according to (hence a function of) the velocity of the block relative to the table, $\dot{x}(t) = \dot{y}(t) - \dot{z}(t)$, so that we have

$$f = \begin{cases} \mu_k\, g\, m, & \text{if } \dot{x}(t) < 0, \\ -\mu_k\, g\, m, & \text{if } \dot{x}(t) > 0, \end{cases}$$

$$= -\mu_k\, g\, m\, \mathrm{sign}(\dot{x}(t)), \tag{5-1}$$

for dynamic equilibrium, where μ_k is a constant representing the kinetic coefficient of friction and $\text{sign}(b) = -1$, 0 and 1 if b is negative, zero and positive, respectively. Note that for a freestanding block at rest, the friction force is always less than or equal to $\mu_s\, g\, m$.

5.1.1 Sliding Condition

If there is relative motion at time t, that is, if $\dot{x}(t) \neq 0$, then $m\,\ddot{y}(t) = -\mu_k\, g\, m\,\text{sign}(\dot{x}(t))$, so that

$$\ddot{y}(t) = -\mu_k\, g\,\text{sign}(\dot{x}(t)). \tag{5-2}$$

Note that $\dot{x}(t) \neq 0$ if the block is in motion before time t and $|\ddot{y}(t)| = \mu_k\, g$, or, the block is at rest before time t and $|\ddot{y}(t)| > \mu_s\, g$. The equation of motion for the block, provided that $\dot{x}(t) \neq 0$, is

$$\ddot{y}(t) + \mu_k\, g\,\text{sign}(\dot{y}(t) - \dot{z}(t)) = 0 \text{ (using block's total response),} \tag{5-3}$$

$$\ddot{x}(t) + \mu_k\, g\,\text{sign}(\dot{x}(t)) = -\ddot{z}(t) \text{ (using block's relative response).} \tag{5-4}$$

5.1.2 Sticking Condition

If there is no relative motion at time t, that is, if $\dot{x}(t) = 0$, then $\dot{y}(t) = \dot{z}(t)$. Note that $\dot{x}(t) = 0$ if the block is at rest before time t and $|\ddot{y}(t)| < \mu_s g$, or, the block is in motion before time t and $|\ddot{y}(t)| < \mu_k g$. Hence, provided that $\dot{x}(t) = 0$, we have

$$\ddot{y}(t) = \ddot{z}(t) \text{ (using block's total response),} \tag{5-5}$$

$$\ddot{x}(t) = 0 \text{ (using block's relative response).} \tag{5-6}$$

5.2 Numerical Solution

If $\dot{x}(t) > 0$, equation 5-4 becomes $\ddot{x}(t) = -\mu_k\, g - \ddot{z}(t)$, so that, for $t_2 \geq t_1 \geq 0$, we have

$$\begin{aligned}
\int_{t_1}^{t_2} \ddot{x}(s)ds &= \int_{t_1}^{t_2} (-\mu_k\, g - \ddot{z}(s))ds \\
\dot{x}(t_2) - \dot{x}(t_1) &= -\mu_k\, g(t_2 - t_1) - \int_{t_1}^{t_2} \ddot{z}(s)ds \\
\dot{x}(t_2) &= \dot{x}(t_1) - \mu_k\, g(t_2 - t_1) - \int_{t_1}^{t_2} \ddot{z}(s)ds. \qquad (5\text{-}7)
\end{aligned}$$

Let $t_1 = t$ and $t_2 = t_1 + \Delta t$, then equation 5-7 becomes

$$\dot{x}(t + \Delta t) = \dot{x}(t) - \mu_k\, g\Delta t - \int_{t}^{t+\Delta t} \ddot{z}(s)ds. \tag{5-8}$$

Using equation 5-7 we can also write

$$
\begin{aligned}
\int_{t_1}^{t_2} \dot{x}(s)ds &= \int_{t_1}^{t_2} \left(\dot{x}(t_1) - \mu_k\, g(s-t_1) - \int_{t_1}^{s} \ddot{z}(r)dr\right) ds \\
x(t_2) - x(t_1) &= \dot{x}(t_1)\int_{t_1}^{t_2} ds - \mu_k\, g \int_{t_1}^{t_2} (s-t_1)ds - \int_{t_1}^{t_2}\int_{t_1}^{s} \ddot{z}(r)drds \\
x(t_2) - x(t_1) &= \dot{x}(t_1)(t_2-t_1) - \mu_k\, g\, (\frac{s^2}{2} - st_1)|_{t_1}^{t_2} - \int_{t_1}^{t_2}\int_{t_1}^{s} \ddot{z}(r)drds \\
x(t_2) - x(t_1) &= \dot{x}(t_1)(t_2-t_1) - \mu_k\, g\, (\frac{t_2^2}{2} - t_2t_1 - \frac{t_1^2}{2} + t_1^2) - \int_{t_1}^{t_2}\int_{t_1}^{s} \ddot{z}(r)drds \\
x(t_2) &= x(t_1) + \dot{x}(t_1)(t_2-t_1) - \mu_k\, g\, \frac{(t_2-t_1)^2}{2} - \int_{t_1}^{t_2}\int_{t_1}^{s} \ddot{z}(r)drds
\end{aligned} \tag{5-9}
$$

Again, for $t_1 = t$ and $t_2 = t_1 + \Delta t$, equation 5-9 becomes

$$x(t+\Delta t) = x(t) - \mu_k\, g\, \frac{\Delta t^2}{2} - \int_{t}^{t+\Delta t}\int_{t}^{s} \ddot{z}(r)drds \tag{5-10}$$

Similarly, for $\dot{x}(t) < 0$, the equation of motion given by equation5-4 using the relative response of the block becomes $\ddot{x}(t) = \mu_k\, g - \ddot{z}(t)$, and we have

$$\dot{x}(t+\Delta t) = \dot{x}(t) + \mu_k\, g\, \Delta t - \int_{t}^{t+\Delta t} \ddot{z}(s)ds, \tag{5-11}$$

$$x(t+\Delta t) = x(t) + \dot{x}(t)\Delta t + \mu_k\, g\, \frac{\Delta t^2}{2} - \int_{t}^{t+\Delta t}\int_{t}^{s} \ddot{z}(r)drds. \tag{5-12}$$

Hence, if $\dot{x}(t) \neq 0$, that is, if the block is sliding at time t, and assuming that sliding continues in $(t, t+\Delta t)$, we can write

$$\ddot{x}(t+\Delta t) = -\mu_k\, g\, \text{sign}(\dot{x}(t)) - \ddot{z}(t+\Delta t), \tag{5-13}$$

$$\dot{x}(t+\Delta t) = \dot{x}(t) - \mu_k\, g\, \Delta t\, \text{sign}(\dot{x}(t)) - \int_{t}^{t+\Delta t} \ddot{z}(s)ds, \tag{5-14}$$

$$x(t+\Delta t) = x(t) + \dot{x}(t)\Delta t - \mu_k\, g\, \frac{\Delta t^2}{2}\, \text{sign}(\dot{x}(t)) - \int_{t}^{t+\Delta t}\int_{t}^{s} \ddot{z}(r)drds, \tag{5-15}$$

by equations 5-4, 5-8, 5-10, 5-11, and 5-12.

If $\dot{x}(t) = 0$, that is, if the block is not sliding at time t, and continue to stick to the table during $(t,\, t+\Delta t)$, we can write

$$\ddot{x}(t+\Delta t) = 0, \tag{5-16}$$

$$\dot{x}(t+\Delta t) = 0, \tag{5-17}$$

$$x(t+\Delta t) = x(t). \tag{5-18}$$

If Δt is small, the following approximations hold

$$\int_{t}^{t+\Delta t} \ddot{z}(s)ds \simeq \frac{\ddot{z}(t+\Delta t) + \ddot{z}(t)}{2}\, \Delta t, \tag{5-19}$$

$$\int_{t}^{t+\Delta t}\int_{t}^{s} \ddot{z}(r)drds \simeq \frac{\ddot{z}(t+\Delta t) + \ddot{z}(t)}{4}\, \Delta t^2, \tag{5-20}$$

so that the relative response of the block in sliding and sticking phases in $(t,\, t+\Delta t)$ can be written as

sliding phase: $\dot{x}(s),\ s \in (t, t+\Delta t)$,

$$\ddot{x}(t+\Delta t) = -\mu_k\, g\, \mathrm{sign}(\dot{x}(t)) - \ddot{z}(t+\Delta t), \tag{5-21}$$

$$\dot{x}(t+\Delta t) = \dot{x}(t) - \mu_k\, g\, \Delta t\, \mathrm{sign}(\dot{x}(t)) - \frac{\ddot{z}(t+\Delta t)+\ddot{z}(t)}{2}\,\Delta t, \tag{5-22}$$

$$x(t+\Delta t) = x(t) + \dot{x}(t)\Delta t - \mu_k\, g\, \frac{\Delta t^2}{2}\, \mathrm{sign}(\dot{x}(t)) - \frac{\ddot{z}(t+\Delta t)+\ddot{z}(t)}{4}\,\Delta t^2, \tag{5-23}$$

sticking phase: $\dot{x}(s) = 0,\ s \in (t, t+\Delta t)$,

$$\ddot{x}(t+\Delta t) = 0, \tag{5-24}$$

$$\dot{x}(t+\Delta t) = 0, \tag{5-25}$$

$$x(t+\Delta t) = x(t). \tag{5-26}$$

5.3 Input Motion

The shake table acceleration used in the experiments performed at the University at Buffalo has the form

$$\ddot{z}(t) = \omega(t)\, \alpha\, g\, \sin(\nu\, t), \qquad t \in [0, t_f], \tag{5-27}$$

where $\omega(t)$ is a modulation function increasing to 1 and starting at $\omega(0) = 0$. We have modeled $\omega(t)$ by

$$\omega(t) = p_1(t)e_1(t) + p_2(t)e_2(t) + p_3(t)e_3(t), \tag{5-28}$$

where

$$\begin{aligned} &p_1(t) = t^3, \quad t \in [0, t_1),\\ &p_2(t) = a_0 + a_1(t-t_1) + a_2(t-t_1)^2 + a_3(t-t_1)^3 + a_4(t-t_1)^4, \quad t \in [t_1, t_2),\\ &p_3(t) = 1, \quad t \in [t_2, \infty), \end{aligned} \tag{5-29}$$

are some polynomials,

$$\begin{aligned} e_1(t) &= \begin{cases} 1, & \text{if } t \in [0, t_1),\\ 0, & \text{otherwise,} \end{cases}\\ e_2(t) &= \begin{cases} 1, & \text{if } t \in [t_1, t_2),\\ 0, & \text{otherwise,} \end{cases}\\ e_3(t) &= \begin{cases} 1, & \text{if } t \in [t_2, \infty),\\ 0, & \text{otherwise,} \end{cases} \end{aligned} \tag{5-30}$$

and $0 < t_1 < t_2$ are predetermined values derived from experiments. The coefficients a_0, a_1, a_2, a_3 and a_4 in $p_2(t)$, in equation 5-29, have been obtained using following continuity and smoothness requirements; $p_2(t_1) = p_1(t_1)$, $\dot{p_2}(t_1) = \dot{p_1}(t_1)$, $\ddot{p_2}(t_1) = \ddot{p_1}(t_1)$, $p_2(t_2) = p_3(t_2)$, and $\dot{p_2}(t_2) = \dot{p_3}(t_2)$.

