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Effect of Boundary Conditions on the Strength and Deformability of Replicas of Natural Fractures in Welded Tuff: Data Report

J. Wibowo, B. Amadei, S. Sture, R. H. Price, A. B. Robertson

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**EFFECT OF BOUNDARY CONDITIONS ON THE STRENGTH
AND DEFORMABILITY OF REPLICAS OF NATURAL FRACTURES
IN WELDED TUFF: DATA REPORT**

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ABSTRACT

Four series of cyclic direct-shear experiments were conducted on several replicas of three natural fractures and a tensile fracture of welded tuff from Yucca Mountain. The objective of these tests was to examine the effect of cyclic loading on joint shear behavior under different boundary conditions. The shear tests were performed under either different levels of constant normal load ranging between 0.6 and 25.6 kips (2.7 and 113.9 kN) or constant normal stiffness ranging between 14.8 and 187.5 kips/in (25.9 and 328.1 kN/cm). Each test in the two categories consisted of five cycles of forward and reverse shear. Normal compression tests were also performed both before and after each shear experiment to measure changes in joint normal deformability. In order to quantify fracture surface damage during shear, fracture-surface fractal dimensions were obtained from measurements before and after shear.

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1. INTRODUCTION

The response of a rough joint to shear loading depends on its surface properties as well as the boundary conditions that are applied across its surfaces by the surrounding rock mass. These boundary conditions can exist in multiple forms and vary between constant normal load (stress), as in the case of slope stability problems, to variable or constant normal stiffness, as in the vicinity of underground excavations. The normal stiffness applied across joint surfaces is defined as the ratio between increments in normal load and increments in normal displacement. It varies between zero for constant normal load conditions and infinity for constant normal displacement conditions. In general, joint shear strength under constant or variable normal stiffness is higher than joint shear strength under constant normal load (stress). The main reasons for the increase in shear strength are that under constant or variable normal stiffness boundary conditions, joint dilatancy created by joint surface roughness is inhibited and joint normal load (stress) increases as shear takes place. The effect of normal stiffness boundary conditions on the shear behavior of rock joints has been investigated either theoretically or experimentally by Goodman (1976), Obert et al. (1976), Leichnitz (1985), Goodman and Boyle (1985), Hutson (1987) and more recently, by Archambault et al. (1990), Bandis (1990), Benmokrane et al. (1991), Ohnishi and Dharmaratne (1990) and Skinas et al. (1990).

In two recent publications, Saeb (1989) and Amadei and Saeb (1990) proposed mathematical and graphical methods to predict the behavior of a rock joint under any normal stiffness boundary condition from the results of conventional constant normal load (or stress) direct shear experiments. An experimental research program was initiated to verify those methods using data collected on several fractures of welded tuff from Yucca Mountain in Nevada. This report presents the results of cyclic direct shear and normal compression tests conducted on replicas of three natural fractures and a tensile fracture in welded tuff. The direct shear experiments were

performed under constant normal loads ranging between 0.6 and 25.6 kips (2.7 and 113.9 kN) and constant normal stiffnesses ranging between 14.8 and 187.5 kips/in (25.9 and 328.1 kN/cm) with different initial normal loads. Each test consisted of five cycles of forward and reverse shear motion. The effect of cyclic loading on the fracture behavior was investigated. In particular, special attention was placed on relating the degradation of fracture surface asperities to the number of cycles. Surface damage was assessed by comparing the values of fractal dimensions determined from profiles on the fracture surfaces before shear (one set of profiles per fracture) and after shear (on all fracture replicas). For each fracture, only one normal compression test was conducted before shear. Normal compression tests were also conducted after shear on all fracture replicas to assess changes in joint normal deformability. ¹

2. EXPERIMENTAL WORK

2.1 Specimen Preparation

Four rectangular joint samples of welded tuff from Yucca Mountain and Rainier Mesa were investigated in this study:

- a. A natural joint sample from the G Tunnel (from Rainier Mesa). The size of the sample was approximately 4.0 in x 8.0 in (10.2 cm x 20.3 cm). In this report, this sample is referred to as G2.
- b. An artificially created joint sample of Topopah Spring Member from the Fran Ridge East Lower Test Pit (FRELTP), east of Yucca Mountain, identified as FRELTP - 0 m - 3 m - 41 - SNL/CSM - A ². The joint was created by tensile splitting of a welded tuff block. The size of the sample was approximately 3.0 in x 6.0 in (7.6 cm x 15.2 cm). This sample is referred to as F2.

¹ In this report the terms "joint" and "fracture" are used interchangeably.

² Identification number provided by Sandia National Laboratories.

- c. A natural joint sample from FRELTP with identification number FRELTP - 0 m - 3 m - 35 - SNL/CSM - A². The size of the sample was approximately 3.0 in x 6.0 in (7.6 cm x 15.2 cm). This sample is referred to as F3.
- d. A natural joint sample from FRELTP with identification number FRELTP - 0 m - 3 m - 35 - SNL/CSM - B². The size of the sample was approximately 3.0 in x 6.0 in (7.6 cm x 15.2 cm). This sample is referred to as F4.

All four joints originated from several blocks of welded tuff provided by Sandia National Laboratories. The blocks were large and irregular in shape. To obtain the natural joint sample and create a regular external configuration with the size mentioned above, the big blocks were cut using a diamond bit masonry saw. The mean plane of the joint coincided with the center plane of the block.

In order to perform several shear tests on fracture surfaces with duplicated initial roughness, replicas of the four joint surfaces were made using gypsum cement (Ultracal 30, produced by United States Gypsum, Chicago, Illinois). Two steps were followed in making the replicas. First, the negative images of the joint surfaces (top and bottom) were created by pouring silicon rubber (Silastic E RTV, produced by Dow Corning Corporation, Midland, Michigan) on the surfaces of the original joints. After 48 hours of hardening, the half-inch-thick negative images were strong enough to be used as negative molds for the joint replicas. Then, twelve to fifteen joint replicas were reproduced using a water-to-gypsum cement ratio of 20%. With this mixture, the unconfined compressive strength of the gypsum cement was measured as approximately 4,000 psi (27.6 MPa).

The bottom portion of each joint replica was placed at the center of the lower shear box specimen holder. Spacers were placed at the bottom of the sample in order to keep the mean joint surfaces horizontal. The mean joint surfaces were adjusted to a horizontal plane by using the air bubble of a 2.0 in x 8.0 in (5.1 cm x 20.3 cm) level placed longitudinally across the joint surfaces.

A gypsum cement mixture was then poured into the lower specimen holder to maintain the replica in place. Following hardening of the gypsum cement, the top part of each joint replica was placed and kept in a mated position above the corresponding bottom part. Then, the assembly consisting of the top and bottom parts of the joint replica and the bottom specimen holder were turned over and placed at the center of the top specimen holder. The upper and lower specimen holders were positioned in a manner that ensured initially parallel alignment. The top part of the joint replica was held in place using gypsum cement.

Bevelled miniature berms or embankments made of gypsum cement were placed along the periphery and up to the surfaces of samples F3 and F4 in order to prevent their edges from breaking off during shear, especially under high normal loads. This helped in keeping most of the test specimen edges intact during shear. For the G2 and F2 samples no slope embankments were constructed. Orange enamel paint was lightly sprayed on the joint surfaces in order to observe surface damage occurring during shear. This paint created a very thin, brittle and easily removed film, which was abraded very easily during shear. The effect of this paint on friction, if any, was considered insignificant. The joint surfaces were then ready for the following test sequence: profilometer recording before shear (one set of profiles for each joint), normal compression before shear (one test for each joint), cyclic shear, normal compression after shear, and profilometer recording after shear.

2.2 Direct Shear Tests

Direct shear tests were conducted according to Experimental Plan (EP) # 44 using the direct shear machine available in the Department of Civil, Environmental, and Architectural Engineering at the University of Colorado at Boulder. For each direct shear test, seven steps were followed:

- identification of each joint specimen,
- placement of joint specimen with the specimen holders on the platens of the direct shear machine,
- application of initial normal load across the joint surfaces,
- cyclic normal compression,
- shearing with five cycles,
- cyclic normal compression, and
- measurement of joint surface area sheared and weight of gouge generated during cyclic shear.

2.2.1 Direct Shear Apparatus

The direct shear experiments were conducted using a servo-controlled direct shear apparatus. Figures 1 and 2 show the different components of the apparatus including two independent Minnesota Testing System (MTS) actuators (used to transmit normal and shear loads), reaction frames, loading fixtures, and shear box specimen holders. The MTS actuators used to apply normal and shear loads have a capacity of 165 kips (734 kN) and 35 kips (156 kN), respectively, and can be operated independently in load or displacement control modes. The actuators are equipped with load cells to measure applied forces and have internal LVDTs for monitoring displacement (stroke). Both actuators are powered by independent, closed-loop continuous flow systems powered by a 20 gpm (76 lpm) generator pump. For cyclic shearing, a function generator provides a sinusoidal reference voltage to the shear load actuator in the displacement control mode. The sinusoidal reference voltage was chosen to avoid a sudden change of shear rate at the maximum shear displacement. Although this sinusoidal reference voltage caused the shear rate to be variable, the shear load response does not show significant difference as explained by Gould (1982). A detailed description of the apparatus and its performance characteristics is given by Gould (1982).

Figure 1. Direct shear apparatus (Schematic side view).
(Gould, 1982)

2.2.2 Instrumentation

The applied loads were measured using the MTS actuator load cells; a 220 kips cell (978 kN, MTS 661.31A-02) mounted on the normal actuator and a 35 kips cell (157 kN, MTS 661.23A-09) mounted on the shear actuator. The range or amplification for the normal load cell was changed between times-one (100% of capacity) and times-ten (10% of capacity) depending on the test condition. The shear load cell was always operated in a times-one (100% of capacity) mode. Since the actuators' internal LVDTs were not sensitive enough and were located too far away from the test specimens to monitor displacements accurately, two external horizontal LVDTs (Schaevitz 1000 HRDC) shown in Figure 3 were used to monitor the relative shear displacements. They had a 1.0 in (2.54 cm) maximum stroke and were of the DC type. Aluminum rods (0.1 in, 2.4 mm dia.) were cemented into the top and bottom parts of each specimen using heavy duty epoxy. Collars were used to connect the rods to the tips of the LVDTs in order to provide a solid mechanical connection during shear direction reversal. The two LVDTs were supported by an unstressed external stand placed on the structural test floor.

In addition, three external vertical LVDTs were used to monitor the normal joint displacement (Figure 4). Two of those LVDTs were Schaevitz 1000 HRDC with a 1.0 in (2.5 cm) maximum stroke. The third LVDT was a Schaevitz 500 HRDC with 0.5 in (1.3 cm) maximum stroke. The normal displacement LVDTs were mounted on holder assemblies made of heavy steel bars, which were attached to supports that were firmly bolted to the thick steel base plate of the direct shear apparatus.

For the real time control tests (i.e., constant stiffness tests), a more precise Schaevitz 200 HR LVDT (AC type), with a 0.2 in (5 mm) maximum stroke, was also used to monitor the normal displacement of the joints. A special holder was constructed that allowed that particular LVDT to be placed between the hydraulic

Figure 3. Shear displacement monitoring LVDTs.
 (1) Schaevitz 1000 HRDC LVDT.
 (2) LVDT holder.

Figure 4. Normal displacement monitoring LVDTs.
 (1) Schaevitz 1000 HRDC LVDT.
 (2) Schaevitz 500 HRDC LVDT.
 (3) LVDT holder.

cylinder and the load cell of the vertical actuator as shown in Figure 5. An initial load had to be applied across the joint surfaces before that LVDT was adjusted into zero position in order to prevent it from going out of range.

2.2.3 Test Control for Normal Stiffness Test

For the joints sheared under constant normal stiffness, their dilatancy caused an additional normal load proportional to the applied stiffness. Direct shear tests under constant normal stiffness were performed following a procedure similar to the constant normal load shear tests with an additional computer system appended to the existing system. The dilatancy monitored by the Schaevitz 200 HR LVDT (AC type) was converted to digital data and manipulated by a computer program to maintain the value of applied stiffness to a predetermined value. As dilatancy occurred, the additional normal load due to stiffness was reconverted to an analog signal, and these additional voltages were added to the existing load applied by the MTS system. Details of the real time control tests have been described by Hutson (1987).

2.2.4 Data Acquisition System

An IBM-XT personal computer with a Tecmar board A/D (analog to digital) converter was used for data collection. Various voltage ranges are software selectable. The MTS system works on a ± 10 v circuit. Since the load cell readings were being supplied by this system, all channels were set for a ± 10 v range. A data acquisition computer program written in Turbo Pascal provided adequate speed, along with good organization and readability.

2.2.5 Testing

The upper half of each joint sample with the specimen holder was attached to the shear machine first. The upper platen was raised to its full height under displacement control and low hydraulic

Figure 5. Normal displacement control LVDT for normal constant stiffness test.
(1) Normal load cell.
(2) Schaevitz 200 HR LVDT.
(3) LVDT holder.

pressure. The upper half of the sample was then inserted, supported by a padded block, and the upper platen was lowered and secured with 13 cap screws. The lower half of the joint specimen was then inserted and bolted into the lower platen with the same number of cap screws. The two specimen holders were brought into contact and the normal actuator was shifted into load control. A small normal load of 0.2 kips was applied to keep the two specimen halves in contact and to remove any mechanical slack. The data acquisition program, which displayed the channel voltage output, was started. Each LVDT was positioned and adjusted so that its voltage output was in the appropriate range to prevent going off scale. Hydraulic pressure was turned to high pressure and the appropriate normal load was applied. The function generator and the test control computer were started.

Two series of direct shear tests were carried out on the joint replicas. The experiment schedule is summarized in Tables 1 through 4. Each experiment in the first series was conducted at different constant normal load levels ranging between 0.6 and 25.6 kips (2.7 and 113.9 kN). These levels corresponded to initial stress levels of 40, 200, 400, and 800 psi (0.2, 0.9, 1.8, and 3.6 MPa) for the G2, F2, F3, and F4 samples. For the F4 sample, a test with a 10.8 kips (48.0 kN) initial normal load corresponding to a 600 psi (2.7 MPa) initial normal stress was also conducted. The second series of direct shear tests was conducted at different levels of initial normal load ranging between 1.3 and 7.5 kips (5.7 and 33.4 kN); constant normal stiffness ranged between 14.8 and 187.5 kips/in (25.9 and 328.1 kN/cm). Each direct shear test consisted of five continuous loading cycles with a sinusoidal pattern, a frequency of 2.8×10^{-4} Hz and an amplitude of 1.6 in (4.1 cm) for test series G2, and a frequency of 3.7×10^{-4} Hz and an amplitude of 1.2 in (3.1 cm) for test series F2, F3, and F4. The nominal shear displacement rate was 0.05 in/min (0.13 cm/min).

