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6. AUTHOR(S)
Barrie Brickle
Russell Walker

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Transportation Technology Center, Inc.
P.O. Box 11130
Pueblo, CO 81001

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13. ABSTRACT

A full-scale locomotive impact test was performed August 1, 2002. The test involved a SD-45 locomotive, modified to meet AAR Specification S-580, and three trailing loaded hopper cars impacting a stationary consist of 35 loaded hopper cars at 32 mph.

There was a large amount of damage to the pilot plate, snowplow, and coupler housing of the locomotive, which climbed up onto the leading hopper car and came to rest at an angle of about 7 degrees. The collision posts and cab of the locomotive were undamaged. The first stationary hopper car was completely destroyed with the sides peeled back by the impacting locomotive. The center sill of the hopper car immediately behind the locomotive was cracked and bent down at the end about 3 inches. The other hopper cars were undamaged and all remained upright.

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Sharma and Associates designed the cab and modifications to the locomotive, which were carried out by National Rail Equipment.

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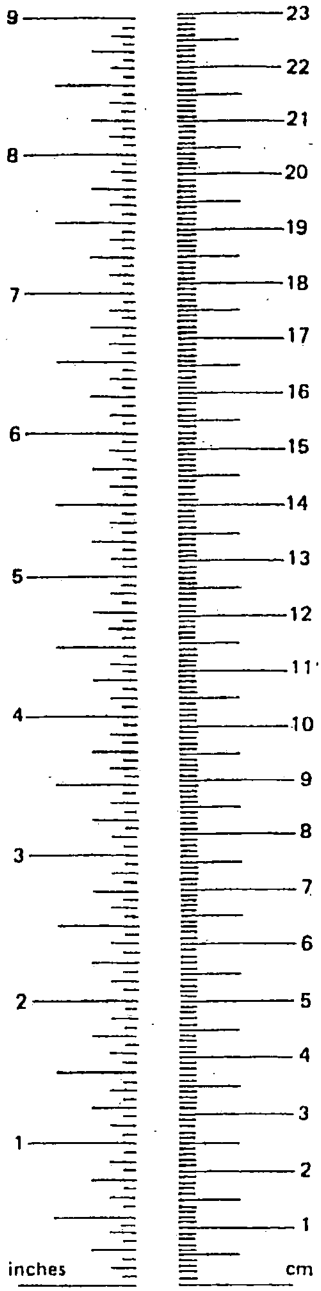
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km
		AREA		
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	m^2
mi^2	square miles	2.60	square kilometers	km^2
	acres	0.40	hectares	ha
		MASS (weight)		
oz	ounces	28.00	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.90	tonnes	t
		VOLUME		
tsp	teaspoons	5.00	milliliters	ml
Tbsp	tablespoons	15.00	milliliters	ml
fl oz	fluid ounces	30.00	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.80	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0 76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



* 1 in. = 2.54 cm (exactly)

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol

LENGTH

mm	millimeters	0.04	inches	in
cm	centimeters	0.40	inches	in
m	meters	3.30	feet	ft
m	meters	1.10	yards	yd
km	kilometers	0.60	miles	mi

AREA

cm^2	square centim.	0.16	square inches	in^2
m^2	square meters	1.20	square yards	yd^2
km^2	square kilom.	0.40	square miles	mi^2
ha	hectares (10,000 m^2)	2.50	acres	

MASS (weight)

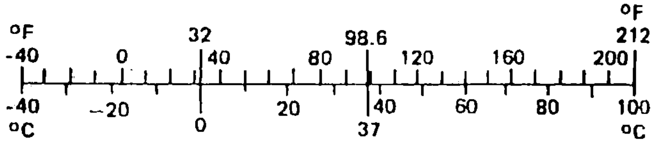
g	grams	0.035	ounces	oz
kg	kilograms	2 2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.10	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36.00	cubic feet	ft^3
m^3	cubic meters	1.30	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius° temperature	9/5 (then add 32	Fahrenheit temperature	°F



Executive Summary

A full-scale locomotive impact test was performed August 1, 2002, at the Federal Railroad Administration's (FRA) Transportation Technology Center, Pueblo, Colorado. The test involved a SD-45 locomotive, modified to meet AAR Specification S-580, and three trailing loaded hopper cars impacting a stationary consist of 35 loaded hopper cars at 32 mph.