Figure 5-3 shows the acceleration of the shake table for $\alpha = 0.8$, $\nu = 2\pi/T$, $T = 0.5$ sec, $t_1 = 0.2\,T$, $t_2 = 10\,T$ and $t_f = 20.2\,T$.

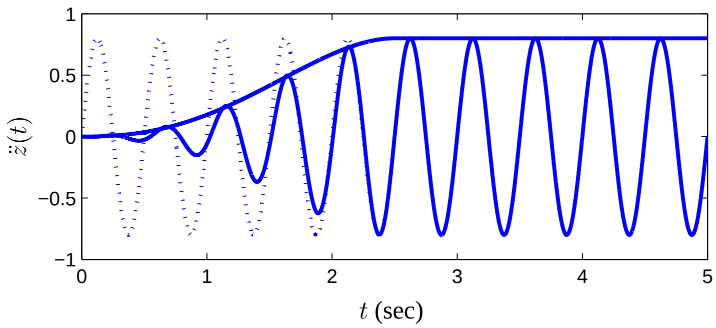


FIGURE 5-3 Modulated Input Motion

5.4 Algorithm

We present an algorithm for calculating the response of the block. Recall that $z(t)$ and $y(t)$ are the displacement of the shake table and of the block relative to an absolute frame, respectively, and $x(t)$ is the displacement of the block relative to the shake table, so that $y(t) = z(t) + x(t)$. We use an example to explain the algorithm for calculating the acceleration, velocity and displacement responses of the block in equations 5-21 - 5-26.

The input acceleration is $\ddot{z}(t) = \omega(t)\,\alpha\,g\,\sin(\nu\,t),\ t \in [0, t_f]$, with $\alpha = 0.8$, $\nu = 2\pi/T$, $T = 0.5$ sec, $t_f = 3.1\,T$, $t_1 = 0.1\,T$ and $t_2 = 2\,T$ (equations 5-27 and 5-28). Figure 5-4 shows the calculated total and relative acceleration and velocity responses of the block, and the acceleration and the velocity of the shake table, for $\mu_s = 0.45$ and $\mu_k = 0.40$.

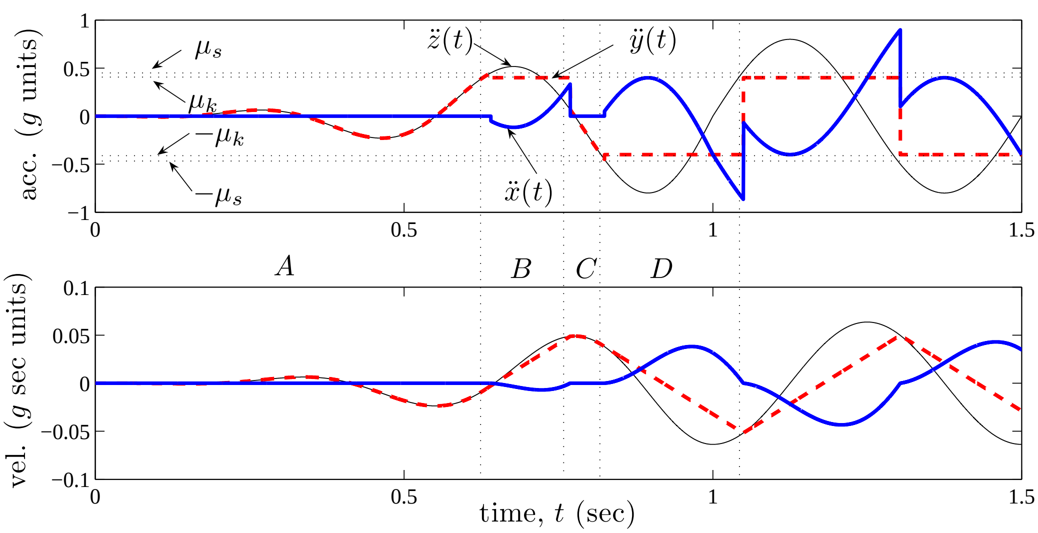


FIGURE 5-4 Algorithm

Figure 5-4 also shows four regions, $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and $\boldsymbol{D}$, with following properties.

- ***Region A*:** In this region $|\ddot{z}(t)| < \mu_s\,g$, hence the block sticks to the table. The relative acceleration, velocity and displacement responses of the block are obtained using equations 5-24, 5-25 and 5-26.

- ***Region B*:** At the beginning of region $\boldsymbol{B}$, $\ddot{z}(t)$ becomes equal to $-\mu_s\, g$ and the motion of the block relative to the table starts. The block motion continues in the same direction with a constant total acceleration $\ddot{y}(t) = -\mu_k\, g$ until the end of region $\boldsymbol{B}$, at which point the relative velocity of the block $\dot{x}(t)$ becomes zero. The relative responses of the block are obtained using equations 5-21, 5-22 and 5-23 with sign$(\dot{x}(t)) = 1$.

- ***Region C*:** At the beginning of region $\boldsymbol{C}$, $\ddot{z}(t) < \mu_k\, g$ hence the block sticks to the table again and remains at rest until the end of region $\boldsymbol{C}$. In this region equations 5-24, 5-25 and 5-26 are used to obtain the relative responses of the block.

- ***Region D*:** At the beginning of region $\boldsymbol{D}$, $\ddot{z}(t)$ becomes equal to $\mu_s\, g$ and block's relative motion starts again and continues with a constant total acceleration $\ddot{y}(t) = \mu_k\, g$ until the block relative velocity $\dot{x}(t)$ becomes zero at the end of the region $\boldsymbol{D}$. Equations 5-21, 5-22 and 5-23 with sign$(\dot{x}(t)) = -1$ are used to obtain the relative response of the block in this region.

A computer algorithm for calculating the block relative acceleration $\ddot{x}(t)$, velocity $\dot{x}(t)$ and displacement $x(t)$, developed by implementing equations 5-21 - 5-26, is presented below.

Algorithm in MATLAB:

$\ddot{x}(1) = 0$
$\dot{x}(1) = 0$
$i = 1$
while $i < lt$, ($lt =$ length of the time vector)
    if $\ddot{x}(i) + \ddot{z}(i) > \mu_s\, g$, then
        $\ddot{x}(i) = \mu_k\, g - \ddot{z}(i)$
        $\dot{x}(i) = \dot{x}(i-1) + \mu_k\, g\, \Delta t - 0.5\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t$
        $x(i) = x(i-1) + \dot{x}(i)\Delta t + \mu_k\, g\, 0.5\, \Delta t^2 - 0.25\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t^2$
        while $\dot{x}(i) < 0$,
            $i = i + 1$
            $\ddot{x}(i) = \mu_k\, g - \ddot{z}(i)$
            $\dot{x}(i) = \dot{x}(i-1) + \mu_k\, g\, \Delta t - 0.5\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t$
            $x(i) = x(i-1) + \dot{x}(i)\Delta t + \mu_k\, g\, 0.5\, \Delta t^2 - 0.25\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t^2$
            if $\dot{x}(i) > 0 \;\Rightarrow\; \dot{x}(i) = 0, \quad x(i) = x(i-1)$
        end
        $i = i + 1$
    if $\ddot{x}(i) + \ddot{z}(i) < -\mu_s\, g$, then
        $\ddot{x}(i) = -\mu_k\, g - \ddot{z}(i)$
        $\dot{x}(i) = \dot{x}(i-1) - \mu_k\, g\, \Delta t - 0.5\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t$
        $x(i) = x(i-1) + \dot{x}(i)\Delta t - \mu_k\, g\, 0.5\, \Delta t^2 - 0.25\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t^2$
        while $\dot{x}(i) > 0$,
            $i = i + 1$
            $\ddot{x}(i) = -\mu_k\, g - \ddot{z}(i)$
            $\dot{x}(i) = \dot{x}(i-1) - \mu_k\, g\, \Delta t - 0.5\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t$
            $x(i) = x(i-1) + \dot{x}(i)\Delta t - \mu_k\, g\, 0.5\, \Delta t^2 - 0.25\, (\ddot{z}(i) + \ddot{z}(i-1))\, \Delta t^2$
            if $\dot{x}(i) < 0 \;\Rightarrow\; \dot{x}(i) = 0, \quad x(i) = x(i-1)$
        end
        $i = i + 1$
    otherwise,
        $\ddot{x}(i) = 0$
        $\dot{x}(i) = 0$
        $x(i) = x(i-1)$
        $i = i + 1$
end

After obtaining the relative responses, $\ddot{x}(t)$, $\dot{x}(t)$ and $x(t)$, of the block, the total responses can be calculated from $\ddot{y}(t) = \ddot{z}(t) + \ddot{x}(t)$, $\dot{y}(t) = \dot{z}(t) + \dot{x}(t)$ and $y(t) = z(t) + x(t)$. The calculated steady state total block acceleration, velocity and displacement responses have zero temporal mean, and are symmetric about the time axis, under the sinusoidal excitation defined in Section 5.3, because of the symmetry of the equation of motion. On the other hand, recorded block responses exhibit drifts since the properties of the block-table interface exhibit spatial variation. To relate calculated results to experimental results, block response records need to be corrected, as shown in the following section.