Table 1
Experiment schedule for G2 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi) *	Const. Stiffness (kips/in)
R1G2	1.3	40	0
R4G2	6.4	200	0
R2G2	12.8	400	0
R3G2	25.6	800	0.
KR5G2	1.3	40	32
KR6G2	6.4	200	64

* Area = 32.00 in²

Table 2
Experiment schedule for F2 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi) *	Const. Stiffness (kips/in)
R5F2	0.6	40	0
R2F2	3.0	200	0
R3F2	5.9	400	0
R4F2	11.8	800	0
KR6F2	3.0	200	14.8
KR7F2	3.0	200	44.3
KR8F2	3.0	200	147.8

* Area = 14.77 in²

Table 3
Experiment schedule for F3 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi) *	Const. Stiffness (kips/in)
R1F3	0.8	40	0
R6F3	3.8	200	0
R4F3	7.5	400	0
R5F3	15.0	800	0
KR7F3	3.8	200	18.8
KR8F3	3.8	200	56.3
KR9F3	3.8	200	187.5
KR10F3	7.5	400	56.3
KR11F3	7.5	400	187.5

* Area = 18.75 in²

Table 4
Experiment schedule for F4 specimens.

Sample	Normal Load (kips)	Init. Normal Stress (psi) *	Const. Stiffness (kips/in)
R1F4	0.7	40	0
R2F4	3.6	200	0
R3F4	7.2	400	0
R4F4	10.8	600	0
R5F4	14.4	800	0
R6F4	10.8	600	0
R8F4	10.8	600	0
R13F4	3.6	200	0
KR7F4	3.6	200	18.0
KR9F4	3.6	200	54.0
KR10F4	3.6	200	179.9
KR11F4	7.2	400	54.0
KR12F4	7.2	400	179.9

* Area = 18.0 in²

Note that in Table 4:

- R6F4 and R8F4 are repetitions of R4F4; a shear test under constant normal load of 10.8 kips (48.0 kN). This was done to observe the reproducibility of the testing procedure and the sensitivity of the shear apparatus.
- R13F4 is a repetition of R2F4; a shear test under constant normal load of 3.6 kips (16.0 kN). However, shearing was started in the opposite direction.

2.3 Normal Compression Tests

As mentioned earlier, before and after shear, joint surfaces were subjected to five cycles of normal loading and unloading to characterize their normal stress versus normal displacement response. The tests were conducted using the normal load actuator of the direct shear machine. The maximum normal stress applied during the first cycle was 100 psi (0.7 MPa). This was followed by four cycles with maximum normal stresses of 200, 400, 800, and 1000 psi (1.4, 2.8, 5.5, and 6.9 MPa). The loading rate was 100 psi/min (0.7 MPa/min). Normal load and normal displacement were measured using the normal load actuator's load cell and the three external vertical HRDC LVDTs, respectively. For each normal compression test, three steps were followed:

- identification of each joint specimen,
- application of a small initial normal load,
- normal loading and unloading with five cycles.

Before the shear experiments were conducted, a normal compression test was performed on one replica of each joint in order to determine its initial normal deformability. After shear, normal compression tests were conducted on all replicas.

2.4 Profilometer Tests

Surface roughness affects all aspects of mechanical properties of rock joints. Depending on the boundary conditions across the joint surfaces, shear through the joint surface asperities or overriding of the asperities can take place. Joint surface roughness also affects joint dilatancy. If the dilatancy is completely or partially suppressed due to the controlled boundary conditions, then normal stresses further increase during shear and the joint has a higher shear strength than if the joint is free to dilate. Measurement of joint surface roughness prior to and after shearing can be useful in assessing joint surface damage and its relation to joint shear strength.

Joint surface roughness profiling was carried out using a mechanical profilometer (Figures 6 and 7). All profilometer tests were conducted according to Experimental Plan (EP) # 45. Detailed description of the equipment can be found in Farrington (1983) and Gamal-Eldin (1989). Basically, the apparatus consists of a table on which two systems of steel rods are installed. An LVDT attached to one set of rods can travel in a horizontal X-Y plane covering the joint surface. The cone apex angle of the profilometer tip is 18 degrees, and the tip radius is about 0.002 in (0.05 mm). The joint sample is placed on a levelling plate below the table. At each selected X,Y point, the height of a point on the sample is measured relative to a reference height with the LVDT.

Before and after the shear tests described in Section 2.2, the bottom and top joint surfaces were profiled along four lines 1.0 in (2.5 cm) apart for the G2 specimens and along four lines 0.8 in (2.0 cm) apart for the F2, F3, and F4 specimens. The horizontal distance between two consecutive sampling points was 0.01 inches (0.3 mm). All X,Y,Z data were recorded by the same data acquisition system used for the direct shear tests. Four steps were followed in each profilometer test:

Figure 6. Mechanical profilometer (Schematic overhead view).
(Farrington, 1983)

Figure 7. Mechanical profilometer (Schematic side view).
(Farrington, 1983)

- identification of each joint specimen,
- placement of joint specimen on levelling plate under profilometer table,
- alignment of X and Y axes on joint surface,
- measurement of surface roughness.

The profiles are called X1, X2, X3, and X4, with X1 and X4 being the closest to the side edges of the test specimens. Before the shear tests, one profilometer test was carried out on both surfaces of one replica of each joint. After shear, profilometer tests were performed on all replica surfaces.

2.5 Sheared Area and Gouge Amount Measurement

After five cycles of shear, some of the orange enamel paint on the joint replica surfaces vanished due to the asperity shear and associated abrasion. The affected area on the joint surfaces was traced on transparent paper and the area was measured with a planimeter.

The loose gouge created during shear was collected in a lightweight paper container at the end of the normal compression test after shear and weighed. The amount of gouge that was compacted on and adhered to the joint surfaces was not measured.

3. TEST RESULTS

3.1 Direct Shear Test Results

All direct shear test results are presented in the form of shear load vs. shear displacement response curves, and normal displacement (dilatancy) versus shear displacement curves. From these curves, the following data were collected:

- peak and residual shear loads for forward and reverse shear in each cycle,
- initial shear stiffness for the forward part of the first cycle calculated with data between 25% and 75% of the peak shear load,
- slope of the dilatancy curve for forward and reverse shear in each cycle measured between 0.1 and 0.4 in (0.3 and 1.0 cm) of shear displacement.

Figures 8 through 11 and Tables 5 through 9 show typical response curves and test data for some of the F4 test specimens. Figures 8a and 8b show the shear load versus shear displacement and dilatancy versus shear displacement curves, respectively, for specimen R2F4 tested under a constant normal load of 3.6 kips (16.0 kN). The peak and residual shear loads in both forward and reverse shear directions decrease as the number of shear cycles increases, but approach a steady state level (Figure 8a). Joint dilatancy decreases gradually in both shear directions as the number of cycles increases (Figure 8b), also approaching steady state behavior. Figures 9a and 9b show an example of response curves for specimen KR10F4 tested under a constant normal stiffness of 179.9 kips/in (314.8 kN/cm) with an initial normal load of 3.6 kips (16.0 kN). Figure 9a shows that under constant normal stiffness, there is no specific peak and residual shear loads as displayed in Figure 8a. Instead, a hardening form of behavior can be observed.

The first cycle, forward shear load - shear displacement response curves for all F4 test specimens are summarized in Figure 10a. The corresponding dilatancy curves are shown in Figure 10b. Specimen R2F4 was tested under a constant normal load of 3.6 kips (16.0 kN) (or zero normal stiffness). Specimens KR7F4, KR9F4, and KR10F4, were tested under constant normal stiffnesses of 18.0, 54.0, and 179.9 kips/in (31.5, 94.5, and 314.8 kN/cm) respectively, with the same initial normal load as R2F4, carry larger shear loads than R2F4 and experience less dilatancy.

Figure 8. (a) Shear load vs. shear displacement, (b) Dilatancy vs. shear displacement. Specimen R2F4, constant normal load $N_0 = 3.6$ kips (16.0 kN).

Figure 9. (a) Shear load vs. shear displacement, (b) Dilatancy vs. shear displacement. Specimen KR10F4, constant normal stiffness $K = 179.9$ kips/in (314.8 kN/cm) and initial normal load $N_0 = 3.6$ kips (16.0 kN).

Figure 10. (a) Shear load vs. shear displacement, (b) Dilatancy vs. shear displacement. First cycle forward shear of F4 samples. Solid lines for constant normal load tests and dashed lines for constant stiffness tests under initial normal loads $N_0 = 3.6$ kips (16.0 kN) and $N_0 = 7.2$ kips (32.0 kN).

Figure 11 shows the paths followed by the F4 specimens tested under constant normal stiffness in a shear load/normal load space for the forward and reverse parts of the first shear load cycle only. In this figure, the peak and residual shear failure envelopes determined from the constant normal load shear tests are also shown for comparison.

Table 5 gives the values of the peak and residual shear loads and the shear stiffness for the F4 samples tested under constant normal load, for forward shear only. Table 6 shows the data for the samples tested under constant normal stiffness. For those samples tested under constant normal stiffness and showing hardening, the peak and residual shear loads are replaced by the shear loads at 0.4 in (1.0 cm) of shear displacement. Tables 7 and 8 give the slopes ($\tan i$) of the corresponding dilatancy curves for forward and reverse shear.

The shear load versus shear displacement curves and normal displacement (dilatancy) versus shear displacement response curves for all test specimens can be found in Appendix A1. In Appendix A2, these response curves have been combined for the forward and reverse parts of each cycle. The values of peak and residual shear loads for the forward and reverse part of each cycle and the values of shear stiffness for the forward part of the first cycle are tabulated in Appendix A3. Note that for the samples tested under constant normal stiffness that showed hardening during shear, the peak and residual shear loads in Appendix A3 are replaced by the shear loads at 0.4 in (1.0 cm) of shear displacement. Values for the slopes of the dilatancy curves are reported in Appendix A4 for the forward and reverse part of each shear cycle. Finally, the paths followed by the test specimens tested under constant normal stiffness in the shear load/normal load space can be found in Appendix A5 for the forward and reverse part of each cycle.

Surface damage occurring during shear was quantified at the end of each shear test by measuring joint surface sheared areas and by

Figure 11. (a) Shear load vs. normal load, first cycle forward shear load path. (b) Shear load vs. normal load, first cycle reverse shear load path. Load paths for constant normal stiffness tests in shear load vs. normal load (T,N) space of F4 samples. The peak and residual envelopes determined from the constant normal load tests are also shown.

weighing the amount of gouge created in shear. As an example, the sheared areas and the amounts of gouge for all F4 samples are tabulated in Table 9. Similar data for samples G2, F2, and F3 can be found in Appendix A6.

Table 5
Peak and residual shear loads for F4 samples,
constant normal load, forward direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Forward	0.7	1.1	0.5	100
	3.6	3.8	2.0	783
	7.2	7.1	4.4	1194
	10.8	10.8	7.3	830
	14.4	13.7	9.2	925
2nd Forward	0.7	0.7	0.5	
	3.6	2.3	1.7	
	7.2	4.5	4.0	
	10.8	7.4	6.6	
	14.4	9.1	8.3	
3rd Forward	0.7	0.6	0.4	
	3.6	2.3	1.7	
	7.2	4.1	3.9	
	10.8	6.9	6.6	
	14.4	8.7	8.0	
4th Forward	0.7	0.5	0.4	
	3.6	1.9	1.6	
	7.2	3.9	3.8	
	10.8	6.7	6.5	
	14.4	8.7	8.0	
5th Forward	0.7	0.5	0.6	
	3.6	1.8	1.7	
	7.2	3.8	3.8	
	10.8	6.6	6.5	
	14.4	8.6	8.0	

Table 6
Peak and residual shear loads or shear loads at 0.4 in shear
displacement for F4 samples,
constant normal stiffness, forward direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Forward	3.6	18.0	4.5	3.4	
	3.6	54.0			4.6
	3.6	179.9			6.6
	7.2	54.0	9.4	7.3	
	7.2	179.9			9.1
2nd Forward	3.6	18.0			3.1
	3.6	54.0			3.9
	3.6	179.9			4.9
	7.2	54.0			6.6
	7.2	179.9			7.2
3rd Forward	3.6	18.0			2.9
	3.6	54.0			3.6
	3.6	179.9			4.7
	7.2	54.0			6.4
	7.2	179.9			6.7
4th Forward	3.6	18.0			2.9
	3.6	54.0			3.5
	3.6	179.9			4.5
	7.2	54.0			6.4
	7.2	179.9			6.5
5th Forward	3.8	18.0			2.8
	3.8	54.0			3.4
	3.8	179.9			4.3
	7.5	54.0			6.3
	7.5	179.9			

Table 7
Slope of dilatancy curves ($\tan i$) for F4 samples,
constant normal load tests.

	Initial Normal Load (kips)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
Forward Shear	0.7	0.14	0.12	0.12	0.11	0.11
	3.6	0.14	0.13	0.13	0.13	0.13
	7.2	0.11	0.11	0.10	0.09	0.09
	10.8	0.10	0.10	0.09	0.09	0.08
	14.4	0.08	0.07	0.07	0.07	0.06
Reverse Shear	0.7	0.14	0.14	0.14	0.14	0.14
	3.6	0.11	0.11	0.11	0.11	0.11
	7.2	0.08	0.08	0.08	0.07	0.07
	10.8	0.09	0.08	0.08	0.08	0.07
	14.4	0.07	0.06	0.06	0.05	0.05

Table 8
Slope of dilatancy curves ($\tan i$) for F4 samples,
constant normal stiffness tests.

	Ini- tial Normal Load (kips)	Constant Normal Stiff- ness (kips/in)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
For- ward Shear	3.6	18.0	0.13	0.12	0.11	0.11	0.11
	3.6	54.0	0.13	0.12	0.11	0.11	0.11
	3.6	179.9	0.10	0.09	0.08	0.08	0.08
	7.2	54.0	0.12	0.11	0.10	0.10	0.10
	7.2	179.9	0.08	0.08	0.08	0.07	
Re- verse Shear	3.6	18.0	0.11	0.11	0.11	0.10	0.10
	3.6	54.0	0.10	0.10	0.09	0.09	0.09
	3.6	179.9	0.08	0.09	0.08	0.08	0.08
	7.2	54.0	0.08	0.09	0.08	0.08	0.08
	7.2	179.9	0.06	0.06	0.06	0.06	

Table 9
Sheared area for F4 samples (bottom half) and
amount of gouge generated in shear.

Sample	Sheared Area (sq.in)	Sheared Area (%)	Gouge (grams)
R1F4	4.5	25	2.4
R2F4	12.2	68	5.1
R3F4	14.5	81	10.4
R4F4	16.4	91	10.5
R5F4	17.2	96	12.8
R6F4	16.4	91	8.7
KR7F4	13.2	73	5.1
R8F4	16.1	89	12.2
KR9F4	13.2	74	5.0
KR10F4	13.5	75	6.9
KR11F4	16.1	90	11.2
KR12F4	15.3	85	10.0
KR13F4	12.6	70	7.4

3.2 Normal Compression Test Results

The normal compression test results are presented in the form of normal load versus normal displacement response curves. Typical response curves for joint normal compression before and after shear testing of sample R1F3 are shown in Figure 12. The test results for all specimens can be found in Appendix B1. The actual joint closure is determined from these response curves after subtracting the deformation of the intact gypsum cement and the system from the total measured normal displacement (as shown in Figure 13). The intact gypsum cement behavior was obtained from a gypsum cement block sample with the same size as the joint replica and also the same height of potting cement.

a

b

Figure 12. (a) Normal load vs. normal displacement before shear, (b) Normal load vs. normal displacement after shear testing under constant normal load $N_0 = 0.8$ kips (3.3 kN). Five cycles normal compression of sample R1F3.