There was a large amount of damage to the pilot plate, snowplow, and coupler housing of the locomotive, which climbed up onto the leading hopper car and came to rest at an angle of about 7 degrees. The collision posts and cab of the locomotive were undamaged. The first stationary hopper car was completely destroyed with the sides peeled back by the impacting locomotive. The center sill of the hopper car immediately behind the locomotive was cracked and bent down at the end about 3 inches. The other hopper cars were undamaged and all remained upright.

The test was done to evaluate the structural crashworthiness of the locomotive by carrying out an impact test based on an historical accident. The onboard instrumentation will allow correlation with analytical predictions.

Strains, displacements, and accelerations were measured on the locomotive and hopper cars during the impact to allow correlation of test results with analytical predictions. Tri-axial accelerometers were placed on the locomotive floor, the event recorder, the first and second moving hopper car, and the first and second stationary hopper car. Longitudinal, lateral, and vertical displacements were measured on each coupler between the locomotive and the first moving hopper car. Longitudinal, lateral, and vertical displacements were measured on each coupler between the first and second stationary hopper cars. The force between the locomotive and first moving hopper car was measured with an instrumented coupler. Strains were measured on the collision posts, the center post of the windshield, and the underframe of the locomotive. An anthropomorphic test device was placed in the locomotive engineer's seat. Foster-Miller Inc. will use all the test measurements to validate the analytical model of the collision.

Transportation Technology Center, Inc. carried out the planning and execution of the test. Under separate contracts with the FRA, Sharma & Associates designed the locomotive modifications, National Rail Equipment made the modifications to the locomotive, and Foster Miller, Inc. coordinated the technical requirements and performed analytical modeling of the impact.

Main Results

- The maximum longitudinal acceleration recorded on the floor of the locomotive was 200 g. When filtered to a corner frequency (Fc) of 100 Hz, the peak acceleration was reduced to 40 g.
- The maximum lateral acceleration recorded on the floor of the locomotive was 110 g. When filtered to Fc = 100 Hz, the peak acceleration was reduced to 17 g.

- The maximum vertical acceleration recorded on the floor of the locomotive was 250 g. When filtered to Fc = 100 Hz, the peak acceleration was reduced to 55 g.
- The maximum longitudinal acceleration recorded on the event recorder was 160 g. When filtered to Fc = 100 Hz, the peak acceleration was reduced to 32 g.
- The maximum lateral acceleration recorded on the event recorder was 140 g. When filtered to Fc = 100 Hz, the peak acceleration was reduced to 14 g.
- The maximum vertical acceleration recorded on the event recorder was 150 g. When filtered to Fc = 100 Hz, the peak acceleration was reduced to 23 g.
- A peak load of more than 1,700,000 pounds was recorded in the instrumented coupler between the locomotive and the first hopper car. The instrumented coupler saturated at this load.
- A maximum strain of 1,570 microstrain was measured on the collision posts of the locomotive during the impact.
- A maximum strain of -2,072 microstrain was measured on the underframe of the locomotive during the impact.
- The maximum chest acceleration was 14.5 g, which meets the recommended National Highway Transportation Safety Association (NHTSA)[1] criterion of 60 g. NHTSA also recommends a criterion for chest deflection, but that was not measured in this test.
- The peak tension in the neck was 253 N, which meets the recommended NHTSA criterion of 4,170 N.
- The peak compression in the neck was 427 N, which meets the recommended NHTSA criterion of 4,000 N.
- The neck injury criteria, Nij, was 0.26, which meets the recommended NHTSA criterion of 1.
- The Head Injury Criterion (15 msec) was 11, which meets the NHTSA criterion of 700.
- The maximum femur load was 4.6 kN, which meets the NHTSA criterion of 10kN.