SECTION 6
ESTIMATION OF KINETIC COEFFICIENT OF FRICTION

The unknown kinetic coefficient of friction μ_k is estimated using the maximum responses of the blocks obtained through experiments at the University at Buffalo, and relationships between the maximum responses and the kinetic coefficient of friction, obtained at Cornell University using theoretical considerations. This section presents the relationships between the maximum acceleration/displacement responses of the block and the kinetic coefficient of friction.

6.1 Maximum Acceleration Response

The maximum absolute total acceleration response, $\max_t |\ddot{y}(t)|$, of a block subjected to the input acceleration defined in Section 5.3, is obtained using equations 5-3 and 5-5 as follows,

$$\begin{aligned}
\textbf{during sliding: } \dot{x}(t) \neq 0 \quad & \Rightarrow \ddot{y}(t) + \mu_k\, g\, \mathrm{sign}(\dot{y}(t) - \dot{z}(t)) = 0, \\
& \Rightarrow |\ddot{y}(t)| = \mu_k\, g, \\
& \Rightarrow \max_t |\ddot{y}(t)| = \mu_k\, g, \qquad (6\text{-}1)
\end{aligned}$$

$$\begin{aligned}
\textbf{during sticking: } \dot{x}(t) = 0 \quad & \Rightarrow \ddot{y}(t) = \ddot{z}(t), \\
& \Rightarrow \max_t |\ddot{y}(t)| = \max_t |\ddot{z}(t)| = \max_t |\omega(t)\, \alpha\, g\, \sin(\nu\, t)|, \qquad (6\text{-}2)
\end{aligned}$$

hence, we have

$$\boxed{\max_t |\ddot{y}(t)| = \begin{cases} \mu_k\, g, & \text{sliding condition,} \\ \max_t |\ddot{z}(t)|, & \text{sticking condition.} \end{cases}} \qquad (6\text{-}3)$$

Figure 6-1 illustrates the relation between $\max_t |\ddot{y}(t)|$ and μ_k given by equation 6-3. The unknown

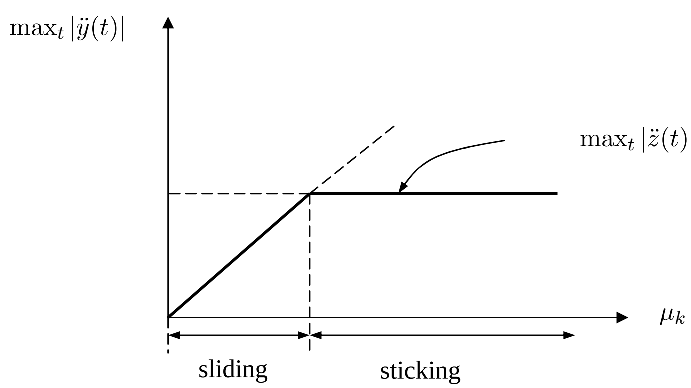


FIGURE 6-1 Relation between $\max_t |\ddot{y}(t)|$ and μ_k

kinetic coefficient of friction can be estimated, for a given maximum acceleration response measured in an experimental study, using the relationship given by equation 6-3 and illustrated in figure 6-1.

6.2 Maximum Displacement Response

Similar to the acceleration response, velocity and displacement responses can be obtained using equations 5-3 and 5-5 as follows,

during sliding: $\dot{x}(t) \neq 0 \;\; \Rightarrow \ddot{y}(t) + \mu_k\, g\, \text{sign}(\dot{y}(t) - \dot{z}(t)) = 0,$

$$\begin{aligned} \text{if } \dot{y}(t) > \dot{z}(t) &\Rightarrow \ddot{y}(t) = -\mu_k\, g, \\ &\Rightarrow \dot{y}(t) = -\mu_k\, g\, t + c_1, \\ &\Rightarrow y(t) = -\mu_k\, g\, t^2/2 + c_1\, t + c_2, \end{aligned} \tag{6-4}$$

$$\begin{aligned} \text{if } \dot{y}(t) < \dot{z}(t) &\Rightarrow \ddot{y}(t) = \mu_k\, g, \\ &\Rightarrow \dot{y}(t) = \mu_k\, g\, t + d_1, \\ &\Rightarrow y(t) = \mu_k\, g\, t^2/2 + d_1\, t + d_2, \end{aligned} \tag{6-5}$$

during sticking: $\dot{x}(t) = 0 \Rightarrow \ddot{y}(t) = \ddot{z}(t),$

$$\begin{aligned} &\Rightarrow \dot{y}(t) = \dot{z}(t), \\ &\Rightarrow y(t) = y(t) + e. \end{aligned} \tag{6-6}$$

It is difficult to obtain a relationship in closed form between the maximum absolute displacement response, $\max_t |y(t)|$, and the kinetic coefficient of friction μ_k. The development of this relationship would require to calculate the constants of integration c_1, c_2, d_1, d_2 and e in equations 6-4, 6-5 and 6-6 at each time the block changes its direction of motion relative to the table or stops, as illustrated in figure 6-2.

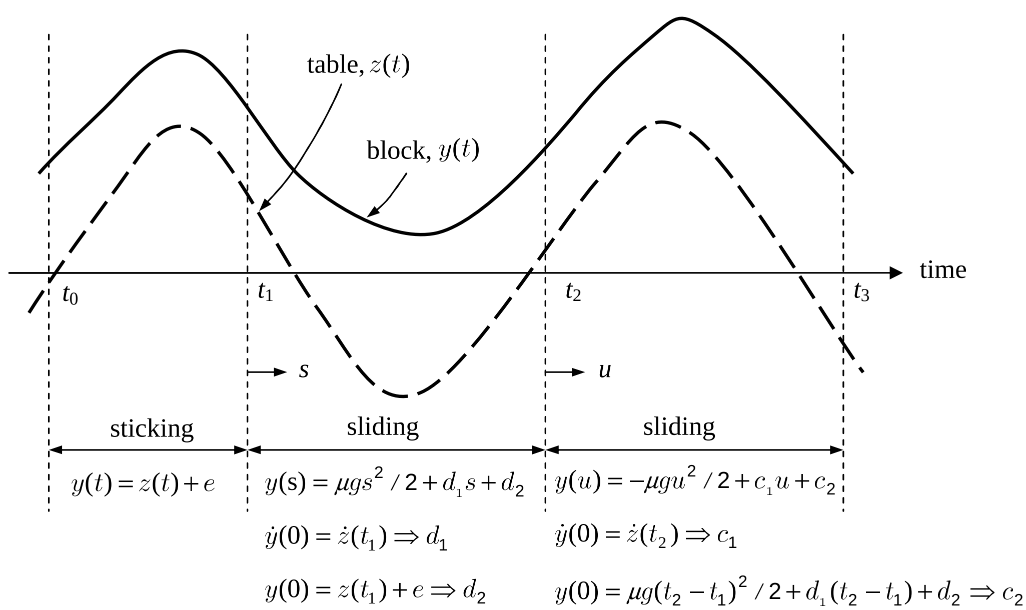


FIGURE 6-2 Displacements of the Table and the Block

The numerical integration scheme given by equations 5-21 - 5-26, and the algorithm defined in Section 5.4 are used to obtain the relationship between the maximum absolute displacement response $\max_t |y(t)|$ and the kinetic coefficient of friction μ_k as illustrated in figure 6-3. The

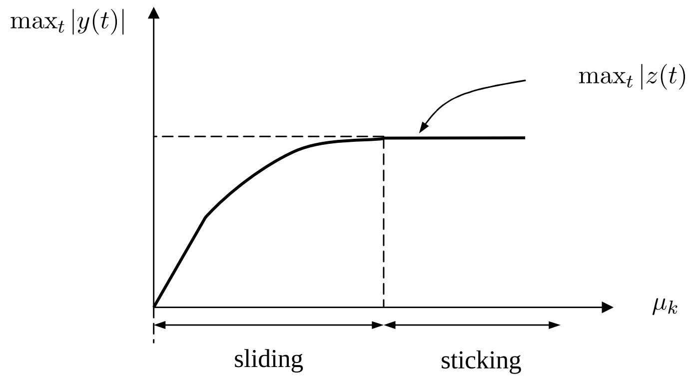


FIGURE 6-3 Relation between $\max_t |y(t)|$ **and** μ_k

unknown kinetic coefficient of friction can be estimated, for a given maximum displacement response measured in an experimental study, using the relationship given by equations 6-4 - 6-6 and illustrated in figure 6-3.

The solution is very sensitive to the time step Δt used in equations 5-21 - 5-26, especially for high frequency input. Switch from sticking to sliding, or visa versa, may happen during the time step Δt and error might build up. It is observed that the maximum response is stable for $\Delta t \leq 0.00005$ for the highest frequency (corresponding to 0.1 sec period) sinusoidal input motions used in the experimental study (see table 4.2). Accordingly, we have used $\Delta t = 0.00001$ for our analysis in this study.

An example of maximum total displacement versus kinetic coefficient of friction curve is shown in figure 6-4. The plot is for (i) an input acceleration given by equations 5-27 and 5-28 with $\alpha = 0.8$,

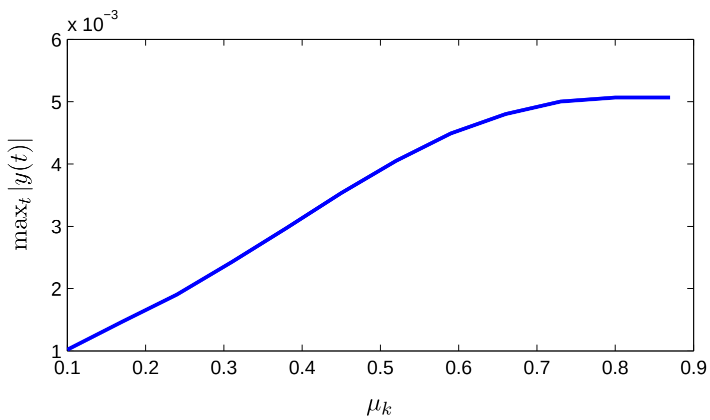


FIGURE 6-4 Example $\max_t |y(t)|$ **versus** μ_k

$\nu = 2\pi/T$, $T = 0.5$ sec, $t_f = 40.2T$, $t_1 = 0.2T$ and $t_2 = 20T$, (ii) kinetic coefficient of friction $\mu_k \in [0.1, 0.9]$, and (iii) $\Delta t = 0.00001$.