Figure 13. Joint closure of specimen R5F3 after shear testing under constant normal load $N_0 = 15.0$ kips (66.7 kN).

The initial joint normal stiffness k_{ni} and maximum closure V_m were determined from the envelope to the five loading/unloading cycles of the joint closure curves using the model of Bandis et al. (1983). In this model, the normal stress σ and joint closure v are related as follows

$$\sigma = \frac{v k_{ni} V_m}{V_m - v} \quad (1)$$

Both k_{ni} and V_m can be determined by regression analysis of $1/\sigma$ versus $1/v$. As an example, Table 10 gives the values of initial stiffness and maximum joint closure for all F3 samples. Values of those two parameters for all samples can be found in Appendix B2.

Table 10
Maximum closure and initial stiffness for samples F3.

	Sample	Maximum Closure V_m (in)	Initial Normal Stiffness k_{ni} (ksi/in)
Before Shear		0.2×10^{-2}	1.9×10^2
After Shear	R1F3	0.9×10^{-2}	1.3×10^2
	R6F3	1.3×10^{-2}	1.2×10^2
	R4F3	0.2×10^{-2}	2.0×10^2
	R5F3	1.2×10^{-2}	1.2×10^2
	KR7F3	3.2×10^{-2}	0.9×10^2
	KR8F3	0.5×10^{-2}	1.9×10^2
	KR9F3	2.4×10^{-2}	0.6×10^2
	KR10F3	2.4×10^{-2}	0.8×10^2
	KR11F3	2.5×10^{-2}	0.8×10^2

3.3 Profilometer Test Results

As an example, two sets of two profiles are presented in Figures 14a and 14b. The first set corresponds to profile X2 which was taken on the lower half of sample R1F4 before shear and on the lower half of sample R3F4 after shear under a constant normal load of 7.2 kips (32.0 kN) (Figure 14a). The second set of profiles corresponds to profile X3 which was taken on the bottom half sample R1F4 before shear and on the bottom half sample R3F4 after shear under a constant normal load of 7.2 kips (32.0 kN) (Figure 14b). The profiles before and after shear show minor differences in micro-roughness. The macro-roughness (large undulation) remains essentially the same. Randomly selected profiles are presented in Appendix C1 for specimens G2, F2, F3, and F4.

Figure 14. (a) Comparison of profiles X2 of bottom half specimen R1F4 before shear and R3F4 after shear testing (offset - 0.2 in (5.1 mm)), (b) Comparison of profiles X3 of bottom half specimen R1F4 before and R3F4 after testing (offset -0.2 in (5.1 mm)). Sample R3F4 was tested under constant normal load $N_0 = 7.2$ kips (32.0 kN).

From the profilometer test results, the roughness of the irregular fracture surfaces was quantified mathematically using the theory of fractal geometry developed by Mendelrot (1983). An inherent property of fractals is their ability to replicate patterns of an object at different scales. A magnified portion of a fractal object is statistically identical to the whole. The dimension of an object in fractal geometry is defined by the quantity D such that:

$$N = S^D \quad (2)$$

where

- N = the number of sub-parts of each fractal unit,
- S = scaling factor defined as $1/r$,
- r = length of each sub-part relative to the initiator length,
and
- D = fractal dimension.

Solving equation (2) for D gives:

$$D = \frac{\log N}{\log \frac{1}{r}} \quad (3)$$

The fractal dimension of an irregular profile can be calculated by using the divider method (Brown, 1987). After measuring the roughness along several profiles on a fracture surface, the fractal dimension D can be obtained by first choosing different values for the length r appearing in equation (3). Knowing the number of sub-parts N for each value of r , the fractal dimension can be determined by regression analysis of $\log N$ versus $\log 1/r$. $\log N$ is then multiplied by different multipliers while $\log 1/r$ remains constant. As the value of the multiplier increases, the value of D converges toward the self-affine fractal dimension (Brown, 1987).

Table 11 gives typical results of fractal dimension analysis for one profile (F4X2) on the bottom half of the F4 samples. The other fractal dimension tables are given in Appendix C2.

Table 11
Fractal dimension for F4X2 bottom.

Sample	Normal Load (kips)	Const. Stiffness (kips/in)	Fractal Dimension
Before Shear			1.13
After Shear			
R1F4	0.7	0	1.12
R2F4	3.6	0	1.11
R3F4	7.2	0	1.11
R4F4	10.8	0	1.11
R5F4	14.4	0	1.10
R6F4	10.8	0	1.11
R8F4	10.8	0	1.11
R13F4	3.6	0	1.11
KR7F4	3.6	18.0	1.11
KR9F4	3.6	54.0	1.11
KR10F4	3.6	179.9	1.11
KR11F4	7.2	54.0	1.10
KR12F4	7.2	179.9	1.15

4. DISCUSSION AND RECOMMENDATIONS

4.1 Observations During Testing

During testing, some situations were encountered either with the testing procedure or with the testing apparatus. These issues, which may indirectly affect the testing results, are discussed below.

- *Sample placement.*

The procedure for sample preparation was discussed in detail in section 2.1. Difficulties were encountered in trying to adjust the mean joint surfaces to a horizontal plane. The adjustment was done by hand and by visual inspection of the air bubble in a level placed across the joint surfaces. Thus, positioning of the joint surfaces at the beginning of each direct shear test may not have been consistent for all samples. This could have influenced the joint dilatancy responses. This problem can be improved by casting the gypsum samples directly into the machine mounting fixture.

- *Embankment around the specimens.*

Sloped embankments made out of gypsum cement were placed along the periphery of the F3 and F4 test specimens in order to alleviate stress concentrations along the edges and to prevent the sample edges from breaking off during shear. Such phenomena had been observed for the G2 and F2 sample for which no embankments were constructed. As the number of cycles of shear increased, surface damage occurred gradually, as would be expected. Placing a gypsum embankment around the test specimens had a positive influence on the experimental results, especially under high initial normal loads, the test result was more reliable from first through fifth cycles.

- *Installation of the specimen on the upper and lower platens.*

During the attachment of the specimens in the shear box holders to the upper and lower platens of the direct shear machine, the upper and lower shear box specimen holders sometimes moved in such a way that joint surfaces were slightly unmated at the beginning of some of the shear tests. Offsets of 0.02 - 0.06 in (0.5 - 1.5 mm) were sometimes measured. This was reflected in some of the dilatancy curves. This problem can be improved by having larger bolt holes at the bottom steel mould, so that the position of the bottom sample can be adjusted during installation when placing their initially joints in the mated position.

- *Direct shear apparatus.*

During testing there was no external restriction in the direction parallel to the joint surface and perpendicular to the shear direction. Visual monitoring of two reference tape markings indicated that the joint moved laterally by as much as 0.05 in (1 mm). This may indicate a slight anisotropy in the mechanical response of the fracture to the applied loading condition.

- *Disturbance in profilometer test results.*

Four profiles were measured for every half part of each test specimen; X1, X2, X3, and X4. The two profiles (X1 and X4) located the closest to the edges of the test specimens (0.3 - 0.5 in, 7.6 - 12.7 mm, from the edges) were sometimes partly sheared off. To avoid discrepancies, especially in calculating the fractal dimensions, it is recommended to consider only the two inner profiles (X2 and X3).

4.2 Accuracy of Test Results

The observations discussed in section 4.1 may have led to some errors in the test results. In order to assess the reproducibility

of the testing procedure and the sensitivity of the shear apparatus, three replicas of the F4 sample were tested under the same conditions, e.g., cyclic shear test under a constant normal load of 10.8 kips (48.0 kN). The results of the three tests are tabulated in Table 12.

Table 12
Comparison of three test results under constant
normal load of 10.8 kips (48.0 kN).

Sample	1st cycle Peak Shear Load (kips)	1st cycle Res- idual Shear Load (kips)	1st cycle Max. Dila- tancy (in)	1st cycle Dila- tancy Slope $\tan i$	Gouge (gram)	Sheared Area (%)	Fractal Dimen- sion X2
R4F4	9.8	7.2	0.04	0.09	10.5	91	1.11
R6F4	11.7	7.5	0.05	0.10	8.7	91	1.11
R8F4	11.3	7.2	0.05	0.12	12.2	89	1.11
Aver- age	10.9	7.3	0.05	0.10	10.5	91	1.11
Error	0.8	0.14	0.005	0.01	1.4	0.9	0.00

According to Table 12, the error (standard deviation) on the peak shear load is 0.8 kips (3.6 kN). The error on the residual shear load (shear load at 0.5 in shear displacement) is 0.14 kips (0.6 kN). The dilatancy shows some variation, but the differences are very small, less than 0.005 in (0.13 mm). The error on the slope ($\tan i$) of the dilatancy curves is about 0.01, which is equivalent to about one degree of dilatancy. The errors on the gouge and sheared area measurements are 1.4 grams and 0.9%, respectively. The measurements of fractal dimension are very consistent.

4.3 Effect of Shear Load Direction

The effect of shear direction was evaluated by conducting a shear test on sample R13F4 under the same conditions as R2F4, except that the shear load started in the opposite (or reverse) direction. R2F4 was sheared in the forward direction first, while R13F4 was sheared in the reverse direction first. Comparison between the results of the two tests is shown in Table 13. According to Table 13, the peak shear loads in the forward direction differ by 0.3 kips (1.3 kN). In the reverse direction, the difference is 0.8 kips (3.6 kN). Residual shear load values in the forward direction are similar while in the reverse direction they differ by 0.3 kips (1.5 kN). The maximum dilatancy values in the forward direction have a 0.02 in (0.4 mm) difference, while in the reverse direction they have a 0.002 in (0.05 mm) difference. The dilatancy slopes ($\tan i$) in the forward direction have a 0.01 difference, which is less than one degree of dilatancy. In the reverse direction they have a 0.02, or about a 1.3 degrees difference. The gouges produced during shear differed by approximately 2.3 grams. Sheared area during shear and fractal dimension are similar for both samples.

4.4 Future Application of the Data

This report is part one of a series of reports under the title of Effect of Boundary Conditions on the Strength and Deformability of Replicas of Natural Fractures in Welded Tuff. This report is a data report. In the second report, the observed and predicted shear behaviors using the graphical method of Amadei and Saeb are compared. The third report discusses additional analysis relative to several commonly used empirical rock joint models.

Table 13
Comparison of the results of tests R2F4 and R13F4 under a
constant normal load of 3.6 kips (16.0 kN).

Conditions	R2F4	R13F4
1st Cycle Forward Peak Shear Load (kips)	3.8	4.1
1st Cycle Forward Residual Shear Load (kips)	2.0	1.9
1st Cycle Reverse Peak Shear Load (kips)	5.1	4.3
1st Cycle Reverse Residual Shear Load (kips)	3.0	2.7
1st Cycle Forward Maximum Dilatancy (in)	0.08	0.06
1st Cycle Reverse Maximum Dilatancy (in)	0.05	0.06
1st Cycle Forward Dilatancy Slope ($\tan i$)	0.14	0.13
1st Cycle Reverse Dilatancy Slope ($\tan i$)	0.11	0.08
Gouge (grams)	5.1	7.4
Sheared Area (%)	68	70
Fractal Dimension, X2 (after shear)	1.11	1.11

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EXPERIMENTAL SCHEDULE

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RF3	Experiment Schedule	A0-3
RF4	Experiment Schedule	A0-4

Table 1
Experiment schedule for RG2 specimens.

Sample	Normal Load (kips)	Initial Normal Stress (psi) *	Constant Stiffness (kips/in)
R1G2	1.3	40	0
R4G2	6.4	200	0
R2G2	12.8	400	0
R3G2	25.6	800	0
KR5G2	1.3	40	32
KR6G2	6.4	200	64

* Area = 32.00 in²

Table 2
Experiment schedule for RF2 specimens.

Sample	Normal Load (kips)	Initial Normal Stress (psi)*	Constant Stiffness (kips/in)
R5F2	0.6	40	0
R2F2	3.0	200	0
R3F2	5.9	400	0
R4F2	11.8	800	0
KR6F2	3.0	200	14.8
KR7F2	3.0	200	44.3
KR8F2	3.0	200	147.8

* Area = 14.77 in²

Table 3
Experiment schedule for RF3 specimens.

Sample	Normal Load (kips)	Initial Normal Stress (psi) *	Constant Stiffness (kips/in)
R1F3	0.8	40	0
R6F3	3.8	200	0
R4F3	7.5	400	0
R5F3	15.0	800	0
KR7F3	3.8	200	18.8
KR8F3	3.8	200	56.3
KR9F3	3.8	200	187.5
KR11F3	7.5	400	56.3
KR10F3	7.5	400	187.5

* Area = 18.75 in²

Table 4
Experiment schedule for RF4 specimens.