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[1] Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II. National Highway Traffic Safety Administration, National Transportation Biomechanics Research Center and Vehicle Research and Test Center, March 2000.

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1.0 INTRODUCTION AND OBJECTIVES

Transportation Technology Center, Inc. (TTCI) performed a full-scale train-to-train impact test August 1, 2002. The test involved an SD-45 locomotive, modified to meet AAR Specification S-580, and three trailing loaded hopper cars impacting a stationary consist of 35 loaded hopper cars at 32 mph.

The purpose of the test was to evaluate the structural crashworthiness of the locomotive and to measure strains, accelerations, and displacements during the impact so that computer models of the locomotive and hopper cars can be validated. The acceleration levels in the crew compartment were measured as well as the head, neck, and chest accelerations on an anthropomorphic test device (ATD) in the driver's seat of the locomotive.

2.0 DESCRIPTION OF TEST LOCOMOTIVE AND HOPPER CARS

The locomotive used for this test was a modified SD-45, with a cab and nose structure designed by Sharma & Associates, and manufactured by National Rail Equipment to represent a SD-70 MAC front end structure (Figure 1).

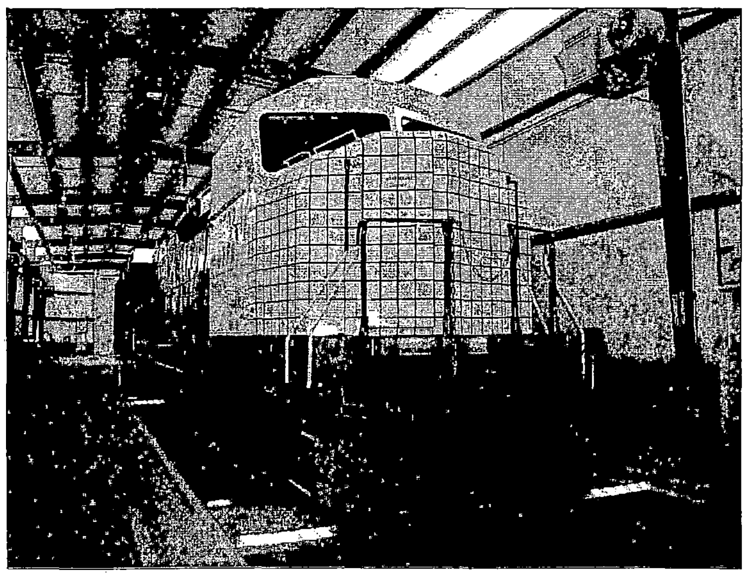

Figure 1. Test Locomotive

The locomotive nose and cab were designed to conform to AAR Specification S-580. A mock console was fitted in the cab, and a driver's seat was mounted on the floor behind the console. An ATD was positioned in the driver's seat as Figure 2 shows.

Figure 2. Console and ATD

An event recorder was mounted behind one of the collision posts of the locomotive facing rearward. A tri-axial accelerometer was mounted near the recorder so that it measured the accelerations going into the event recorder (see Figure 3).