SECTION 7
DATA ANALYSIS

A series of shake table experiments on rigid blocks have been performed at the University at Buffalo to characterize the kinetic coefficient of friction for three different interfaces, (i) wood on steel, (ii) carpet on steel, and (iii) Poly-Tetra-Fluoro-Ethylene (PTFE) on steel (explained in detail in Section 4). The interfaces are selected such that there would be low, medium and high level of friction. The surface of the shake table is steel and the other surface, that is, wood, carpet or PTFE, is attached to the bottom of the blocks. The excitations are modulated unidirectional sine waves with different amplitudes and frequencies to account for the uncertainty related to the dependence of the kinetic coefficient of friction on the loading. To account for the uncertainty related to the experimental errors six nominally identical blocks are tested simultaneously for a given amplitude, period pair.

7.1 Data Source

A total of 50 tests were performed at the University at Buffalo and were assigned numbers form 1 to 50. Some of the tests were not useful in the estimation of kinetic coefficient of friction due to several reasons.

- In 17 tests (tests 1, 2, 3, 10, 11, 12, 19, 20, 21, 26, 27, 28, 35, 36, 44, 45 and 46) amplitudes of the input accelerations were not sufficiently large to initiate sliding, that is, the blocks were stuck to the shake table during the tests.
- 3 tests (tests 17, 36 and 50) did not result in any or useful data due to errors in measuring devices for acceleration or displacement responses.

The remaining 30 tests are tabulated below according to the interface types and input acceleration properties. Tables 7-1, 7-2 and 7-3 give the tests numbers for input accelerations with different amplitudes and accelerations for carpet-steel, wood-steel and PTFE-steel interfaces, respectively.

TABLE 7-1 Test Numbers for Carpet-Steel Interface

	Period (sec)		
Amplitude (in g units)	**0.75**	**0.50**	**0.10**
low (∼0.60)	38	14; 39	15; 40
medium (∼0.80)	13	16; 41	42
high (∼1.00)			18; 43

Experiments were performed using small (tests 1, 2, . . ., 25) and large (tests 26, 27, . . ., 50) blocks to determine the effect of the size of the contact surface on the kinetic coefficient of friction estimates. Acceleration and displacement measuring devices were attached to each block and to the shake table. Figures 7-1, 7-2 and 7-3 show the acceleration and displacement records of block 1 in tests 4 and 9 for wood-steel interface, tests 38 and 43 for carpet-steel interface, and tests 22 and 25 for PTFE-steel interface, respectively. Low frequency ($\nu = 2\,\pi/0.75$) excitations were used for tests 4, 38 and 22, and high frequency ($\nu = 2\,\pi/0.1$) excitations were used for tests 9, 43 and 25. Further details about the tests can be found in Section 4.

TABLE 7-2 Test Numbers for Wood-Steel Interface

Amplitude (in g units)	Period (sec) 0.75	0.50	0.10
low (∼0.60)	4; 29	5; 30	6; 31
medium (∼0.80)		7; 32	8; 33
high (∼1.00)			9; 34

TABLE 7-3 Test Numbers for PTFE-Steel Interface

Amplitude (in g units)	Period (sec) 0.75	0.50	0.10
low (∼0.60)	22; 47	23; 48	24; 49
high (∼1.00)			25

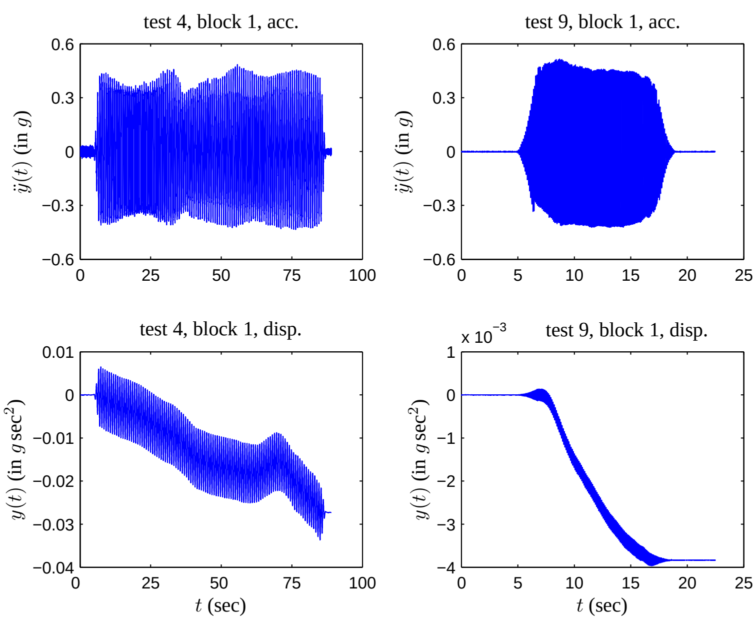


FIGURE 7-1 Wood-Steel Interface Sample Responses

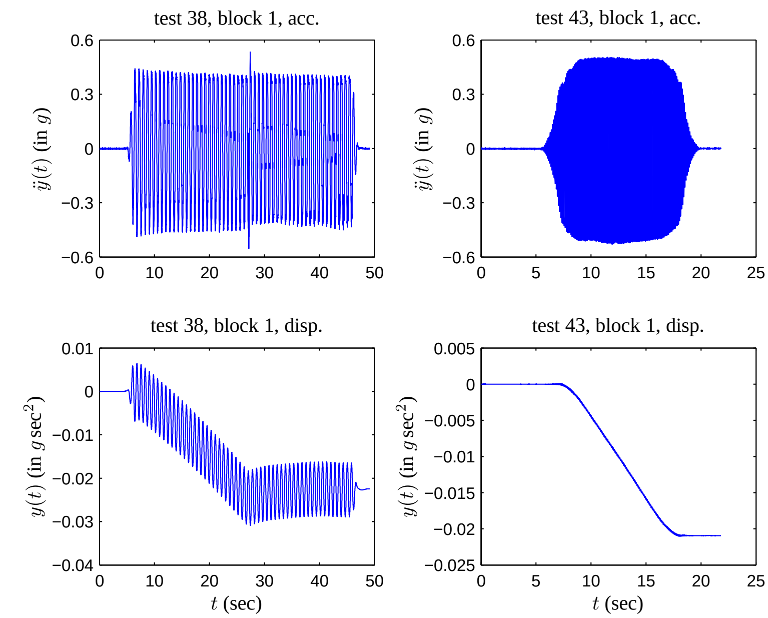


FIGURE 7-2 Carpet-Steel Interface Sample Responses

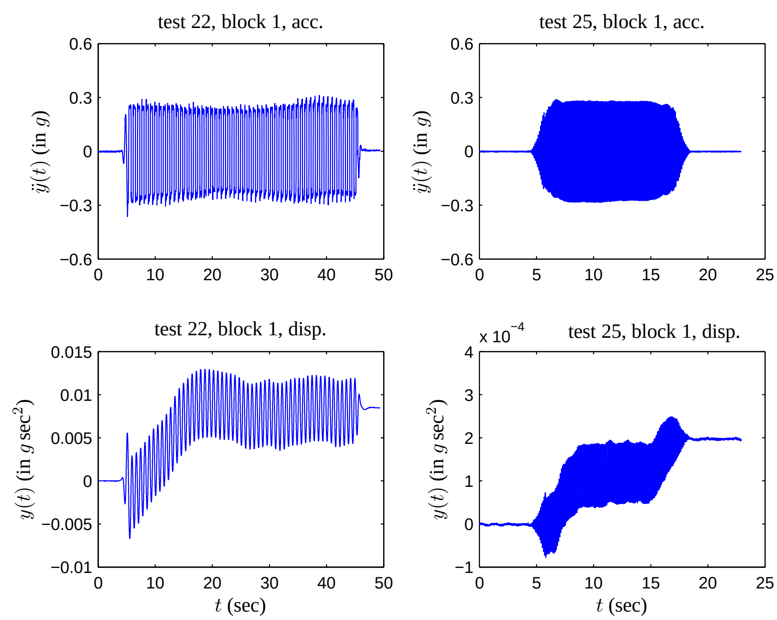


FIGURE 7-3 PTFE-Steel Interface Sample Responses

7.2 Estimation Procedure

Two methods are used to estimate the kinetic coefficient of friction. The methods are based on acceleration and displacement records of blocks obtained in Section 4.

7.2.1 Acceleration-Based Estimates of Kinetic Coefficient of Friction

Let $a(t)$, $t \in [0, t_f]$, be the recorded acceleration time history of a block in a given test, with respect to a fixed frame. The corresponding block acceleration in calculations is denoted by $\ddot{y}(t)$. The following 4-step procedure was used to find estimates $\mu_{k,acc}$ of μ_k based on acceleration records.

- ***Step 1:*** The acceleration record $a(t)$, $t \in [0, t_f]$, is corrected by subtracting its temporal mean

$$m_a = \frac{1}{t_f} \int_0^{t_f} a(s) ds. \tag{7-1}$$

The corrected acceleration record is

$$a_c(t) = a(t) - m_a, \quad t \in [0, t_f]. \tag{7-2}$$

- ***Step 2:*** The steady state part of the corrected acceleration response record $a_c(t)$ is obtained using its energy at time t defined by

$$e(t) = \int_0^t a_c^2(s) ds, \quad 0 \le t \le t_f. \tag{7-3}$$

The time interval of the steady state part, $[t_a, t_b]$, is defined by the conditions

$$\begin{aligned} e(t_a) &= 0.15\, e(t_f), \\ e(t_b) &= 0.85\, e(t_f). \end{aligned} \tag{7-4}$$

Hence, the steady state corrected acceleration is

$$a_{ss,c}(t) = a_c(t), \quad t \in [t_a, t_b]. \tag{7-5}$$

Figure 7-4 shows the table acceleration $\ddot{z}(t)$ and $a_{ss,c}(t)$ for block 1 in test 38 (low frequency excitation).