Sample	Normal Load (kips)	Initial Normal Stress (psi)*	Constant Stiffness (kips/in)
R1F4	0.7	40	0
R2F4	3.6	200	0
R3F4	7.2	400	0
R4F4	10.8	600	0
R5F4	14.4	800	0
R6F4	10.8	600	0
R8F4	10.8	600	0
R13F4	3.6	200	0
KR7F4	3.6	200	18.0
KR9F4	3.6	200	54.0
KR10F4	3.6	200	179.9
KR11F4	7.2	400	54.0
KR12F4	7.2	400	179.9

* Area = 18.0 in²

APPENDIX A1
CYCLIC SHEAR & DILATANCY

SAMPLE	DESCRIPTION	PAGE
R1G2	Cyclic Shear; Normal Load = 1.3 kips	A1-1
R1G2	Dilatancy; Normal Load = 1.3 kips	A1-1
R4G2	Cyclic Shear; Normal Load = 6.4 kips	A1-2
R4G2	Dilatancy; Normal Load = 6.4 kips	A1-2
R2G2	Cyclic Shear; Normal Load = 12.8 kips	A1-3
R2G2	Dilatancy; Normal Load = 12.8 kips	A1-3
R3G2	Cyclic Shear; Normal Load = 25.6 kips	A1-4
R3G2	Dilatancy; Normal Load = 25.6 kips	A1-4
KR5G2	Cyclic Shear; Normal Load = 1.3 kips, K = 32 kips/in	A1-5
KR5G2	Dilatancy; Normal Load = 1.3 kips, K = 32 kips/in	A1-5
KR6G2	Cyclic Shear; Normal Load = 6.4 kips, K = 64 kips/in	A1-6
KR6G2	Dilatancy; Normal Load = 6.4 kips, K = 64 kips/in	A1-6
R5F2	Cyclic Shear; Normal Load = 0.6 kips	A1-7
R5F2	Dilatancy; Normal Load = 0.6 kips	A1-7
R2F2	Cyclic Shear; Normal Load = 3.0 kips	A1-8
R2F2	Dilatancy; Normal Load = 3.0 kips	A1-8
R3F2	Cyclic Shear; Normal Load = 5.9 kips	A1-9
R3F2	Dilatancy; Normal Load = 5.9 kips	A1-9
R4F2	Cyclic Shear; Normal Load = 11.8 kips	A1-10
R4F2	Dilatancy; Normal Load = 11.8 kips	A1-10
KR6F2	Cyclic Shear; Normal Load = 3.0 kips, K = 14.8 kips/in	A1-11
KR6F2	Dilatancy; Normal Load = 3.0 kips, K = 14.8 kips/in	A1-11
KR7F2	Cyclic Shear; Normal Load = 3.0 kips, K = 44.3 kips/in	A1-12

SAMPLE	DESCRIPTION	PAGE
KR7F2	Dilatancy; Normal Load = 3.0 kips, K = 44.3 kips/in	A1-12
KR8F2	Cyclic Shear; Normal Load = 3.0 kips, K = 147.7 kips/in	A1-13
KR8F2	Dilatancy; Normal Load = 3.0 kips, K = 147.7 kips/in	A1-13
R1F3	Cyclic Shear; Normal Load = 0.8 kips	A1-14
R1F3	Dilatancy; Normal Load = 0.8 kips	A1-14
R6F3	Cyclic Shear; Normal Load = 3.8 kips	A1-15
R6F3	Dilatancy; Normal Load = 3.8 kips	A1-15
R4F3	Cyclic Shear; Normal Load = 7.5 kips	A1-16
R4F3	Dilatancy; Normal Load = 7.5 kips	A1-16
R5F3	Cyclic Shear; Normal Load = 15.0 kips	A1-17
R5F3	Dilatancy; Normal Load = 15.0 kips	A1-17
KR7F3	Cyclic Shear; Normal Load = 3.8 kips, K = 18.8 kips/in	A1-18
KR7F3	Dilatancy; Normal Load = 3.8 kips, K = 18.8 kips/in	A1-18
KR8F3	Cyclic Shear; Normal Load = 3.8 kips, K = 56.3 kips/in	A1-19
KR8F3	Dilatancy; Normal Load = 3.8 kips, K = 56.3 kips/in	A1-19
KR9F3	Cyclic Shear; Normal Load = 3.8 kips, K = 187.5 kips/in	A1-20
KR9F3	Dilatancy; Normal Load = 3.8 kips, K = 187.5 kips/in	A1-20
KR11F3	Cyclic Shear; Normal Load = 7.5 kips, K = 56.3 kips/in	A1-21
KR11F3	Dilatancy; Normal Load = 7.5 kips, K = 56.3 kips/in	A1-21
KR10F3	Cyclic Shear; Normal Load = 7.5 kips, K = 187.5 kips/in	A1-22
KR10F3	Dilatancy; Normal Load = 7.5 kips, K = 187.5 kips/in	A1-22

SAMPLE	DESCRIPTION	PAGE
R1F4	Cyclic Shear; Normal Load = 0.7 kips	A1-23
R1F4	Dilatancy; Normal Load = 0.7 kips	A1-23
R2F4	Cyclic Shear; Normal Load = 3.6 kips	A1-24
R2F4	Dilatancy; Normal Load = 3.6 kips	A1-24
R3F4	Cyclic Shear; Normal Load = 7.2 kips	A1-25
R3F4	Dilatancy; Normal Load = 7.2 kips	A1-25
R4F4	Cyclic Shear; Normal Load = 10.8 kips	A1-26
R4F4	Dilatancy; Normal Load = 10.8 kips	A1-26
R6F4	Cyclic Shear; Normal Load = 10.8 kips	A1-27
R6F4	Dilatancy; Normal Load = 10.8 kips	A1-27
R8F4	Cyclic Shear; Normal Load = 10.8 kips	A1-28
R8F4	Dilatancy; Normal Load = 10.8 kips	A1-28
R5F4	Cyclic Shear; Normal Load = 14.4 kips	A1-29
R5F4	Dilatancy; Normal Load = 14.4 kips	A1-29
KR7F4	Cyclic Shear; Normal Load = 3.6 kips, K = 18.0 kips/in	A1-30
KR7F4	Dilatancy; Normal Load = 3.6 kips, K = 18.0 kips/in	A1-30
KR9F4	Cyclic Shear; Normal Load = 3.6 kips, K = 54.0 kips/in	A1-31
KR9F4	Dilatancy; Normal Load = 3.6 kips, K = 54.0 kips/in	A1-31
KR10F4	Cyclic Shear; Normal Load = 3.6 kips, K = 179.9 kips/in	A1-32
KR10F4	Dilatancy; Normal Load = 3.6 kips, K = 179.9 kips/in	A1-32
KR11F4	Cyclic Shear; Normal Load = 7.2 kips, K = 54.0 kips/in	A1-33
KR11F4	Dilatancy; Normal Load = 7.2 kips, K = 54.0 kips/in	A1-33
KR12F4	Cyclic Shear; Normal Load = 7.2 kips, K = 179.9 kips/in	A1-34
KR12F4	Dilatancy; Normal Load = 7.2 kips, K = 179.9 kips/in	A1-34

SAMPLE	DESCRIPTION	PAGE
R13F4	Cyclic Shear; Normal Load = 3.6 kips	A1-35
R13F4	Dilatancy; Normal Load = 3.6 kips	A1-35

CYCLIC SHEAR R1G2

NORMAL LOAD = 1.3 KIPS

DILATANCY R1G2

NORMAL LOAD = 1.3 KIPS

CYCLIC SHEAR R4G2

NORMAL LOAD = 6.4 KIPS

DILATANCY R4G2

NORMAL LOAD = 6.4 KIPS

CYCLIC SHEAR R2G2

NORMAL LOAD = 12.8 KIPS

DILATANCY R2G2

NORMAL LOAD = 12.8 KIPS

CYCLIC SHEAR R3G2

NORMAL LOAD = 25.6 KIPS

DILATANCY R3G2

NORMAL LOAD = 25.6 KIPS

CYCLIC SHEAR KR5G2

NORMAL LOAD = 1.3 KIPS, $K=32$ KIPS/IN

DILATANCY KR5G2

NORMAL LOAD = 1.3 KIPS, $K=32$ KIPS/IN

CYCLIC SHEAR KR6G2

NORMAL LOAD = 6.4 KIPS, $K=64$ KIPS/IN

DILATANCY KR6G2

NORMAL LOAD = 6.4 KIPS, $K=64$ KIPS/IN

CYCLIC SHEAR R5F2

NORMAL LOAD = 0.6 KIPS

DILATANCY R5F2

NORMAL LOAD = 0.6 KIPS

CYCLIC SHEAR R2F2

NORMAL LOAD = 3.0 KIPS

DILATANCY R2F2

NORMAL LOAD = 3.0 KIPS

CYCLIC SHEAR R3F2

NORMAL LOAD = 5.9 KIPS

DILATANCY R3F2

NORMAL LOAD = 5.9 KIPS

CYCLIC SHEAR R4F2

NORMAL LOAD = 11.8 KIPS

DILATANCY R4F2

NORMAL LOAD = 11.8 KIPS

CYCLIC SHEAR KR6F2

NORMAL LOAD = 3.0 KIPS, $K=14.8$ KIPS/IN

DILATANCY KR6F2

NORMAL LOAD = 3.0 KIPS, $K=14.8$ KIPS/IN

CYCLIC SHEAR KR7F2

NORMAL LOAD = 3.0 KIPS, $K=44.3$ KIPS/IN

DILATANCY KR7F2

NORMAL LOAD = 3.0 KIPS, $K=44.3$ KIPS/IN

CYCLIC SHEAR KR8F2

NORMAL LOAD = 3.0 KIPS, $K=147.7$ KIPS/IN

DILATANCY KR8F2

NORMAL LOAD = 3.0 KIPS, $K=147.7$ KIPS/IN

CYCLIC SHEAR R1F3

NORMAL LOAD = 0.8 KIPS

DILATANCY R1F3

NORMAL LOAD = 0.8 KIPS

CYCLIC SHEAR R6F3

NORMAL LOAD = 3.8 KIPS

DILATANCY R6F3

NORMAL LOAD = 3.8 KIPS

CYCLIC SHEAR R4F3

NORMAL LOAD = 7.5 KIPS

DILATANCY R4F3

NORMAL LOAD = 7.5 KIPS

CYCLIC SHEAR R5F3

NORMAL LOAD = 15 KIPS

DILATANCY R5F3

NORMAL LOAD = 15 KIPS

CYCLIC SHEAR KR7F3

NORMAL LOAD = 3.8 KIPS, $K=18.8$ KIPS/IN

DILATANCY KR7F3

NORMAL LOAD = 3.8 KIPS, $K=18.8$ KIPS/IN

CYCLIC SHEAR KR8F3

NORMAL LOAD = 3.8 KIPS, $K=56.3$ KIPS/IN

DILATANCY KR8F3

NORMAL LOAD = 3.8 KIPS, $K=56.3$ KIPS/IN

CYCLIC SHEAR KR9F3

NORMAL LOAD = 3.8 KIPS, $K=187.5$ KIPS/IN

DILATANCY KR9F3

NORMAL LOAD = 3.8 KIPS, $K=187.5$ KIPS/IN

CYCLIC SHEAR KR11F3

NORMAL LOAD = 7.5 KIPS, K=56.3 KIPS/IN

DILATANCY KR11F3

NORMAL LOAD = 7.5 KIPS, K=56.3 KIPS/IN

CYCLIC SHEAR KR10F3

NORMAL LOAD=7.5 KIPS, K=187.5 KIPS/IN

DILATANCY KR10F3

NORMAL FORCE=7.5 KIPS, K=187.5 KIPS/IN

CYCLIC SHEAR R1F4

NORMAL LOAD=0.7 KIPS

DILATANCY R1F4

NORMAL LOAD=0.7 KIPS

CYCLIC SHEAR R2F4

NORMAL LOAD = 3.6 KIPS

DILATANCY R2F4

NORMAL LOAD = 3.6 KIPS

CYCLIC SHEAR R3F4

NORMAL LOAD=7.2 KIPS

DILATANCY R3F4

NORMAL LOAD=7.2 KIPS

CYCLIC SHEAR R4F4

NORMAL LOAD=10.8 KIPS

DILATANCY R4F4

NORMAL LOAD=10.8 KIPS

CYCLIC SHEAR R6F4

NORMAL LOAD = 10.8 KIPS

DILATANCY R6F4

NORMAL LOAD = 10.8 KIPS

CYCLIC SHEAR R8F4

NORMAL LOAD = 10.8 KIPS

DILATANCY R8F4

NORMAL LOAD = 10.8 KIPS

CYCLIC SHEAR R5F4

NORMAL LOAD = 14.4 KIPS

DILATANCY R5F4

NORMAL LOAD = 14.4 KIPS

CYCLIC SHEAR KR7F4

NORMAL LOAD=3.6 KIPS, K=18.0 KIPS/IN

DILATANCY KR7F4

NORMAL LOAD=3.6 KIPS, K=18.0 KIPS/IN

CYCLIC SHEAR KR9F4

NORMAL LOAD=3.6 KIPS, K=54.0 KIPS/IN

DILATANCY KR9F4

NORMAL LOAD=3.6 KIPS, K=54.0 KIPS/IN

CYCLIC SHEAR KR10F4

NORMAL LOAD=3.6 KIPS, K=179.9 KIPS/IN

DILATANCY KR10F4

NORMAL LOAD=3.6 KIPS, K=179.9 KIPS/IN

CYCLIC SHEAR KR11F4

NORMAL LOAD=7.2 KIPS, K=54.0 KIPS/IN

DILATANCY KR11F4

NORMAL LOAD=7.2 KIPS, K=54.0 KIPS/IN

CYCLIC SHEAR KR12F4

NORMAL LOAD=7.2 KIPS, K=179.9 KIPS/IN

DILATANCY KR12F4

NORMAL LOAD=7.2 KIPS, K=179.9 KIPS/IN

CYCLIC SHEAR R13F4

NORMAL LOAD = 3.6 KIPS

DILATANCY R13F4

NORMAL LOAD = 3.6 KIPS

APPENDIX A2
SUMMARY OF CYCLIC SHEAR & DILATANCY

SAMPLE	DESCRIPTION	PAGE
RG2	Cyclic Shear - 1st Cycle Forward	A2-1
RG2	Dilatancy - 1st Cycle Forward	A2-1
RG2	Cyclic Shear - 1st Cycle Reverse	A2-2
RG2	Dilatancy - 1st Cycle Reverse	A2-2
RG2	Cyclic Shear - 2nd Cycle Forward	A2-3
RG2	Dilatancy - 2nd Cycle Forward	A2-3
RG2	Cyclic Shear - 2nd Cycle Reverse	A2-4
RG2	Dilatancy - 2nd Cycle Reverse	A2-4
RG2	Cyclic Shear - 3rd Cycle Forward	A2-5
RG2	Dilatancy - 3rd Cycle Forward	A2-5
RG2	Cyclic Shear - 3rd Cycle Reverse	A2-6
RG2	Dilatancy - 3rd Cycle Reverse	A2-6
RG2	Cyclic Shear - 4th Cycle Forward	A2-7
RG2	Dilatancy - 4th Cycle Forward	A2-7
RG2	Cyclic Shear - 4th Cycle Reverse	A2-8
RG2	Dilatancy - 4th Cycle Reverse	A2-8
RG2	Cyclic Shear - 5th Cycle Forward	A2-9
RG2	Dilatancy - 5th Cycle Forward	A2-9
RG2	Cyclic Shear - 5th Cycle Reverse	A2-10
RG2	Dilatancy - 5th Cycle Reverse	A2-10
RF2	Cyclic Shear - 1st Cycle Forward	A2-11
RF2	Dilatancy - 1st Cycle Forward	A2-11
RF2	Cyclic Shear - 1st Cycle Reverse	A2-12
RF2	Dilatancy - 1st Cycle Reverse	A2-12
RF2	Cyclic Shear - 2nd Cycle Forward	A2-13
RF2	Dilatancy - 2nd Cycle Forward	A2-13
RF2	Cyclic Shear - 2nd Cycle Reverse	A2-14
RF2	Dilatancy - 2nd Cycle Reverse	A2-14
RF2	Cyclic Shear - 3rd Cycle Forward	A2-15
RF2	Dilatancy - 3rd Cycle Forward	A2-15
RF2	Cyclic Shear - 3rd Cycle Reverse	A2-16