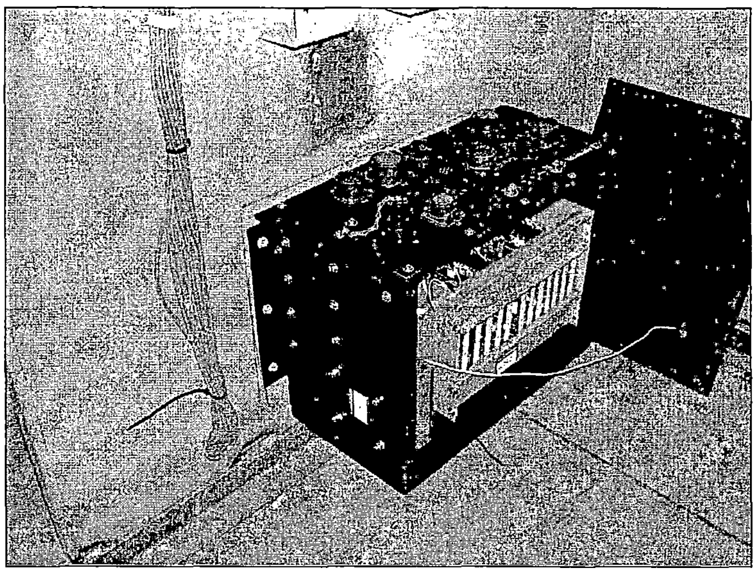

Figure 3. Event Recorder and Accelerometer Mount

The couplers were left installed at the impact ends of both the locomotive and the leading stationary hopper car. Flat plates were welded to the front of each coupler in order to mount Tape Switches™ to trigger the instrumentation at impact. An instrumented coupler was fitted between the locomotive and the first hopper car.

Tri-axial accelerometers were mounted in the center of the center sill of the first two hopper cars behind the locomotive and on the first two stationary hopper cars.

String potentiometers were mounted on the rear of the locomotive and at the leading end of the first moving hopper car in order to measure the coupler displacements. String potentiometers were also mounted between the coupler and the carbodies of the first two stationary hopper cars as Figure 4 shows.

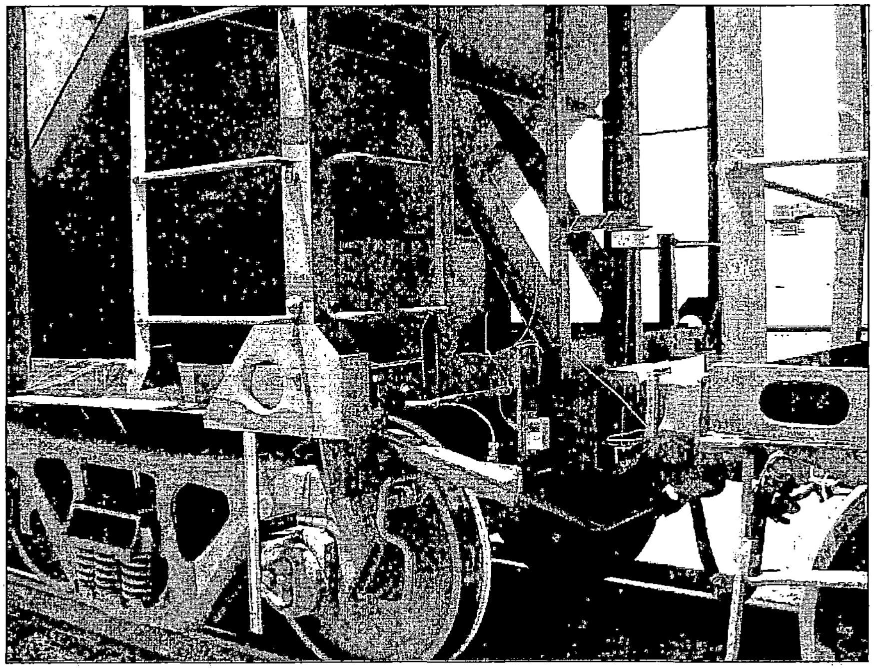

Figure 4. String Potentiometers

3.0 TEST METHODOLOGY

The test was performed at the FRA's Transportation Technology Center (TTC), Pueblo, Colorado, according to the procedures outlined in the Test Implementation Plan for the train-to-train test, included as the appendix of this report.

The Impact Test was performed by pushing the moving test consist (locomotive and three loaded hopper cars) with a locomotive, releasing it at a pre-determined point, then letting it run along the track into the stationary consist (35 loaded hopper cars). The stationary hopper cars were bunched up before the test.

The release distance and the speed of the moving consist at release were calculated from a series of speed calibration tests completed before the test. Simulation calculations were also performed using TOES™ (TTCI's train action model) based on the actual track profile. The target speed for the test was 32 mph.