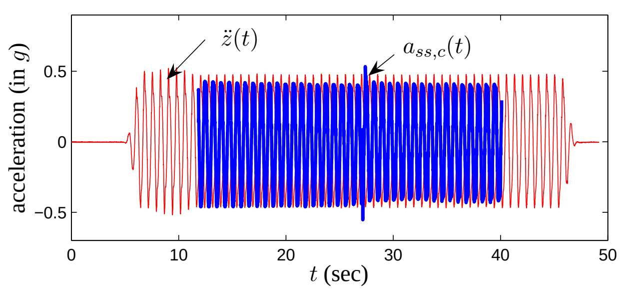


FIGURE 7-4 Steady State Corrected Acceleration (Test 38, Block 1)

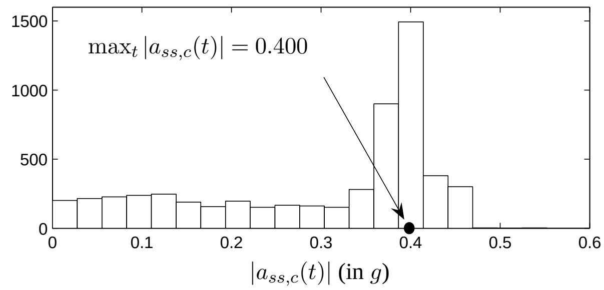
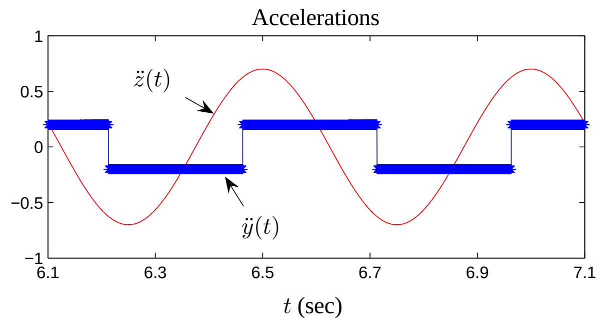
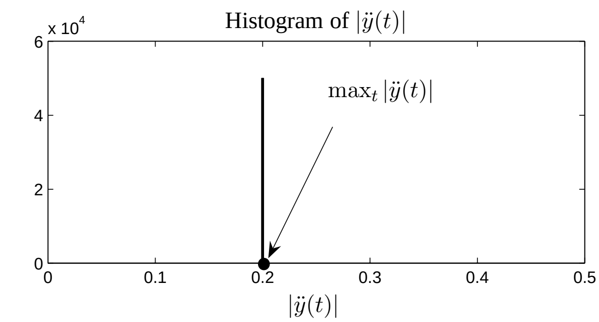


FIGURE 7-5 Histogram of $|a_{ss,c}(t)|$ (Test 38, Block 1)

- ***Step 3:*** The maximum absolute acceleration $\max_t |a_{ss,c}(t)|$ for $t \in [t_a, t_b]$ is estimated by its most likely value from the histogram of $|a_{ss,c}(t)|$. Figure 7-5 shows the histogram of $|a_{ss,c}(t)|$ and the proposed estimate for $\max_t |a_{ss,c}(t)|$ for block 1 in test 38. This estimate has been selected using the following observations.
  - If the amplitude of the excitation $\ddot{z}(t)$ is much larger than the kinetic coefficient of friction μ_k, the block never sticks to the table during the steady state excitation. In this case, the calculated steady state total block acceleration $\ddot{y}(t)$ is a piecewise constant function with zero temporal mean and constant absolute value (figure 7-6 (a)). The



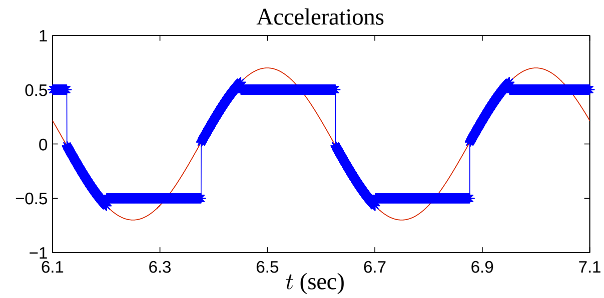
(a)



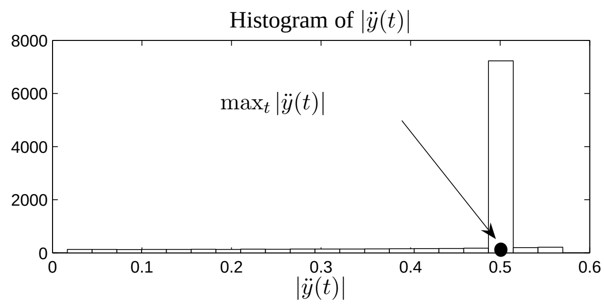
(b)

FIGURE 7-6 Acceleration Illustration for No Sticking Case

  histogram of steady state $|\ddot{y}(t)|$ is then a delta function centered at $\max_t |\ddot{y}(t)|$, as illustrated in figure 7-6 (b).
  - If the amplitude of the excitation $\ddot{z}(t)$ is larger than but close to μ_k, the block has consecutive sticking and sliding phases as illustrated in figure 7-7 (a). Then, $\max_t |\ddot{y}(t)|$ in the sliding phase can also be estimated by the most likely value of $|\ddot{y}(t)|$, obtained



(a)



(b)

FIGURE 7-7 Acceleration Illustration for Stick-Slip Case

from the histogram of $|\ddot{y}(t)|$, as shown in figure 7-7 (b). Note that the most likely value of $|\ddot{y}(t)|$ does not correspond to the last bin of the histogram since $\mu_s > \mu_k$.

– In an actual experiment, assuming that sliding occurs, the steady state acceleration record resembles the plot in figure 7-7 (a). Figure 7-8 shows a portion of $a_{ss,c}(t)$ of

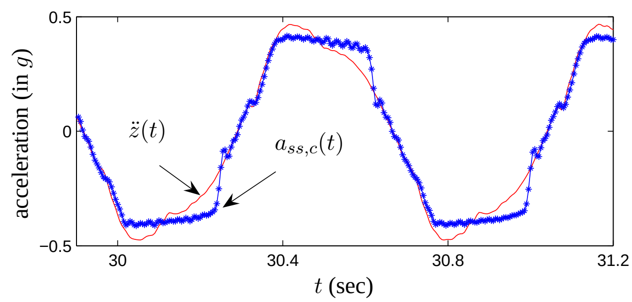


FIGURE 7-8 Accelerations (Test 38, Block 1)

block 1 in test 38. This suggests that an estimate for the maximum absolute steady state acceleration $\max_t |a_{ss,c}(t)|$ in the sliding phase can be obtained from the histogram of $|a_{ss,c}(t)|$, as in the ideal cases above.

- ***Step 4:*** The kinetic coefficient of friction is obtained using equation 6-3. Figure 7-9 shows the kinetic coefficient of friction $\mu_{k,acc}$ obtained using the acceleration response of block 1 in test 38.

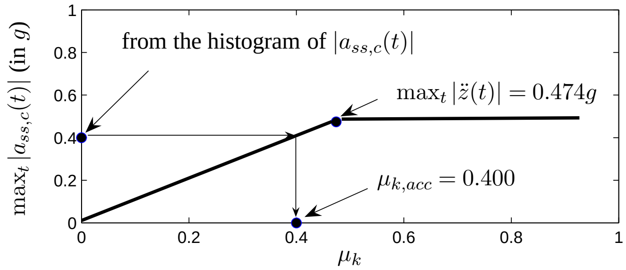


FIGURE 7-9 Kinetic Coefficient of Friction from Accelerations (Test 38, Block 1)

Another example, using the acceleration response of block 1 in test 43, is provided to show the effect of high frequency excitation. ***Steps 1*** to ***4*** were applied to the acceleration record of the block. Figure 7-10 shows the input acceleration $\ddot{z}(t)$ and the steady state, corrected acceleration $a_{ss,c}(t)$ of the block, figure 7-11 shows the histogram of $|a_{ss,c}(t)|$ and $\max_t |a_{ss,c}(t)|$, and figure 7-12 shows the kinetic coefficient of friction $\mu_{k,acc}$, for block 1 in test 43.

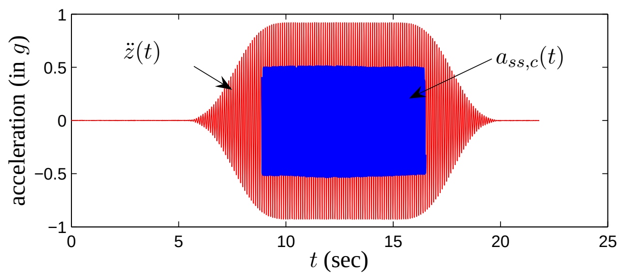


FIGURE 7-10 Steady State Corrected Acceleration (Test 43, Block 1)

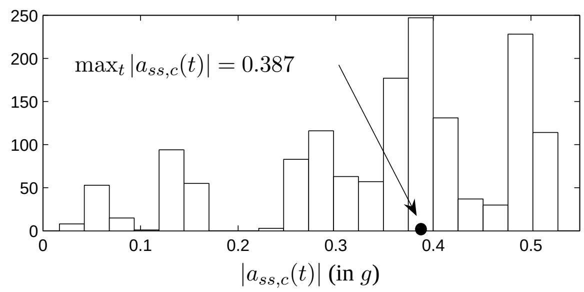


FIGURE 7-11 Histogram of $|a_{ss,c}(t)|$ (Test 43, Block 1)

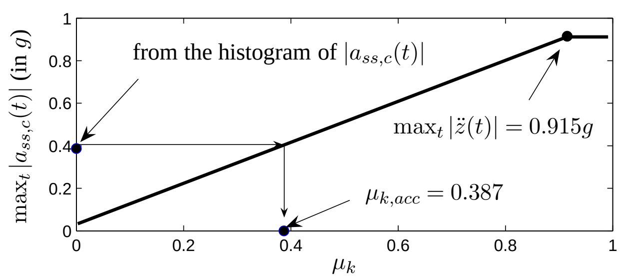


FIGURE 7-12 Kinetic Coefficient of Friction from Accelerations (Test 43, Block 1)

7.2.2 Displacement-Based Estimates of Kinetic Coefficient of Friction

Let $d(t)$, $t \in [0, t_f]$, be the recorded displacement time history of a block in a given test, with respect to a fixed frame. The corresponding block displacement in calculations is denoted by $y(t)$. The following 4-step procedure was used to find estimates $\mu_{k,disp}$ of μ_k based on displacement records.