SAMPLE	DESCRIPTION	PAGE
RF2	Dilatancy - 3rd Cycle Reverse	A2-16
RF2	Cyclic Shear - 4th Cycle Forward	A2-17
RF2	Dilatancy - 4th Cycle Forward	A2-17
RF2	Cyclic Shear - 4th Cycle Reverse	A2-18
RF2	Dilatancy - 4th Cycle Reverse	A2-18
RF2	Cyclic Shear - 5th Cycle Forward	A2-19
RF2	Dilatancy - 5th Cycle Forward	A2-19
RF2	Cyclic Shear - 5th Cycle Reverse	A2-20
RF2	Dilatancy - 5th Cycle Reverse	A2-20
RF3	Cyclic Shear - 1st Cycle Forward	A2-21
RF3	Dilatancy - 1st Cycle Forward	A2-21
RF3	Cyclic Shear - 1st Cycle Reverse	A2-22
RF3	Dilatancy - 1st Cycle Reverse	A2-22
RF3	Cyclic Shear - 2nd Cycle Forward	A2-23
RF3	Dilatancy - 2nd Cycle Forward	A2-23
RF3	Cyclic Shear - 2nd Cycle Reverse	A2-24
RF3	Dilatancy - 2nd Cycle Reverse	A2-24
RF3	Cyclic Shear - 3rd Cycle Forward	A2-25
RF3	Dilatancy - 3rd Cycle Forward	A2-25
RF3	Cyclic Shear - 3rd Cycle Reverse	A2-26
RF3	Dilatancy - 3rd Cycle Reverse	A2-26
RF3	Cyclic Shear - 4th Cycle Forward	A2-27
RF3	Dilatancy - 4th Cycle Forward	A2-27
RF3	Cyclic Shear - 4th Cycle Reverse	A2-28
RF3	Dilatancy - 4th Cycle Reverse	A2-28
RF3	Cyclic Shear - 5th Cycle Forward	A2-29
RF3	Dilatancy - 5th Cycle Forward	A2-29
RF3	Cyclic Shear - 5th Cycle Reverse	A2-30
RF3	Dilatancy - 5th Cycle Reverse	A2-30
RF4	Cyclic Shear - 1st Cycle Forward	A2-31
RF4	Dilatancy - 1st Cycle Forward	A2-31
RF4	Cyclic Shear - 1st Cycle Reverse	A2-32

SAMPLE	DESCRIPTION	PAGE
RF4	Dilatancy - 1st Cycle Reverse	A2-32
RF4	Cyclic Shear - 2nd Cycle Forward	A2-33
RF4	Dilatancy - 2nd Cycle Forward	A2-33
RF4	Cyclic Shear - 2nd Cycle Reverse	A2-34
RF4	Dilatancy - 2nd Cycle Reverse	A2-34
RF4	Cyclic Shear - 3rd Cycle Forward	A2-35
RF4	Dilatancy - 3rd Cycle Forward	A2-35
RF4	Cyclic Shear - 3rd Cycle Reverse	A2-36
RF4	Dilatancy - 3rd Cycle Reverse	A2-36
RF4	Cyclic Shear - 4th Cycle Forward	A2-37
RF4	Dilatancy - 4th Cycle Forward	A2-37
RF4	Cyclic Shear - 4th Cycle Reverse	A2-38
RF4	Dilatancy - 4th Cycle Reverse	A2-38
RF4	Cyclic Shear - 5th Cycle Forward	A2-39
RF4	Dilatancy - 5th Cycle Forward	A2-39
RF4	Cyclic Shear - 5th Cycle Reverse	A2-40
RF4	Dilatancy - 5th Cycle Reverse	A2-40

CYCLIC SHEAR RG2

1ST CYCLE FORWARD

DILATANCY RG2

1ST CYCLE FORWARD

CYCLIC SHEAR RG2

1ST CYCLE REVERSE

DILATANCY RG2

1ST CYCLE REVERSE

CYCLIC SHEAR RG2

2ND CYCLE FORWARD

DILATANCY RG2

2ND CYCLE FORWARD

CYCLIC SHEAR RG2

2ND CYCLE REVERSE

DILATANCY RG2

2ND CYCLE REVERSE

CYCLIC SHEAR RG2

3RD CYCLE FORWARD

DILATANCY RG2

3RD CYCLE FORWARD

CYCLIC SHEAR RG2

3RD CYCLE REVERSE

DILATANCY RG2

3RD CYCLE REVERSE

CYCLIC SHEAR RG2

4TH CYCLE FORWARD

DILATANCY RG2

4TH CYCLE FORWARD

CYCLIC SHEAR RG2

4TH CYCLE REVERSE

DILATANCY RG2

4TH CYCLE REVERSE

CYCLIC SHEAR RG2 5TH CYCLE FORWARD

DILATANCY RG2 5TH CYCLE FORWARD

CYCLIC SHEAR RG2

5TH CYCLE REVERSE

DILATANCY RG2

5TH CYCLE REVERSE

CYCLIC SHEAR RF2

1ST CYCLE FORWARD

DILATANCY RF2

1ST CYCLE FORWARD

CYCLIC SHEAR RF2

1ST CYCLE REVERSE

DILATANCY RF2

1ST CYCLE REVERSE

CYCLIC SHEAR RF2

2ND CYCLE FORWARD

DILATANCY RF2

2ND CYCLE FORWARD

CYCLIC SHEAR RF2

2ND CYCLE REVERSE

DILATANCY RF2

2ND CYCLE REVERSE

CYCLIC SHEAR RF2

3RD CYCLE FORWARD

DILATANCY RF2

3RD CYCLE FORWARD

CYCLIC SHEAR RF2

3RD CYCLE REVERSE

DILATANCY RF2

3RD CYCLE REVERSE

CYCLIC SHEAR RF2

4TH CYCLE FORWARD

DILATANCY RF2

4TH CYCLE FORWARD

CYCLIC SHEAR RF2

4TH CYCLE REVERSE

DILATANCY RF2

4TH CYCLE REVERSE

CYCLIC SHEAR RF2

5TH CYCLE FORWARD

DILATANCY RF2

5TH CYCLE FORWARD

CYCLIC SHEAR RF2

5TH CYCLE REVERSE

DILATANCY RF2

5TH CYCLE REVERSE

CYCLIC SHEAR RF3

1ST CYCLE FORWARD

DILATANCY RF3

1ST CYCLE FORWARD

CYCLIC SHEAR RF3

1ST CYCLE REVERSE

DILATANCY RF3

1ST CYCLE REVERSE

CYCLIC SHEAR RF3

2ND CYCLE FORWARD

DILATANCY RF3

2ND CYCLE FORWARD

CYCLIC SHEAR RF3

2ND CYCLE REVERSE

DILATANCY RF3

2ND CYCLE REVERSE

CYCLIC SHEAR RF3

3RD CYCLE FORWARD

DILATANCY RF3

3RD CYCLE FORWARD

CYCLIC SHEAR RF3

3RD CYCLE REVERSE

DILATANCY RF3

3RD CYCLE REVERSE

CYCLIC SHEAR RF3

4TH CYCLE FORWARD

DILATANCY RF3

4TH CYCLE FORWARD

CYCLIC SHEAR RF3

4TH CYCLE REVERSE

DILATANCY RF3

4TH CYCLE REVERSE

CYCLIC SHEAR RF3

5TH CYCLE FORWARD

DILATANCY RF3

5TH CYCLE FORWARD

CYCLIC SHEAR RF3

5TH CYCLE REVERSE

DILATANCY RF3

5TH CYCLE REVERSE

CYCLIC SHEAR RF4 1ST CYCLE FORWARD

DILATANCY RF4 1ST CYCLE FORWARD

CYCLIC SHEAR RF4

1ST CYCLE REVERSE

DILATANCY RF4

1ST CYCLE REVERSE

CYCLIC SHEAR RF4

2ND CYCLE FORWARD

DILATANCY RF4

2ND CYCLE FORWARD

CYCLIC SHEAR RF4

2ND CYCLE REVERSE

DILATANCY RF4

2ND CYCLE REVERSE

CYCLIC SHEAR RF4 3RD CYCLE FORWARD

DILATANCY RF4 3RD CYCLE FORWARD

CYCLIC SHEAR RF4

3RD CYCLE REVERSE

DILATANCY RF4

3RD CYCLE REVERSE

CYCLIC SHEAR RF4

4TH CYCLE FORWARD

DILATANCY RF4

4TH CYCLE FORWARD

CYCLIC SHEAR RF4

4TH CYCLE REVERSE

DILATANCY RF4

4TH CYCLE REVERSE

CYCLIC SHEAR RF4

5TH CYCLE FORWARD

DILATANCY RF4

5TH CYCLE FORWARD

CYCLIC SHEAR RF4

5TH CYCLE REVERSE

DILATANCY RF4

5TH CYCLE REVERSE

APPENDIX A3
PEAK & RESIDUAL SHEAR LOAD TABLES

SAMPLE	DESCRIPTION	PAGE
RG2	Constant Normal Load, Forward Direction	A3-1
RG2	Constant Normal Load, Reverse Direction	A3-2
RG2	Constant Normal Stiffness, Forward Direction	A3-3
RG2	Constant Normal Stiffness, Reverse Direction	A3-4
RF2	Constant Normal Load, Forward Direction	A3-5
RF2	Constant Normal Load, Reverse Direction	A3-6
RF2	Constant Normal Stiffness, Forward Direction	A3-7
RF2	Constant Normal Stiffness, Reverse Direction	A3-8
RF3	Constant Normal Load, Forward Direction	A3-9
RF3	Constant Normal Load, Reverse Direction	A3-10
RF3	Constant Normal Stiffness, Forward Direction	A3-11
RF3	Constant Normal Stiffness, Reverse Direction	A3-12
RF4	Constant Normal Load, Forward Direction	A3-13
RF4	Constant Normal Load, Reverse Direction	A3-14
RF4	Constant Normal Stiffness, Forward Direction	A3-15
RF4	Constant Normal Stiffness, Reverse Direction	A3-16

Peak and residual shear loads for RG2 samples,
constant normal load, forward direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Forward	1.3	1.7	1.0	24.6
	6.4	6.5	4.9	323.6
	12.8	13.4	10.9	4688.0
	25.6	24.2	18.0	512.7
2nd Forward	1.3	1.5	1.2	
	6.4	5.6	4.7	
	12.8	11.5	9.6	
	25.6	18.2	15.8	
3rd Forward	1.3	1.4	1.1	
	6.4	5.7	5.6	
	12.8	-	-	
	25.6	14.7	12.1	
4th Forward	1.3	1.4	1.1	
	6.4	5.7	5.5	
	12.8	-	-	
	25.6	-	-	
5th Forward	1.3	1.3	1.2	
	6.4	5.8	5.5	
	12.8	-	-	
	25.6	-	-	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RG2 samples,
constant normal load, reverse direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Reverse	1.3	1.3	0.9	
	6.4	5.9	5.2	
	12.8	9.9	9.1	
	25.6	20.6	19.9	
2nd Reverse	1.3	1.0	0.9	
	6.4	5.4	5.0	
	12.8	9.6	9.3	
	25.6	19.8	18.2	
3rd Reverse	1.3	1.0	0.9	
	6.4	5.6	5.4	
	12.8	-	-	
	25.6	-	-	
4th Reverse	1.3	1.0	0.9	
	6.4	5.4	4.8	
	12.8	-	-	
	25.6	-	-	
5th Reverse	1.3	1.0	0.9	
	6.4	5.6	4.9	
	12.8	-	-	
	25.6	-	-	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RG2 samples,
constant normal stiffness, forward direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Forward	1.3 6.4	32.0 64.0			2.5 8.70
2nd Forward	1.3 6.4	32.0 64.0			2.0 6.7
3rd Forward	1.3 6.4	32.0 64.0			1.7 5.8
4th Forward	1.3 6.4	32.0 64.0	4.1	3.5	1.4
5th Forward	1.3 6.4	32.0 64.0			1.5 1.2

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RG2 samples,
constant normal stiffness, reverse direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Reverse	1.3 6.4	32.0 64.0			1.1 4.5
2nd Reverse	1.3 6.4	32.0 64.0			0.8 4.1
3rd Reverse	1.3 6.4	32.0 64.0			0.8 3.3
4th Reverse	1.3 6.4	32.0 64.0	2.3	1.3	0.8
5th Reverse	1.3 6.4	32.0 64.0			0.8 0.5

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF2 samples,
constant normal load, forward direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Forward	0.6	0.7	0.3	186
	3.0	2.9	1.8	138
	5.9	4.9	3.1	183
	11.8	9.1	5.9	561
2nd Forward	0.6	0.3	0.2	
	3.0	2.0	1.5	
	5.9	3.2	2.7	
	11.8	6.1	5.3	
3rd Forward	0.6	0.3	0.2	
	3.0	1.9	1.5	
	5.9	2.9	2.6	
	11.8	5.5	4.9	
4th Forward	0.6	0.3	0.2	
	3.0	1.8	1.5	
	5.9	2.8	2.6	
	11.8	5.1	4.7	
5th Forward	0.6	0.2	0.2	
	3.0	1.7	1.3	
	5.9	3.0	2.5	
	11.8	-	-	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF2 samples,
constant normal load, reverse direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Reverse	0.6	0.6	0.2	
	3.0	2.3	1.3	
	5.9	3.8	2.4	
	11.8	7.5	5.0	
2nd Reverse	0.6	0.5	0.3	
	3.0	1.6	1.2	
	5.9	2.6	2.2	
	11.8	5.0	4.6	
3rd Reverse	0.6	0.5	0.3	
	3.0	1.4	1.2	
	5.9	2.5	2.2	
	11.8	4.5	3.6	
4th Reverse	0.6	0.5	0.3	
	3.0	1.3	1.1	
	5.9	2.3	2.2	
	11.8	3.7	2.7	
5th Reverse	0.6	0.4	0.3	
	3.0	1.3	1.1	
	5.9	2.3	1.7	
	11.8	-	-	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF2 samples,
constant normal stiffness, forward direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Forward	3.0	14.8	2.4	1.8	
	3.0	44.3			2.8
	3.0	147.7			4.7
2nd Forward	3.0	14.8	1.9	1.7	
	3.0	44.3			2.3
	3.0	147.7			3.8
3rd Forward	3.0	14.8			
	3.0	44.3			2.0
	3.0	147.7			3.6
4th Forward	3.0	14.8	1.7	1.6	
	3.0	44.3			1.5
	3.0	147.7			3.6
5th Forward	3.0	14.8	1.7	1.5	
	3.0	44.3			
	3.0	147.7			3.6

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF2 samples,
constant normal stiffness, reverse direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Reverse	3.0	14.8	2.2	1.1	
	3.0	44.3	2.0	1.4	
	3.0	147.7	2.4	1.4	
2nd Reverse	3.0	14.8	1.8	1.2	
	3.0	44.3	1.8	1.4	
	3.0	147.7	1.7	1.2	
3rd Reverse	3.0	14.8	1.6	1.2	
	3.0	44.3	1.6	1.3	
	3.0	147.7	1.6	1.2	
4th Reverse	3.0	14.8	1.6	1.2	
	3.0	44.3			
	3.0	147.7	1.6	1.3	
5th Reverse	3.0	14.8	1.6	1.2	
	3.0	44.3			
	3.0	147.7	1.6	1.2	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF3 samples,
constant normal load, forward direction.

Cycle	Normal Load (Kips)	Peak Shear Load (Kips)	Residual Shear Load (Kips)	Initial Shear Stiffness (Kips/in)
1st Forward	0.8	1.0	0.3	167
	3.8	3.3	2.2	1620
	7.5	6.5	4.4	849
	15.0	10.9	8.5	866
2nd Forward	0.8	0.6	0.3	
	3.8	2.6	2.0	
	7.5	4.9	3.9	
	15.0	8.0	7.0	
3rd Forward	0.8	0.6	0.3	
	3.8	2.5	2.0	
	7.5	4.8	3.5	
	15.0	7.7	6.4	
4th Forward	0.8	0.8	0.4	
	3.8	2.5	1.9	
	7.5	4.7	3.4	
	15.0	7.8	6.6	
5th Forward	0.8	0.5	0.3	
	3.8	2.5	1.9	
	7.5	4.5	3.3	
	15.0	7.8	6.5	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF3 samples,
constant normal load, reverse direction.