- ***Step 1:*** The displacement record $d(t)$, $t \in [0, t_f]$, is corrected by subtracting its drift

$$d_a(t) = \int_{t-t_c/2}^{t+t_c/2} d(s)ds. \tag{7-6}$$

  The corrected displacement record is

$$d_c(t) = d(t) - d_a(t), \quad t \in [0, t_f]. \tag{7-7}$$

  In equation 7-6 $t_c = 1/f_c$ is the window length. The cut-off frequency f_c is selected such that the low frequencies are removed from $d(t)$. It is assumed that $f_c = f_{\max}/2$, where $f_{\max} = 1/T$ and T is the period of the excitation. The corrected displacement record $d_c(t)$ has zero mean and has no drift. Figure 7-13 (a) shows the displacement record $d(t)$, figure 7-13 (b) shows the Fourier amplitude spectra of $d(t)$ and the cut-off frequency f_c, figure 7-13 (c) shows the drift $d_a(t)$, and figure 7-13 (d) shows the corrected displacement response $d_c(t)$, for block 1 in tests 65 (low frequency excitation).

- ***Step 2:*** The steady state part of the corrected displacement response record $d_c(t)$ is obtained as in ***Step 2*** in Section 7.2.1. The steady state corrected displacement is

$$d_{ss,c}(t) = d_c(t), \quad t \in [t_a, t_b]. \tag{7-8}$$

  Figure 7-14 shows the displacement of table $z(t)$ and $d_{ss,c}(t)$ for block 1 in test 38.

- ***Step 3:*** The maximum absolute displacement $\max_t |d_{ss,c}(t)|$ for $t \in [t_a, t_b]$ is estimated by its most likely value from the histogram of $|d_{ss,c}(t)|$. Figure 7-15 shows the histogram of $|d_{ss,c}(t)|$ and the proposed estimate for $\max_t |d_{ss,c}(t)|$ for block 1 in test 38. This estimate has been selected using the following observations.

  – If the amplitude of the excitation $\ddot{z}(t)$ is much larger than the kinetic coefficient of friction μ_k, the block never sticks to the table once the excitation becomes steady state. In this case, the calculated steady state total block displacement $y(t)$ consists of pieces of parabola (see figure 6-2) and is illustrated in figure 7-16 (a). Since the data is clustered around the peaks of $y(t)$ and the total displacement response has zero temporal mean, the maximum absolute total block displacement $\max_t |y(t)|$ in the sliding phase is estimated by the most likely value of $|y(t)|$ as illustrated in figure 7-16 (b).

  – If the amplitude of the excitation $\ddot{z}(t)$ is larger than but close to μ_k, the block has consecutive sticking and sliding phases as illustrated in figure 7-17 (a). Again, $\max_t |y(t)|$ in the sliding phase is estimated by the most likely value of $|y(t)|$, obtained from the histogram of $|y(t)|$, as shown in figure 7-17 (b).

  – In an actual experiment, assuming that sliding occurs, the steady state displacement record resembles the plot in figure 7-17 (a). Figure 7-18 shows a portion of $d_{ss,c}(t)$ of block 1 in test 38. This suggests that an estimate for the maximum absolute steady state displacement $\max_t |d_{ss,c}(t)|$ in the sliding phase can be obtained from the histogram of $|d_{ss,c}(t)|$, as in the ideal cases above.

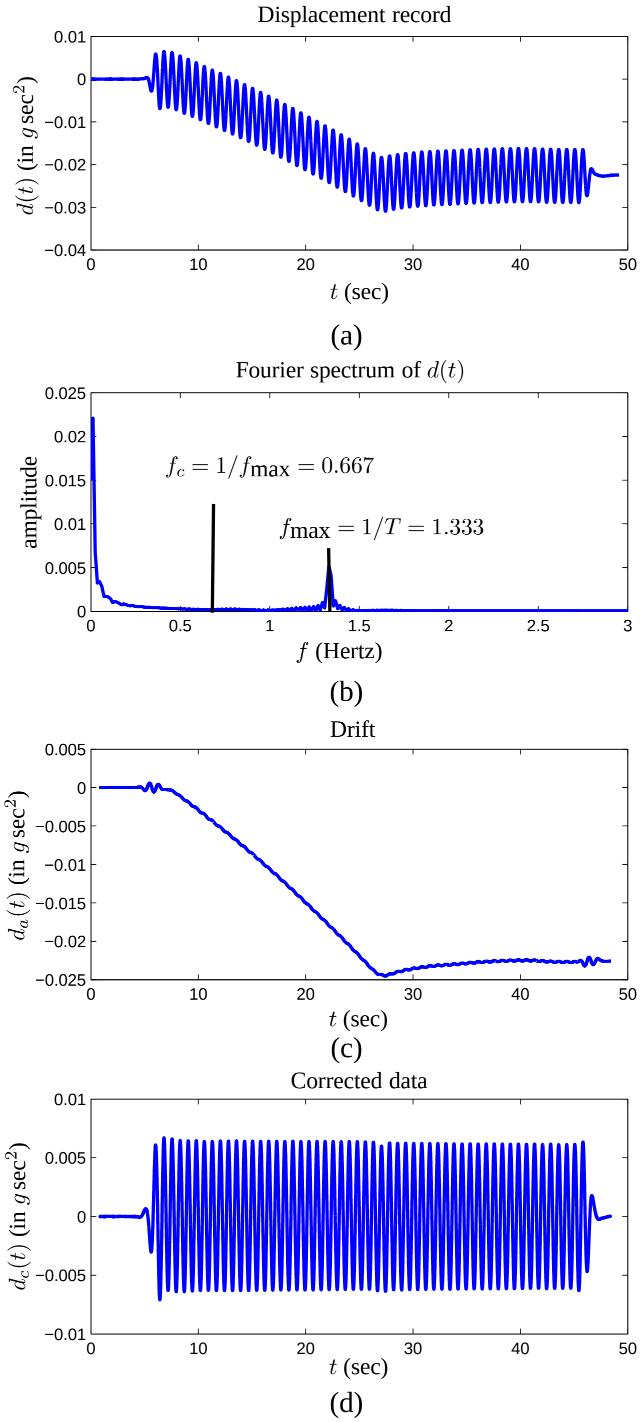


FIGURE 7-13 Drift Correction (Test 38, Block 1)

- ***Step 4:*** The kinetic coefficient of friction is obtained using the relation between $\max_t |d_{ss,c}(t)|$ and μ_k as illustrated in figure 6-4. Figure 7-19 shows the kinetic coefficient of friction $\mu_{k,disp}$ obtained using displacement responses from block 1 in test 38.

Another example using, the displacement record of block 1 in test 43, is provided to show the effect of high frequency excitation. ***Steps 1*** to ***4*** were applied to the displacement record of the block.

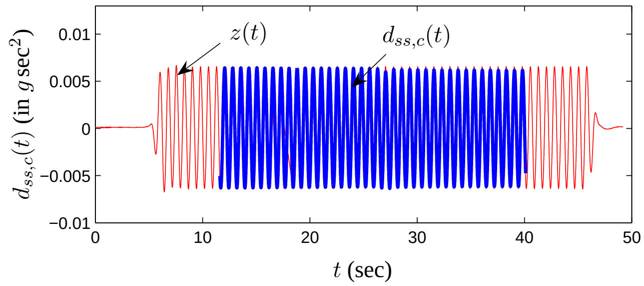


FIGURE 7-14 Steady State Corrected Displacement (Test 38, Block 1)

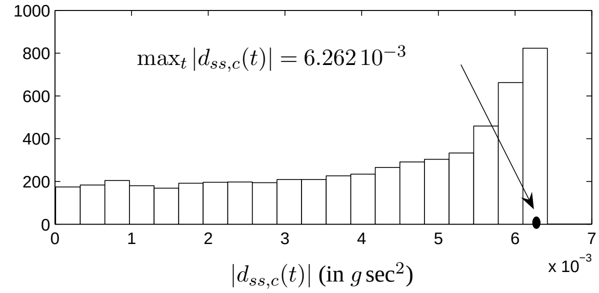
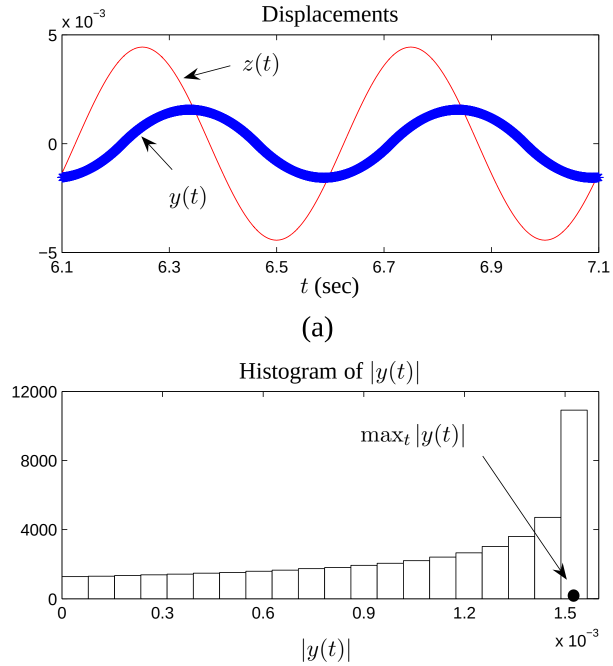