Cycle	Normal Load (Kips)	Peak Shear Load (Kips)	Residual Shear Load (Kips)	Initial Shear Stiffness (Kips/in)
1st Reverse	0.8	1.3	0.4	
	3.8	4.4	2.3	
	7.5	7.4	4.7	
	15.0	12.5	9.2	
2nd Reverse	0.8	0.8	0.4	
	3.8	3.4	2.3	
	7.5	5.4	4.1	
	15.0	9.7	7.8	
3rd Reverse	0.8	0.7	0.4	
	3.8	3.2	2.2	
	7.5	4.9	3.9	
	15.0	8.9	7.7	
4th Reverse	0.8	0.7	0.4	
	3.8	3.0	2.3	
	7.5	4.7	3.8	
	15.0	8.9	8.0	
5th Reverse	0.8	0.7	0.4	
	3.8	2.9	2.3	
	7.5	4.5	3.8	
	15.0	8.8	8.1	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF3 samples,
constant normal stiffness, forward direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Forward	3.8	18.8	7.6	6.4	3.1
	3.8	56.3			3.9
	3.8	187.5			5.3
	7.5	56.3			
	7.5	187.5			10.2
2nd Forward	3.8	18.8			2.4
	3.8	56.3			3.4
	3.8	187.5			4.1
	7.5	56.3			5.3
	7.5	187.5			7.8
3rd Forward	3.8	18.8			2.1
	3.8	56.3			3.1
	3.8	187.5			3.7
	7.5	56.3			5.0
	7.5	187.5			7.1
4th Forward	3.8	18.8			2.0
	3.8	56.3			3.0
	3.8	187.5			3.7
	7.5	56.3			4.7
	7.5	187.5			6.8
5th Forward	3.8	18.8			2.0
	3.8	56.3			2.9
	3.8	187.5			3.5
	7.5	56.3			4.7
	7.5	187.5			6.8

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF3 samples,
constant normal stiffness, reverse direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Reverse	3.8	18.8	3.9	3.4	
	3.8	56.3			4.1
	3.8	187.5	10.0	8.5	5.4
	7.5	56.3			
	7.5	187.5			10.6
2nd Reverse	3.8	18.8	3.1	2.7	
	3.8	56.3			3.5
	3.8	187.5			4.2
	7.5	56.3			7.3
	7.5	187.5			7.8
3rd Reverse	3.8	18.8	3.0	2.7	
	3.8	56.3			3.3
	3.8	187.5			3.9
	7.5	56.3			6.9
	7.5	187.5			7.4
4th Reverse	3.8	18.8	2.9	2.7	
	3.8	56.3			3.1
	3.8	187.5			3.9
	7.5	56.3			6.9
	7.5	187.5			7.1
5th Reverse	3.8	18.8	2.8	2.7	
	3.8	56.3			2.9
	3.8	187.5			3.8
	7.5	56.3			6.6
	7.5	187.5			6.6

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF4 samples,
constant normal load, forward direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Forward	0.7	1.1	0.5	100
	3.6	3.8	2.0	783
	7.2	7.1	4.4	1194
	10.8	10.8	7.3	830
	14.4	13.7	9.2	925
2nd Forward	0.7	0.7	0.5	
	3.6	2.3	1.7	
	7.2	4.5	4.0	
	10.8	7.4	6.6	
	14.4	9.1	8.3	
3rd Forward	0.7	0.6	0.4	
	3.6	2.0	1.7	
	7.2	4.1	3.9	
	10.8	6.9	6.6	
	14.4	8.7	8.0	
4th Forward	0.7	0.5	0.4	
	3.6	1.9	1.6	
	7.2	3.9	3.8	
	10.8	6.7	6.5	
	14.4	8.7	8.0	
5th Forward	0.7	0.5	0.6	
	3.6	1.8	1.7	
	7.2	3.8	3.8	
	10.8	6.6	6.5	
	14.4	8.6	8.0	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF4 samples,
constant normal load, reverse direction.

Cycle	Constant Normal Load (kips)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Stiffness (kips/in)
1st Reverse	0.7	1.2	0.7	
	3.6	5.1	3.0	
	7.2	7.8	5.5	
	10.8	10.9	7.5	
	14.4	12.9	9.7	
2nd Reverse	0.7	0.8	0.6	
	3.6	3.8	3.0	
	7.2	5.8	5.3	
	10.8	8.0	7.3	
	14.4	10.3	9.2	
3rd Reverse	0.7	0.7	0.6	
	3.6	3.6	3.1	
	7.2	5.4	5.0	
	10.8	7.6	7.2	
	14.4	9.8	8.9	
4th Reverse	0.7	0.7	0.5	
	3.6	3.5	3.1	
	7.2	5.3	5.0	
	10.8	7.4	7.1	
	14.4	9.5	8.9	
5th Reverse	0.7	0.7	0.6	
	3.6	3.4	3.1	
	7.2	5.3	5.0	
	10.8	7.3	7.1	
	14.4	9.2	8.8	

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF4 samples,
constant normal stiffness, forward direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Forward	3.6	18.0	4.5	3.4	4.6
	3.6	54.0			
	3.6	179.9	9.4	7.3	6.6
	7.2	54.0			
	7.2	179.9			
2nd Forward	3.6	18.0			3.1
	3.6	54.0			3.9
	3.6	179.9			4.9
	7.2	54.0			6.6
	7.2	179.9			7.2
3rd Forward	3.6	18.0			2.9
	3.6	54.0			3.6
	3.6	179.9			4.7
	7.2	54.0			6.4
	7.2	179.9			6.7
4th Forward	3.6	18.0			2.9
	3.6	54.0			3.5
	3.6	179.9			4.5
	7.2	54.0			6.4
	7.2	179.9			6.5
5th Forward	3.6	18.0			2.8
	3.6	54.0			3.4
	3.6	179.9			4.3
	7.2	54.0			6.3
	7.2	179.9			

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Peak and residual shear loads for RF4 samples,
constant normal stiffness, reverse direction.

Cycle	Initial Normal Load (kips)	Constant Normal Stiffness (kips/in)	Peak Shear Load (kips)	Residual Shear Load (kips)	Shear Load at 0.4 in Shear Displ. (kips)
1st Reverse	3.6	18.0	4.4	3.0	
	3.6	54.0	4.7	3.9	
	3.6	179.9			5.6
	7.2	54.0	8.3	6.0	
	7.2	179.9			7.2
2nd Reverse	3.6	18.0	3.3	3.0	
	3.6	54.0			3.7
	3.6	179.9			4.9
	7.2	54.0			6.2
	7.2	179.9			6.8
3rd Reverse	3.6	18.0	3.1	2.9	
	3.6	54.0			3.5
	3.6	179.9			4.6
	7.2	54.0			6.1
	7.2	179.9			6.4
4th Reverse	3.6	18.0			3.0
	3.6	54.0			3.4
	3.6	179.9			4.4
	7.2	54.0			6.0
	7.2	179.9			6.2
5th Reverse	3.6	18.0			2.9
	3.6	54.0			3.4
	3.6	179.9			4.3
	7.2	54.0			5.8
	7.2	179.9			

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

APPENDIX A4
SLOPE OF DILATANCY ($\tan i$) TABLES

SAMPLE	DESCRIPTION	PAGE
RG2	Slope of Dilatancy, Constant Normal Load	A4-1
RG2	Slope of Dilatancy, Constant Normal Stiffness	A4-2
RF2	Slope of Dilatancy, Constant Normal Load	A4-3
RF2	Slope of Dilatancy, Constant Normal Stiffness	A4-4
RF3	Slope of Dilatancy, Constant Normal Load	A4-5
RF3	Slope of Dilatancy, Constant Normal Stiffness	A4-6
RF4	Slope of Dilatancy, Constant Normal Load	A4-7
RF4	Slope of Dilatancy, Constant Normal Stiffness	A4-8

Slope of dilatancy curves ($\tan i$) for RG2 samples,
constant normal load tests.

	Initial Normal Load (kips)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
Forward Shear	1.3	0.21	0.17	0.15	0.13	0.11
	6.4	0.10	0.01	-0.03	-0.01	-0.01
	12.8	0.12	0.07	-	-	-
	25.6	-0.05	-0.05	-0.19	-	-
Reverse Shear	1.3	0.06	0.05	0.04	0.03	0.04
	6.4	0.04	-0.02	-0.01	-0.01	-0.01
	12.8	0.00	-0.01	-	-	-
	25.6	-0.04	-0.04	-	-	-

Note: 1 kip = 4.45 kN

Slope of dilatancy curves ($\tan i$) for RG2 samples,
constant normal stiffness tests.

	Ini- tial Normal Load (kips)	Constant Normal Stiff- ness (kips/in)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
For- ward Shear	1.3	32.0	0.14	0.12	0.11	0.11	0.11
	6.4	64.0	0.12	0.09	0.07	0.07	0.04
Re- verse Shear	1.3	32.0	0.06	0.03	0.02	0.01	0.01
	6.4	64.0	-0.00	-0.04	0.00	-0.01	-0.02

Slope of dilatancy curves ($\tan i$) for RF2 samples,
constant normal load tests.

	Initial Normal Load (kips)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
Forward Shear	0.6	0.17	0.14	0.13	0.08	-
	3.0	0.14	0.13	0.12	0.12	0.12
	5.9	0.11	0.10	0.10	0.09	0.07
	11.8	0.07	0.08	0.05	0.07	-
Reverse Shear	0.6	0.16	0.16	0.14	0.08	-
	3.0	0.04	0.03	0.02	0.02	0.02
	5.9	0.01	0.01	0.01	0.01	0.00
	11.8	-0.01	-0.02	-0.03	-0.12	-

Slope of dilatancy curves ($\tan i$) for RF2 samples,
constant normal stiffness tests.

	Ini- tial Normal Load (kips)	Constant Normal Stiff- ness (kips/in)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
For- ward Shear	3.0	14.8	0.14	0.13	0.13	0.12	0.12
	3.0	44.3	0.11	0.10	0.08	0.05	-
	3.0	147.8	0.11	0.11	0.10	0.10	0.10
Re- verse Shear	3.0	14.8	0.04	0.03	0.02	0.02	0.02
	3.0	44.3	0.03	0.02	0.01	-0.03	-
	3.0	147.8	0.01	0.01	0.01	0.01	0.07

Slope of dilatancy curves ($\tan i$) for RF3 samples,
constant normal load tests.

	Initial Normal Load (kips)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
Forward Shear	0.8	0.18	0.18	0.17	0.17	0.17
	3.8	0.18	0.18	0.18	0.17	0.17
	7.5	0.16	0.15	0.13	0.12	0.12
	15.0	0.10	0.09	0.08	0.08	0.08
Reverse Shear	0.8	0.26	0.27	0.27	0.26	0.27
	3.8	0.19	0.19	0.19	0.19	0.18
	7.5	0.14	0.13	0.12	0.11	0.11
	15.0	0.09	0.07	0.07	0.06	0.06

Slope of dilatancy curves ($\tan i$) for RF3 samples,
constant normal stiffness tests.

	Ini- tial Normal Load (kips)	Constant Normal Stiff- ness (kips/in)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
For- ward Shear	3.8	18.8	0.16	0.13	0.13	0.13	0.12
	3.8	56.3	0.15	0.15	0.15	0.15	0.15
	3.8	187.5	0.10	0.10	0.10	0.10	0.10
	7.5	56.3	0.09	0.08	0.08	0.08	0.07
	7.5	187.5	0.09	0.08	0.08	0.07	0.07
Re- verse Shear	3.8	18.8	0.16	0.15	0.14	0.13	0.13
	3.8	56.3	0.16	0.16	0.15	0.15	0.15
	3.8	187.5	0.11	0.11	0.10	0.10	0.10
	7.5	56.3	0.09	0.07	0.07	0.06	0.06
	7.5	187.5	0.10	0.09	0.08	0.08	0.07

Slope of dilatancy curves ($\tan i$) for RF4 samples,
constant normal load tests.

	Initial Normal Load (kips)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
Forward Shear	0.7	0.14	0.12	0.12	0.11	0.11
	3.6	0.14	0.13	0.13	0.13	0.13
	7.2	0.11	0.11	0.10	0.09	0.09
	10.8	0.10	0.10	0.09	0.09	0.08
	14.4	0.08	0.07	0.07	0.07	0.06
Reverse Shear	0.7	0.14	0.14	0.14	0.14	0.14
	3.6	0.11	0.11	0.11	0.11	0.11
	7.2	0.08	0.08	0.08	0.07	0.07
	10.8	0.09	0.08	0.08	0.08	0.07
	14.4	0.07	0.06	0.06	0.05	0.05

Slope of dilatancy curves ($\tan i$) for RF4 samples,
constant normal stiffness tests.

	Initial Normal Load (kips)	Constant Normal Stiff- ness (kips/in)	$\tan i$ 1st cycle	$\tan i$ 2nd cycle	$\tan i$ 3rd cycle	$\tan i$ 4th cycle	$\tan i$ 5th cycle
For- ward Shear	3.6	18.0	0.13	0.12	0.11	0.11	0.11
	3.6	54.0	0.13	0.12	0.11	0.11	0.11
	3.6	179.9	0.10	0.09	0.08	0.08	0.08
	7.2	54.0	0.12	0.11	0.10	0.10	0.10
	7.2	179.9	0.08	0.08	0.08	0.07	-
Re- verse Shear	3.6	18.0	0.11	0.11	0.11	0.10	0.10
	3.6	54.0	0.10	0.10	0.09	0.09	0.09
	3.6	179.9	0.08	0.09	0.08	0.08	0.08
	7.2	54.0	0.08	0.09	0.08	0.08	0.08
	7.2	179.9	0.06	0.06	0.06	0.06	-

APPENDIX A5
SHEAR LOAD PATH

SAMPLE	DESCRIPTION	PAGE
RG2	Peak & Residual Shear Load, 1st Cycle Forward	A5-1
RG2	Peak & Residual Shear Load, 1st Cycle Reverse	A5-1
RG2	Peak & Residual Shear Load, 2nd Cycle Forward	A5-2
RG2	Peak & Residual Shear Load, 2nd Cycle Reverse	A5-2
RG2	Peak & Residual Shear Load, 3rd Cycle Forward	A5-3
RG2	Peak & Residual Shear Load, 3rd Cycle Reverse	A5-3
RG2	Peak & Residual Shear Load, 4th Cycle Forward	A5-4
RG2	Peak & Residual Shear Load, 4th Cycle Reverse	A5-4
RG2	Peak & Residual Shear Load, 5th Cycle Forward	A5-5
RG2	Peak & Residual Shear Load, 5th Cycle Reverse	A5-5
RF2	Peak & Residual Shear Load, 1st Cycle Forward	A5-6
RF2	Peak & Residual Shear Load, 1st Cycle Reverse	A5-6
RF2	Peak & Residual Shear Load, 2nd Cycle Forward	A5-7
RF2	Peak & Residual Shear Load, 2nd Cycle Reverse, K = 14.8 kips/in	A5-7
RF2	Peak & Residual Shear Load, 2nd Cycle Reverse, K = 44.3 kips/in	A5-8
RF2	Peak & Residual Shear Load, 2nd Cycle Reverse, K = 147.7 kips/in	A5-8
RF2	Peak & Residual Shear Load, 3rd Cycle Forward	A5-9
RF2	Peak & Residual Shear Load, 3rd Cycle Reverse, K = 14.8 kips/in	A5-9
RF2	Peak & Residual Shear Load, 3rd Cycle Reverse, K = 44.3 kips/in	A5-10
RF2	Peak & Residual Shear Load, 3rd Cycle Reverse, K = 147.7 kips/in	A5-10
RF2	Peak & Residual Shear Load, 4th Cycle Forward	A5-11
RF2	Peak & Residual Shear Load, 4th Cycle Reverse	A5-11
RF2	Peak & Residual Shear Load, 5th Cycle Forward	A5-12

SAMPLE	DESCRIPTION	PAGE
RF2	Peak & Residual Shear Load, 5th Cycle Reverse, K = 14.8 kips/in	A5-12
RF2	Peak & Residual Shear Load, 5th Cycle Reverse, K = 147.7 kips/in	A5-13
RF3	Peak & Residual Shear Load, 1st Cycle Forward	A5-14
RF3	Peak & Residual Shear Load, 1st Cycle Reverse	A5-14
RF3	Peak & Residual Shear Load, 2nd Cycle Forward	A5-15
RF3	Peak & Residual Shear Load, 2nd Cycle Reverse	A5-15
RF3	Peak & Residual Shear Load, 3rd Cycle Forward	A5-16
RF3	Peak & Residual Shear Load, 3rd Cycle Reverse	A5-16
RF3	Peak & Residual Shear Load, 4th Cycle Forward	A5-17
RF3	Peak & Residual Shear Load, 4th Cycle Reverse	A5-17
RF3	Peak & Residual Shear Load, 5th Cycle Forward	A5-18
RF3	Peak & Residual Shear Load, 5th Cycle Reverse	A5-18
RF4	Peak & Residual Shear Load, 1st Cycle Forward	A5-19
RF4	Peak & Residual Shear Load, 1st Cycle Reverse	A5-19
RF4	Peak & Residual Shear Load, 2nd Cycle Forward	A5-20
RF4	Peak & Residual Shear Load, 2nd Cycle Reverse	A5-20
RF4	Peak & Residual Shear Load, 3rd Cycle Forward	A5-21
RF4	Peak & Residual Shear Load, 3rd Cycle Reverse	A5-21
RF4	Peak & Residual Shear Load, 4th Cycle Forward	A5-22
RF4	Peak & Residual Shear Load, 4th Cycle Reverse	A5-22
RF4	Peak & Residual Shear Load, 5th Cycle Forward	A5-23
RF4	Peak & Residual Shear Load, 5th Cycle Reverse	A5-23

PEAK & RESIDUAL SHEAR LOAD RG2 1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 1ST CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RG2 2ND CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 2ND CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RG2 3RD CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 3RD CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RG2 4TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 4TH CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RG2 5TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RG2 5TH CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF2 1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 1ST CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF2
2ND CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2
2ND CYCLE REVERSE, K=14.8 KIPS/N

PEAK & RESIDUAL SHEAR LOAD RF2
2ND CYCLE REVERSE, K=44.3 KIPS/IN

PEAK & RESIDUAL SHEAR LOAD RF2
2ND CYCLE REVERSE, K=147.7 KIPS/IN

PEAK & RESIDUAL SHEAR LOAD RF2 3RD CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 3RD CYCLE REVERSE, $K = 14.8 \text{ KIPS/IN}$

PEAK & RESIDUAL SHEAR LOAD RF2
3RD CYCLE REVERSE, K=44.3 KIPS/IN

PEAK & RESIDUAL SHEAR LOAD RF2
3RD CYCLE REVERSE, K=147.7 KIPS/IN

PEAK & RESIDUAL SHEAR LOAD RF2 4TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 4TH CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF2 5TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF2 5TH CYCLE REVERSE, $K = 14.8 \text{ KIPS/IN}$

PEAK & RESIDUAL SHEAR LOAD RF2 5TH CYCLE REVERSE, K=147.7 KIPS/IN

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 1ST CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF3 2ND CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 2ND CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF3 3RD CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 3RD CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF3 4TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 4TH CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF3 5TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF3 5TH CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 1ST CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF4 2ND CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 2ND CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF4 3RD CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 3RD CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF4 4TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 4TH CYCLE REVERSE

PEAK & RESIDUAL SHEAR LOAD RF4 5TH CYCLE FORWARD

PEAK & RESIDUAL SHEAR LOAD RF4 5TH CYCLE REVERSE

APPENDIX A6
SHEARED AREA & GOUGE TABLES

SAMPLE	DESCRIPTION	PAGE
RG2	Sheared Area & Gouge	A6-1
RF2	Sheared Area & Gouge	A6-2
RF3	Sheared Area & Gouge	A6-3
RF4	Sheared Area & Gouge	A6-4

Sheared area for RG2 samples and
amount of gouge generated in shear.

Sample	Bottom Sheared Area (sq in)	Bottom Sheared Area (%)	Top Sheared Area (sq in)	Top Sheared Area (%)	Gouge (grams)
R1G2	-	-	-	-	36.6
R4G2	-	-	-	-	237.0
R2G2	-	-	-	-	317.3
R3G2	-	-	-	-	1173.7
KR5G2	-	-	-	-	46.3
KR6G2	21.1	66	20.8	65	246.5

Note: 1 sq in = 6.45 cm²

Sheared area for RF2 samples and
amount of gouge generated in shear.

Sample	Bottom Sheared Area (sq in)	Bottom Sheared Area (%)	Top Sheared Area (sq in)	Top Sheared Area (%)	Gouge (grams)
R5F2	3.5	23	3.7	25	22.1
R2F2	6.2	32	5.2	35	77.4
R3F2	6.8	46	5.5	37	182.0
R4F2	13.5	91	8.7	59	437.3
KR6F2	9.1	61	8.8	60	81.6
KR7F2	7.4	50	6.8	46	86.8
KR8F2	10.8	73	10.8	73	62.2

Note: 1 sq in = 6.45 cm²

Sheared area for RF3 samples and
amount of gouge generated in shear.

Sample	Bottom Sheared Area (sq in)	Bottom Sheared Area (%)	Top Sheared Area (sq in)	Top Sheared Area (%)	Gouge (grams)
R1F3	7.8	42	6.9	37	1.1
R6F3	14.4	77	13.6	73	2.1
R4F3	13.3	71	12.9	69	5.6
R5F3	17.4	93	17.7	94	16.0
KR7F3	12.3	66	10.7	57	9.0
KR8F3	11.8	63	12.1	64	4.8
KR9F3	11.7	62	11.0	58	7.7
KR10F3	17.2	92	15.5	83	18.1
KR11F3	16.8	90	17.1	91	22.3

Note: 1 sq in = 6.45 cm²

Sheared area for RF4 samples and
amount of gouge generated in shear.

Sample	Bottom Sheared Area (sq in)	Bottom Sheared Area (%)	Top Sheared Area (sq in)	Top Sheared Area (%)	Gouge (grams)
R1F4	4.5	25	5.1	29	2.4
R2F4	12.2	68	11.9	66	5.1
R3F4	14.5	81	14.8	82	10.4
R4F4	16.4	91	16.0	89	10.5
R5F4	17.2	95	17.0	94	12.8
R6F4	16.4	91	16.2	90	8.7
KR7F4	13.2	73	11.5	64	5.1
R8F4	16.0	89	15.6	87	12.2
KR9F4	13.2	73	13.3	74	5.0
KR10F4	13.5	75	12.5	69	6.9
KR11F4	16.1	90	16.2	90	11.2
KR12F4	15.3	85	15.1	85	10.0
KR13F4	12.6	70	12.9	72	7.4

Note: 1 sq in = 6.45 cm²

APPENDIX B1
CYCLIC COMPRESSION

SAMPLE	DESCRIPTION	PAGE
RG2	Solid Block	B1-1
R4G2	Before Shear	B1-1
R1G2	After Shear; Normal Load = 1.3 kips	B1-2
R4G2	After Shear; Normal Load = 6.4 kips	B1-2
R2G2	After Shear; Normal Load = 12.8 kips	B1-3
R3G2	After Shear; Normal Load = 25.6 kips	B1-3
KR5G2	After Shear; Normal Load = 1.3 kips, K = 32 kips/in	B1-4
KR6G2	After Shear; Normal Load = 6.4 kips, K = 64 kips/in	B1-4
RF2	Solid Block	B1-5
R5F2	Before Shear	B1-5
R5F2	After Shear; Normal Load = 0.6 kips	B1-6
R2F2	After Shear; Normal Load = 3.0 kips	B1-6
R3G2	After Shear; Normal Load = 5.9 kips	B1-7
R4F2	After Shear; Normal Load = 11.8 kips	B1-7
KR6F2	After Shear; Normal Load = 3.0 kips, K = 14.8 kips/in	B1-8
KR7F2	After Shear; Normal Load = 3.0 kips, K = 44.3 kips/in	B1-8
KR8F2	After Shear; Normal Load = 3.0 kips, K = 147.7 kips/in	B1-9
RF3	Solid Block	B1-10
R1F3	Before Shear	B1-10
R1F3	After Shear; Normal Load = 0.8 kips	B1-11
R6F3	After Shear; Normal Load = 3.8 kips	B1-11
R4F3	After Shear; Normal Load = 7.5 kips	B1-12
R5F3	After Shear; Normal Load = 15.0 kips	B1-12
KR7F3	After Shear; Normal Load = 3.8 kips, K = 18.8 kips/in	B1-13

SAMPLE	DESCRIPTION	PAGE
KR8F3	After Shear; Normal Load = 3.8 kips, K = 56.3 kips/in	B1-13
KR9F3	After Shear; Normal Load = 3.8 kips, K = 187.5 kips/in	B1-14
KR11F3	After Shear; Normal Load = 7.5 kips, K = 56.3 kips/in	B1-14
KR10F3	After Shear; Normal Load = 7.5 kips, K = 187.5 kips/in	B1-15
RF4	Solid Block	B1-16
R5F4	Before Shear	B1-16
R1F4	After Shear; Normal Load = 0.7 kips	B1-17
R2F4	After Shear; Normal Load = 3.6 kips	B1-17
R3F4	After Shear; Normal Load = 7.2 kips	B1-18
R4F4	After Shear; Normal Load = 10.8 kips	B1-18
R6F4	After Shear; Normal Load = 10.8 kips	B1-19
R8F4	After Shear; Normal Load = 10.8 kips	B1-19
R5F4	After Shear; Normal Load = 14.4 kips	B1-20
KR7F4	After Shear; Normal Load = 3.6 kips, K = 18.0 kips/in	B1-20
KR9F4	After Shear; Normal Load = 3.6 kips, K = 54.0 kips/in	B1-21
KR10F4	After Shear; Normal Load = 3.6 kips, K = 179.9 kips/in	B1-21
KR11F4	After Shear; Normal Load = 7.2 kips, K = 54.0 kips/in	B1-22
KR12F4	After Shear; Normal Load = 7.2 kips, K = 179.9 kips/in	B1-22
R13F4	After Shear (Reverse); Normal Load = 3.6 kips	B1-23

CYCLIC COMPRESSION RG2 SOLID BLOCK

CYCLIC COMPRESSION R4G2 BEFORE SHEAR

CYCLIC COMPRESSION R1G2

AFTER SHEAR; NORMAL LOAD = 1.3 KIPS

CYCLIC COMPRESSION R4G2

AFTER SHEAR; NORMAL LOAD = 6.4 KIPS

CYCLIC COMPRESSION R2G2

AFTER SHEAR; NORMAL LOAD = 12.8 KIPS

CYCLIC COMPRESSION R3G2

AFTER SHEAR; NORMAL LOAD = 25.6 KIPS

CYCLIC COMPRESSION KR5G2

AFTER SHEAR

NORMAL LOAD = 1.3 KIPS, $K = 32$ KIPS/IN

CYCLIC COMPRESSION KR6G2

AFTER SHEAR

NORMAL LOAD = 6.4 KIPS, $K = 64$ KIPS/IN

CYCLIC COMPRESSION RF2 SOLID BLOCK

CYCLIC COMPRESSION R5F2 BEFORE SHEAR

CYCLIC COMPRESSION R5F2

AFTER SHEAR; NORMAL LOAD = 0.6 KIPS

CYCLIC COMPRESSION R2F2

AFTER SHEAR; NORMAL LOAD = 3.0 KIPS

CYCLIC COMPRESSION R3F2

AFTER SHEAR; NORMAL LOAD = 5.9 KIPS

CYCLIC COMPRESSION R4F2

AFTER SHEAR; NORMAL LOAD = 11.8 KIPS

CYCLIC COMPRESSION KR6F2

AFTER SHEAR

NORMAL LOAD = 3.0 KIPS, $K = 14.8$ KIPS/IN

CYCLIC COMPRESSION KR7F2

AFTER SHEAR

NORMAL LOAD = 3.0 KIPS, $K = 44.3$ KIPS/IN

CYCLIC COMPRESSION KR8F2

AFTER SHEAR

NORMAL LOAD = 3.0 KIPS, $K = 147.7$ KIPS/IN

CYCLIC COMPRESSION RF3

SOLID BLOCK

CYCLIC COMPRESSION R1F3

BEFORE SHEAR

CYCLIC COMPRESSION R1F3

AFTER SHEAR; NORMAL LOAD = 0.8 KIPS

CYCLIC COMPRESSION R6F3

AFTER SHEAR; NORMAL LOAD = 3.8 KIPS

CYCLIC COMPRESSION R4F3

AFTER SHEAR; NORMAL LOAD = 7.5 KIPS

CYCLIC COMPRESSION R5F3

AFTER SHEAR; NORMAL LOAD = 15 KIPS

CYCLIC COMPRESSION KR7F3

AFTER SHEAR

NORMAL LOAD = 3.8 KIPS, $K = 18.8$ KIPS/IN

CYCLIC COMPRESSION KR8F3

AFTER SHEAR

NORMAL LOAD = 3.8 KIPS, $K = 56.3$ KIPS/IN

CYCLIC COMPRESSION KR9F3

AFTER SHEAR

NORMAL LOAD = 3.8 KIPS, $K = 187.5$ KIPS/IN

CYCLIC COMPRESSION KR11F3

AFTER SHEAR

NORMAL LOAD = 7.5 KIPS, $K = 56.3$ KIPS/IN

CYCLIC COMPRESSION KR10F3

AFTER SHEAR

NORMAL LOAD = 7.5 KIPS, $K = 187.5$ KIPS/IN

CYCLIC COMPRESSION RF4 SOLID BLOCK

CYCLIC COMPRESSION R5F4 BEFORE SHEAR

CYCLIC COMPRESSION R1F4

AFTER SHEAR; NORMAL LOAD=0.7 KIPS

CYCLIC COMPRESSION R2F4

AFTER SHEAR; NORMAL LOAD=3.6 KIPS

CYCLIC COMPRESSION R3F4

AFTER SHEAR; NORMAL LOAD=7.2 KIPS

CYCLIC COMPRESSION R4F4

AFTER SHEAR; NORMAL LOAD=10.8 KIPS

CYCLIC COMPRESSION R6F4

AFTER SHEAR; NORMAL LOAD=10.8 KIPS

CYCLIC COMPRESSION R8F4

AFTER SHEAR; NORMAL LOAD=10.8 KIPS

CYCLIC COMPRESSION R5F4

AFTER SHEAR; NORMAL LOAD=14.4 KIPS

CYCLIC COMPRESSION KR7F4

AFTER SHEAR
NORMAL LOAD = 3.6 KIPS, K = 18.0 KIPS/IN

CYCLIC COMPRESSION KR9F4

AFTER SHEAR

NORMAL LOAD = 3.6 KIPS, $K = 54.0$ KIPS/IN

CYCLIC COMPRESSION KR10F4

AFTER SHEAR

NORMAL LOAD = 3.6 KIPS, $K = 179.9$ KIPS/IN

APPENDIX B2
MAXIMUM CLOSURE & INITIAL STIFFNESS TABLES

SAMPLE	DESCRIPTION	PAGE
RG2	Maximum Closure & Initial Stiffness	B2-1
RF2	Maximum Closure & Initial Stiffness	B2-2
RF3	Maximum Closure & Initial Stiffness	B2-3
RF4	Maximum Closure & Initial Stiffness	B2-4

Maximum closure and initial stiffness for samples RG2.