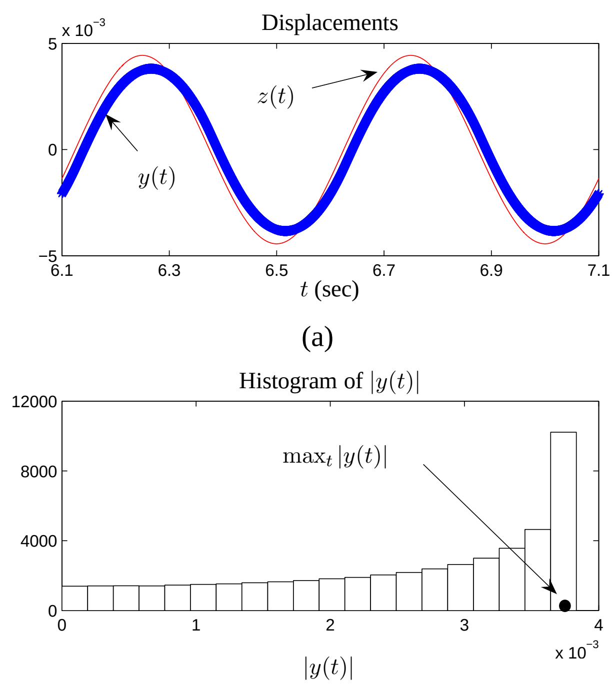
FIGURE 7-15 Histogram of $|d_{ss,c}(t)|$ (Test 38, Block 1)

Figure 7-20 (a) shows the displacement record $d(t)$, figure 7-20 (b) shows the Fourier amplitude spectra of $d(t)$ and the cut-off frequency f_c, figure 7-20 (c) shows the drift $d_a(t)$, figure 7-20 (d) shows the corrected displacement response $d_c(t)$. Figure 7-21 shows the input displacement $z(t)$ and the steady state, corrected displacement $d_{ss,c}(t)$. Figure 7-22 shows the histogram of $|d_{ss,c}(t)|$ and $\max_t |d_{ss,c}(t)|$. Figure 7-23 shows the kinetic coefficient of friction $\mu_{k,disp}$ obtained using block 1 in test 43.



(b)

FIGURE 7-16 Displacement Illustration for No Sticking Case



(b)

FIGURE 7-17 Displacement Illustration for Stick-Slip Case

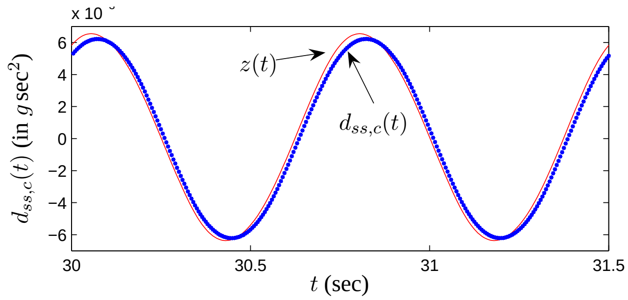


FIGURE 7-18 Displacements (Test 38, Block 1)

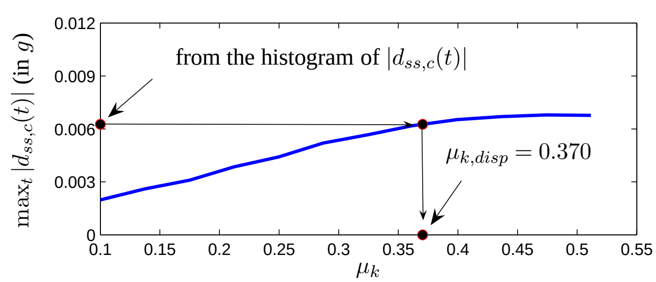


FIGURE 7-19 Kinetic Coefficient of Friction from Displacements (Test 38, Block 1)

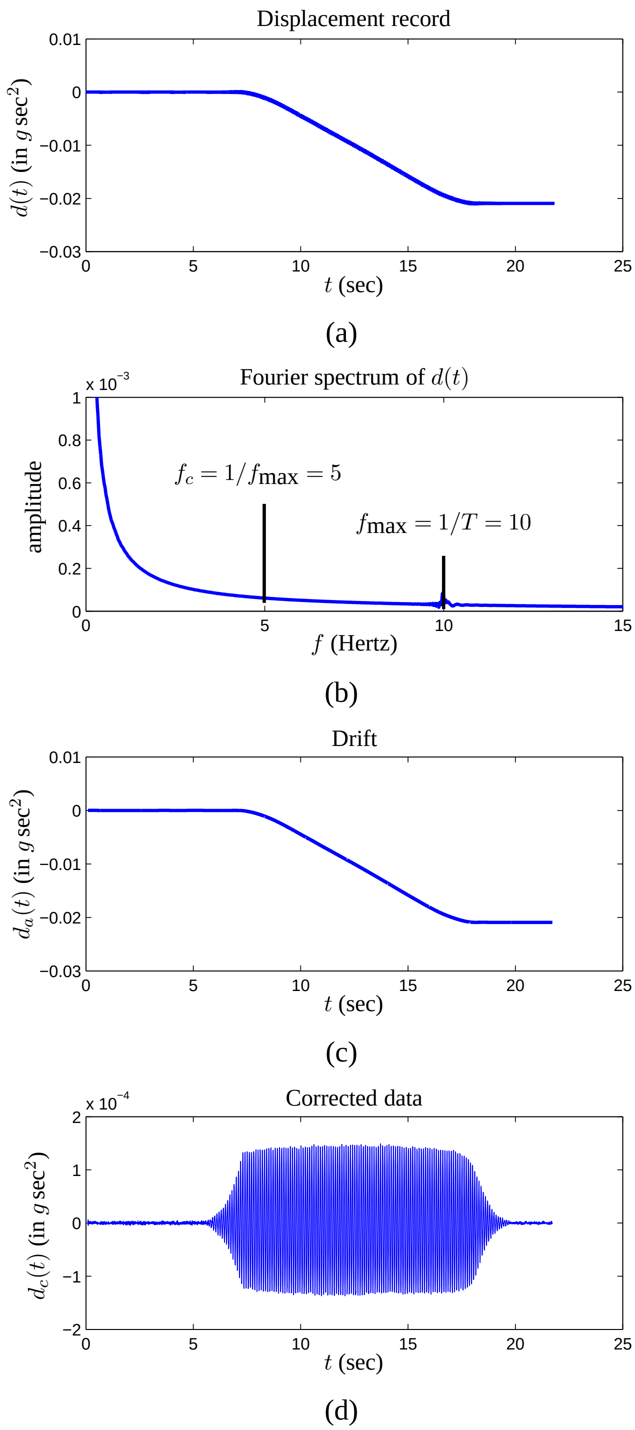


FIGURE 7-20 Displacements (Test 43, Block 1)

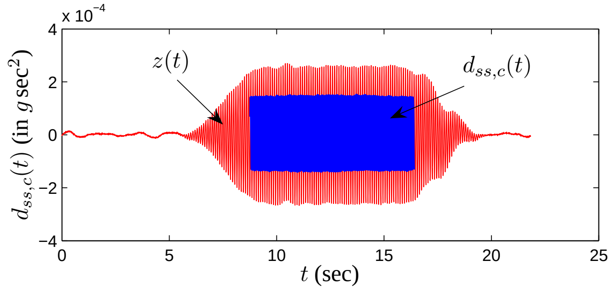


FIGURE 7-21 Steady State Corrected Displacement (Test 43, Block 1)

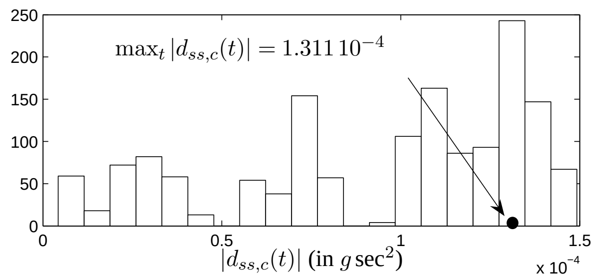


FIGURE 7-22 Histogram of $|d_{ss,c}(t)|$ (Test 43, Block 1)

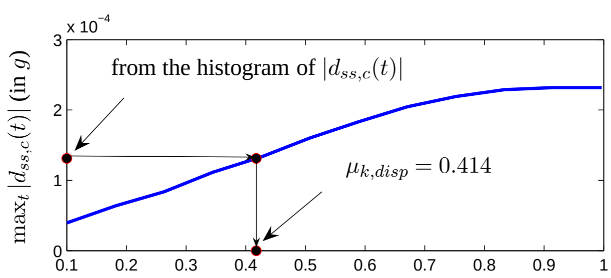


FIGURE 7-23 Kinetic Coefficient of Friction from Displacements (Test 43, Block 1)

SECTION 8
RESULTS

For a given interface type, the kinetic coefficient of friction is obtained using the acceleration and displacement responses of all the blocks in each test for that interface type following the procedures described in Section 7.2. Figures 8-1, 8-2 and 8-3 show the ($\mu_{k,acc}$, $\mu_{k,disp}$) pairs obtained for