	Sample	Maximum Closure V_m (in)	Initial Normal Stiffness k_{ni} (ksi/in)
Before Shear		3.9×10^{-2}	0.9×10^2
After Shear	R1G2	5.0×10^{-2}	0.2×10^2
	R4G2	11.9×10^{-2}	0.2×10^2
	R2G2	8.2×10^{-2}	0.3×10^2
	R3G2	-	-
	KR5G2	1.8×10^{-2}	0.6×10^2
	KR6G2	10.7×10^{-2}	0.2×10^2

Note: 1 in = 2.54 cm, 1 ksi/in = 2.72 MPa/cm

Maximum closure and initial stiffness for samples RF2.

	Sample	Maximum Closure V_m (in)	Initial Normal Stiffness k_{ni} (ksi/in)
Before Shear		0.7×10^{-2}	2.0×10^2
After Shear	R5F2	-	-
	R2F2	0.6×10^{-2}	1.0×10^2
	R3F2	0.7×10^{-2}	3.3×10^2
	R4F2	-	-
	KR6F2	-	-
	KR7F2	1.9×10^{-2}	2.1×10^2
	KR8F2	-	-

Note: 1 in = 2.54 cm, 1 ksi/in = 2.72 MPa/cm

Maximum closure and initial stiffness for samples RF3.

	Sample	Maximum Closure V_m (in)	Initial Normal Stiffness k_{ni} (ksi/in)
Before Shear		0.2×10^{-2}	1.9×10^2
After Shear	R1F3	0.9×10^{-2}	1.3×10^2
	R6F3	1.3×10^{-2}	1.2×10^2
	R4F3	0.2×10^{-2}	2.0×10^2
	R5F3	1.2×10^{-2}	1.2×10^2
	KR7F3	3.2×10^{-2}	0.9×10^2
	KR8F3	0.5×10^{-2}	1.9×10^2
	KR9F3	2.4×10^{-2}	0.6×10^2
	KR11F3	2.5×10^{-2}	0.8×10^2
	KR10F3	2.4×10^{-2}	0.8×10^2

Note: 1 in = 2.54 cm, 1 ksi/in = 2.72 MPa/cm

Maximum closure and initial stiffness for samples RF4.

	Sample	Maximum Closure V_m (in)	Initial Normal Stiffness k_{ni} (ksi/in)
Before Shear		2.9×10^{-2}	0.5×10^2
After Shear	R1F4	3.7×10^{-2}	0.6×10^2
	R2F4	2.5×10^{-2}	1.3×10^2
	R3F4	2.5×10^{-2}	0.7×10^2
	R4F4	2.8×10^{-2}	0.7×10^2
	R5F4	2.5×10^{-2}	0.9×10^2
	R6F4	2.2×10^{-2}	1.2×10^2
	R8F4	2.3×10^{-2}	1.5×10^2
	KR7F4	3.5×10^{-2}	1.6×10^2
	KR9F4	3.0×10^{-2}	0.8×10^2
	KR10F4	2.6×10^{-2}	0.9×10^2
	KR11F4	2.0×10^{-2}	1.0×10^2
	KR12F4	1.8×10^{-2}	0.9×10^2
	KR13F4	3.6×10^{-2}	0.9×10^2

Note: 1 in = 2.54 cm, 1 ksi/in = 2.72 MPa/cm

APPENDIX C1
PROFILES

SAMPLE	DESCRIPTION	PAGE
RG2	G2X2 Bottom Before Shear	C1-1
RG2	G2X3 Bottom Before Shear	C1-1
RG2	G2X2 Bottom After Shear, Normal Load = 12.8 kips	C1-2
RG2	G2X3 Bottom After Shear, Normal Load = 12.8 kips	C1-2
RF2	F2X2 Bottom Before Shear	C1-3
RF2	F2X3 Bottom Before Shear	C1-3
RF2	F2X2 Bottom After Shear, Normal Load = 5.9 kips	C1-4
RF2	F2X3 Bottom After Shear, Normal Load = 5.9 kips	C1-4
RF3	F3X2 Bottom Before Shear	C1-5
RF3	F3X3 Bottom Before Shear	C1-5
RF3	F3X2 Bottom After Shear, Normal Load = 0.8 kips	C1-6
RF3	F3X3 Bottom After Shear, Normal Load = 0.8 kips	C1-6
RF4	F4X2 Bottom Before Shear	C1-7
RF4	F4X3 Bottom Before Shear	C1-7
RF4	F4X2 Bottom After Shear, Normal Load = 7.2 kips	C1-8
RF4	F4X3 Bottom After Shear, Normal Load = 7.2 kips	C1-8

Profile G2X2 Bottom

Before Shear

Profile G2X3 Bottom

Before Shear

Profile G2X2 Bottom
After Shear, Normal Load = 12.8 Kips

Profile G2X3 Bottom
After Shear, Normal Load = 12.8 Kips

Profile F2X2 Bottom Before Shear

Profile F2X3 Bottom Before Shear

Profile F2X2 Bottom
After Shear, Normal Load = 5.90 Kips

Profile F2X3 Bottom
After Shear, Normal Load = 5.90 Kips

Profile F3X2 Bottom Before Shear

Profile F3X3 Bottom Before Shear

Profile F3X2 Bottom

After Shear, Normal Load=0.8 Kips

Profile F3X3 Bottom

After Shear, Normal Load=0.8 Kips

Profile F4X2 Bottom

Before Shear

Profile F4X3 Bottom

Before Shear

Profile F4X2 Bottom
After Shear, Normal Load = 7.2 Kips

Profile F4X3 Bottom
After Shear, Normal Load = 7.2 Kips

APPENDIX C2
FRACTAL DIMENSION TABLES

SAMPLE	DESCRIPTION	PAGE
RG2	G2X2 Bottom	C2 - 1
RG2	G2X3 Bottom	C2 - 1
RG2	G2X3 Top	C2 - 2
RG2	G2X3 Top	C2 - 2
RF2	F2X2 Bottom	C2 - 3
RF2	F2X3 Bottom	C2 - 3
RF2	F2X2 Top	C2 - 4
RF2	F2X3 Top	C2 - 4
RF3	F3X2 Bottom	C2 - 5
RF3	F3X3 Bottom	C2 - 5
RF3	F3X2 Top	C2 - 6
RF3	F3X3 Top	C2 - 6
RF4	F4X2 Bottom	C2 - 7
RF4	F4X3 Bottom	C2 - 8
RF4	F4X2 Top	C2 - 9
RF4	F4X3 Top	C2 - 10

Fractal Dimension for G2X2 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.21
After Shear			
R1G2	1.3	0	1.11
R4G2	6.4	0	1.11
R2G2	12.8	0	1.09
R3G2	25.6	0	1.08
KR5G2	1.3	32.0	1.09
KR6G2	6.4	64.0	1.09

Fractal Dimension for G2X3 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.19
After Shear			
R1G2	1.3	0	1.65
R4G2	6.4	0	1.13
R2G2	12.8	0	1.11
R3G2	25.6	0	1.13
KR5G2	1.3	32.0	1.19
KR6G2	6.4	64.0	1.10

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for G2X2 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.15
After Shear			
R1G2	1.3	0	1.10
R4G2	6.4	0	1.16
R2G2	12.8	0	1.14
R3G2	25.6	0	1.13
KR5G2	1.3	32.0	1.20
KR6G2	6.4	64.0	1.19

Fractal Dimension for G2X3 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.23
After Shear			
R1G2	1.3	0	1.21
R4G2	6.4	0	1.32
R2G2	12.8	0	1.16
R3G2	25.6	0	1.13
KR5G2	1.3	32.0	1.13
KR6G2	6.4	64.0	1.15

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F2X2 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.15
After Shear			
R5F2	0.6	0	1.13
R2F2	3.0	0	1.07
R3F2	5.9	0	1.06
R4F2	11.8	0	1.05
KR6F2	3.0	14.8	1.09
KR7F2	3.0	44.3	1.08
KR8F2	3.0	147.8	1.08

Fractal Dimension for F2X3 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.16
After Shear			
R5F2	0.6	0	1.16
R2F2	3.0	0	1.13
R3F2	5.9	0	1.15
R4F2	11.8	0	1.14
KR6F2	3.0	14.8	1.15
KR7F2	3.0	44.3	1.14
KR8F2	3.0	147.8	1.12

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F2X2 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.15
After Shear			
R5F2	0.6	0	1.16
R2F2	3.0	0	1.16
R3F2	5.9	0	1.12
R4F2	11.8	0	1.25
KR6F2	3.0	14.8	1.15
KR7F2	3.0	44.3	1.09
KR8F2	3.0	147.8	1.11

Fractal Dimension for F2X3 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.13
After Shear			
R5F2	0.6	0	1.16
R2F2	3.0	0	1.16
R3F2	5.9	0	1.14
R4F2	11.8	0	1.11
KR6F2	3.0	14.8	1.17
KR7F2	3.0	44.3	1.11
KR8F2	3.0	147.8	1.07

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F3X2 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.14
After Shear			
R1F3	0.8	0	1.09
R6F3	3.8	0	1.11
R4F3	7.5	0	1.12
R5F3	15.0	0	1.09
KR7F3	3.8	18.8	1.10
KR8F3	3.8	56.3	1.10
KR9F3	3.8	187.5	1.10
KR10F3	7.5	56.3	1.09
KR11F3	7.5	187.5	1.11

Fractal Dimension for F3X3 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.09
After Shear			
R1F3	0.8	0	1.08
R6F3	3.8	0	1.05
R4F3	7.5	0	1.12
R5F3	15.0	0	1.11
KR7F3	3.8	18.8	1.07
KR8F3	3.8	56.3	1.07
KR9F3	3.8	187.5	1.10
KR10F3	3.8	56.3	1.10
KR11F3	3.8	187.5	1.10

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F3X2 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.11
After Shear			
R1F3	0.8	0	1.10
R6F3	3.8	0	1.10
R4F3	7.5	0	1.12
R5F3	15.0	0	1.09
KR7F3	3.8	18.8	1.12
KR8F3	3.8	56.3	1.08
KR9F3	3.8	187.5	1.06
KR10F3	7.5	56.3	1.11
KR11F3	7.5	187.5	1.06

Fractal Dimension for F3X3 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.09
After Shear			
R1F3	0.8	0	1.08
R6F3	3.8	0	1.06
R4F3	7.5	0	1.06
R5F3	15.0	0	1.11
KR7F3	3.8	18.8	1.08
KR8F3	3.8	56.3	1.05
KR9F3	3.8	187.5	1.06
KR10F3	3.8	56.3	1.09
KR11F3	3.8	187.5	1.05

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F4X2 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.13
After Shear			
R1F4	0.7	0	1.12
R2F4	3.6	0	1.11
R3F4	7.2	0	1.11
R4F4	10.8	0	1.11
R5F4	14.4	0	1.10
R6F4	10.8	0	1.11
R8F4	10.8	0	1.11
KR7F4	3.6	18.0	1.11
KR9F4	3.6	54.0	1.11
KR10F4	3.6	180.0	1.11
KR11F4	7.2	54.0	1.10
KR12F4	7.2	180.0	1.15
R13F3	3.6	0	1.11

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F4X3 Bottom.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.12
After Shear			
R1F4	0.7	0	1.11
R2F4	3.6	0	1.10
R3F4	7.2	0	1.07
R4F4	10.8	0	1.08
R5F4	14.4	0	1.09
R6F4	10.8	0	1.10
R8F4	10.8	0	1.07
KR7F4	3.6	18.0	1.11
KR9F4	3.6	54.0	1.10
KR10F4	3.6	180.0	1.06
KR11F4	7.2	54.0	1.08
KR12F4	7.2	180.0	1.10
R13F3	3.6	0	1.08

Note: 1 kip = 4.448 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F4X2 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.18
After Shear			
R1F4	0.7	0	1.10
R2F4	3.6	0	1.08
R3F4	7.2	0	1.08
R4F4	10.8	0	1.11
R5F4	14.4	0	1.12
R6F4	10.8	0	1.08
R8F4	10.8	0	1.08
KR7F4	3.6	18.0	1.11
KR9F4	3.6	54.0	1.07
KR10F4	3.6	180.0	1.14
KR11F4	7.2	54.0	1.07
KR12F4	7.2	180.0	1.15
R13F3	3.6	0	1.07

Note: 1 kip = 4.45 kN, 1 kip/in = 1.75 kN/cm

Fractal Dimension for F4X3 Top.

Sample	Normal Load (kips)	Constant Stiffness (kips/in)	Fractal Dimension
Before Shear			1.15
After Shear			
R1F4	0.7	0	1.14
R2F4	3.6	0	1.10
R3F4	7.2	0	1.06
R4F4	10.8	0	1.07
R5F4	14.4	0	1.07
R6F4	10.8	0	1.05
R8F4	10.8	0	1.06
KR7F4	3.6	18.0	1.09
KR9F4	3.6	54.0	1.09
KR10F4	3.6	180.0	1.11
KR11F4	7.2	54.0	1.14
KR12F4	7.2	180.0	1.10
R13F3	3.6	0	1.11

Note: 1 kip = 4.45kN, 1 kip/in = 1.75 kN/cm

APPENDIX

Information from the Reference Information Base Used in this Report

This report contains no information from the Reference Information Base.

Candidate Information for the Reference Information Base

This report contains no candidate information for the Reference Information Base.

Candidate Information for the Geographic Nodal Information Study and Evaluation System

This report contains no candidate information for the Geographic Nodal Information Study and Evaluation System.

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