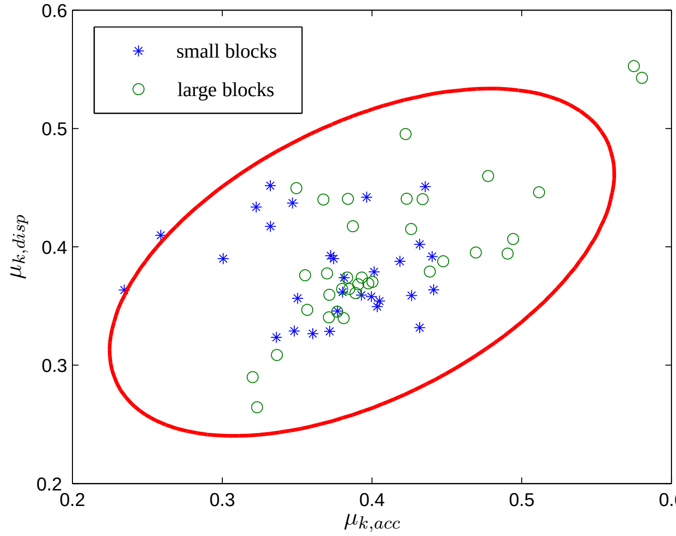


FIGURE 8-1 Carpet-Steel Interface Friction Coefficients

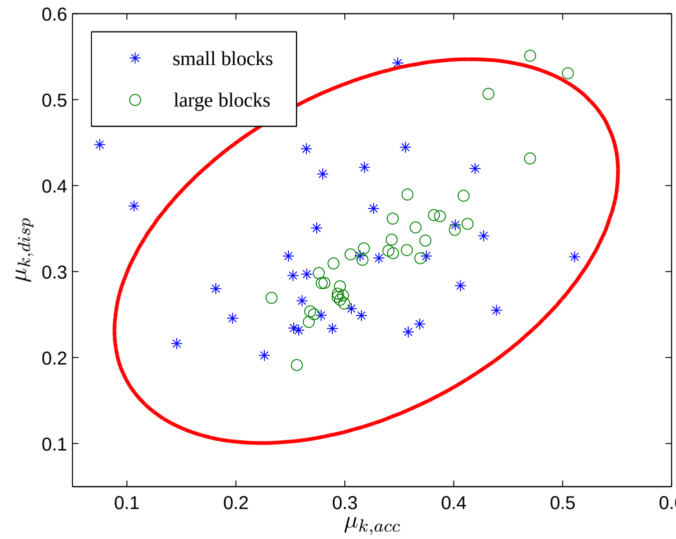


FIGURE 8-2 Wood-Steel Interface Friction Coefficients

carpet-steel, wood-steel and PTFE-steel interfaces, respectively.

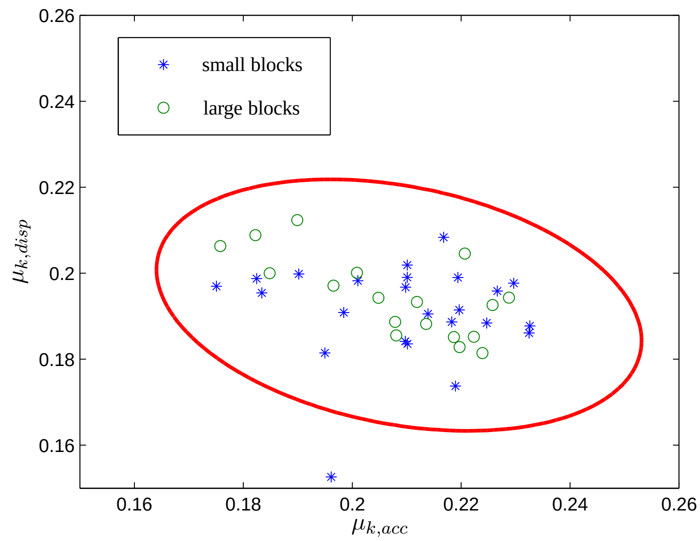


FIGURE 8-3 PTFE-Steel Interface Friction Coefficients

Statistics of $\mu_{k,acc}$ and $\mu_{k,disp}$ are calculated using (i) only the small blocks, (ii) only the large blocks, and (iii) all the blocks, are shown in tables 8-1, 8-2 and 8-3, for carpet-steel, wood-steel

TABLE 8-1 Statistics of Kinetic Coefficients of Friction for Carpet-Steel Interface

Statistics	small blocks		large blocks		all blocks	
	$\mu_{k,acc}$	$\mu_{k,disp}$	$\mu_{k,acc}$	$\mu_{k,disp}$	$\mu_{k,acc}$	$\mu_{k,disp}$
mean	0.374	0.379	0.410	0.394	0.393	0.387
standard deviation	0.051	0.038	0.063	0.062	0.060	0.053
coefficient of variation	0.137	0.101	0.154	0.157	0.153	0.136
correlation coefficient	-0.100		0.752		0.509	

TABLE 8-2 Statistics of Kinetic Coefficients of Friction for Wood-Steel Interface

Statistics	small blocks		large blocks		all blocks	
	$\mu_{k,acc}$	$\mu_{k,disp}$	$\mu_{k,acc}$	$\mu_{k,disp}$	$\mu_{k,acc}$	$\mu_{k,disp}$
mean	0.299	0.317	0.339	0.330	0.320	0.324
standard deviation	0.094	0.083	0.066	0.078	0.083	0.080
coefficient of variation	0.315	0.261	0.194	0.236	0.260	0.247
correlation coefficient	0.069		0.907		0.415	

and PTFE-steel interfaces, respectively. It is observed that the correlation between $\mu_{k,acc}$ and $\mu_{k,disp}$ obtained using the large blocks is significantly higher than the correlation obtained using the small blocks. This suggests that the estimates of μ_k based on small blocks have more noise than those corresponding to large blocks. However, the estimated means and the coefficients of variation are insensitive to block size. It is concluded that there is no apparent size effect in the estimates of $\mu_{k,acc}$ and $\mu_{k,disp}$.

TABLE 8-3 Statistics of Kinetic Coefficients of Friction for PTFE-Steel Interface

	small blocks		**large blocks**		**all blocks**	
Statistics	$\mu_{k,acc}$	$\mu_{k,disp}$	$\mu_{k,acc}$	$\mu_{k,disp}$	$\mu_{k,acc}$	$\mu_{k,disp}$
mean	0.209	0.191	0.208	0.194	0.209	0.193
standard deviation	0.016	0.011	0.016	0.009	0.016	0.010
coefficient of variation	0.077	0.059	0.078	0.048	0.076	0.054
correlation coefficient	-0.020		-0.705		-0.284	

Assuming that $\mu_{k,acc}$ and $\mu_{k,disp}$ are correlated Gaussian random variables with means, standard deviations and correlation coefficients given in tables 8-1, 8-2 and 8-3 for carpet-steel, wood-steel and PTFE-steel interfaces, respectively, contour lines of the joint probability density function of $\mu_{k,acc}$ and $\mu_{k,disp}$ corresponding to 90% probability are shown in figures 8-1, 8-2 and 8-3. Most of the data points are in the 90% probability contour for all three interfaces.

The mean values of the estimates of the static and kinetic coefficients of friction for carpet-steel, wood-steel, and PTFE-steel interfaces given in tables 3-4 - 3-6 and tables 8-1 - 8-3, respectively, are summarized in table 8-4. The mean kinetic coefficients of friction for carpet-steel, wood-steel and

TABLE 8-4 Coefficients of Friction for Carpet, Wood and PTFE - Steel Interfaces

	Coefficient of friction	
Interface	**static**	**kinetic**
carpet-steel	0.450	0.395
wood-steel	0.400	0.322
PTFE-steel	0.270	0.201

PTFE-steel interfaces are 12.22%, 19.50% and 25.56% less than their corresponding mean static coefficient of frictions, respectively.

The 90% probability contours obtained using shake table tests results and theoretical consideration for wood-steel and carpet-steel interfaces, shown in figures 8-2 and 8-1, respectively, include the preliminary estimates of the kinetic coefficient of friction given in tables 3-9 and 3-10, which are obtained using tilts tests.

SECTION 9
CONCLUSIONS

This report describes the first phase of research supported by the Multidisciplinary Center for Earthquake Engineering Research on the seismic performance evaluation of a broad range of freestanding nonstructural components that can be modeled as rigid blocks. More specifically, the main objective of this study was to characterize the static and kinetic coefficients of friction for three interfaces representative of common interfaces between the block-type nonstructural components and their supporting floors. The established coefficients of friction can be used in the seismic performance analysis of block-type nonstructural components.

The interfaces used in this study were Poly-Tetra-Fluoro-Ethylene on steel, wood on steel, and carpet on steel, which resulted in low, moderate, and high coefficients of friction, respectively. Two sets of blocks with different geometry were designed and constructed to model block-type nonstructural components. The block geometries were selected to assure that the blocks would respond to a broad range of uniaxial sinusoidal base excitations by either sticking or sliding.

The static coefficients of friction for the three interfaces were characterized by a series of standard pull and tilt tests. The uncertainties associated with the imperfections in the block-floor interfaces were accounted for by repeating the characterization tests to generate a sufficient number of data points. The mean static coefficients of friction were found to be 0.45 for the carpet-steel, 0.40 for the wood-steel, and 0.27 for the PTFE-steel interfaces. The coefficient of variation was less than 7% for the carpet-steel interface, 10% for the wood-steel interface, and 20% for the PTFE-steel interface. The established static coefficients of friction were deemed to be insensitive to the block size. Preliminary estimates of the kinetic coefficients of friction, which were required to predict the maximum displacements of the blocks in the earthquake simulator experiments, were obtained by a series of tilt tests for the carpet-steel and wood-steel interfaces. The mean values of the preliminary estimates of the kinetic coefficients of friction were 0.33 for the carpet-steel and 0.20 for the wood-steel interfaces, which are 26.67% and 50.00% less than their corresponding mean static coefficient of frictions.

Estimates of the kinetic coefficients of friction for the three interfaces were obtained using acceleration and displacement-based methods. The methods use (i) maximum responses of the blocks obtained through experiments and (ii) relationships between the maximum responses and the kinetic coefficient of friction obtained using theoretical considerations. The methods accounted explicitly for the uncertainty in experimental errors, imperfections in block-floor interfaces, and the relationship between the kinetic coefficient of friction and the loading, and the block size. The mean kinetic coefficients of friction were found to be 0.40 for the carpet-steel, 0.32 for the wood-steel, and 0.20 for the PTFE-steel interfaces. The coefficient of variation was less than 16% for the carpet-steel interface, 26% for the wood-steel interface, and 8% for the PTFE-steel interface. The mean kinetic coefficients of friction for carpet-steel, wood-steel and PTFE-steel interfaces were 12.22%, 19.50%, and 25.56% less than their corresponding mean static coefficients of friction, respectively. It is shown that most of the pairs of acceleration and displacement-based estimates of the kinetic coefficient of friction were included in the 90% probability contour of these parameters assumed to be Gaussian random variables with the second moment properties estimated from experiments. It is also shown that, the estimated means and the coefficients of variation of the kinetic coefficients of friction were insensitive to block size.

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