4.0 RESULTS

4.1 Items Measured Before The Test

4.1.1 Lengths

Moving Consist

Length of locomotive over the ends of the anti-climbers = 70 ft
Length of first hopper car over strikers = 47 ft 5 in.
Length of second hopper car over strikers = 46 ft 5 in.
Length of third hopper car over strikers = 51 ft 5 in.

Stationary Consist

Length of first hopper car over strikers =52 ft 2 in.
Length of second hopper car over strikers = 46 ft
Length of third hopper car over strikers = 47 ft 2 in.
Length of fourth hopper car over strikers = 51 ft 8 in.

4.1.2 Weights

Moving Consist

Weight of locomotive = 381,769 lb
Weight of first hopper car = 264,414 lb — NW 1400~~?~~88
Weight of second hopper car = 267,439 lb
Weight of third hopper car = 264,684 lb

Total weight = 1,178,306 lb

Stationary Consist

Weight of first hopper car = 275,018 lb
Weight of second hopper car = 265,801 lb
Weight of third hopper car = 264,649 lb
Weight of fourth hopper car = 166,122 lb UP 41318

Total weight of 35 car train = 9,418,000 lb

(Note: The accuracy of the weighbridge is within 50 lb. Only the first four cars of the target train were weighed immediately before the test, the weight of the rest of the train was calculated from earlier records.)

4.1.3 Weather Conditions

Weather conditions just before the test:

- Temperature = 79°F
- Wind speed = 13 mph from the east

4.1.4 Photographs Taken Before Test

Photographs showing the vehicles, before impact, are shown in Figures 5 and 6.

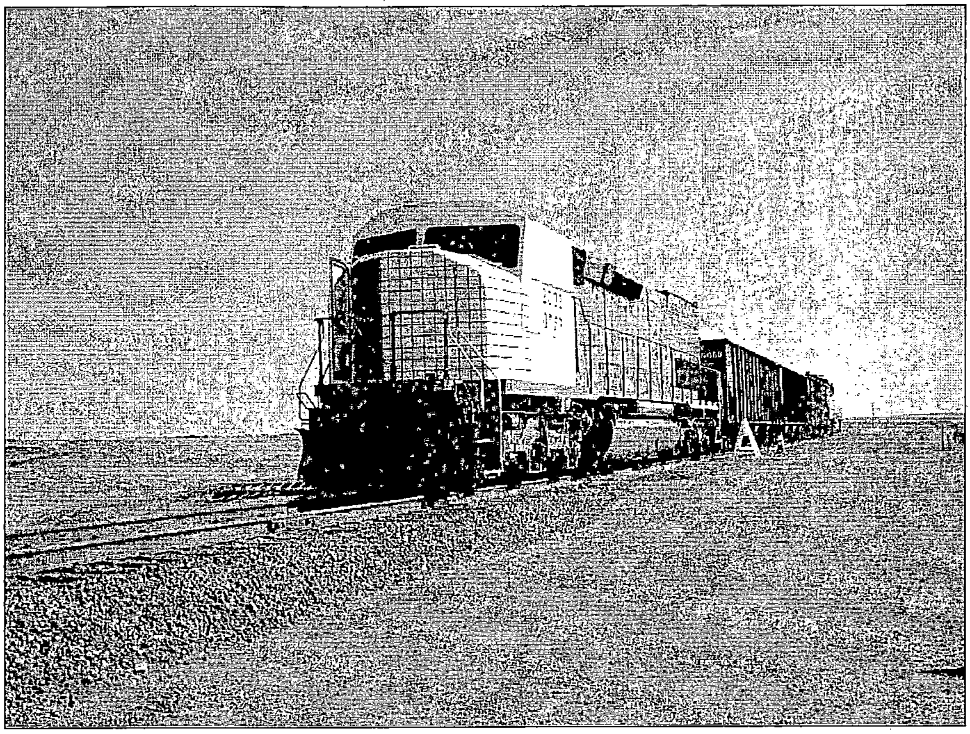

Figure 5. Locomotive and Moving Consist before Impact

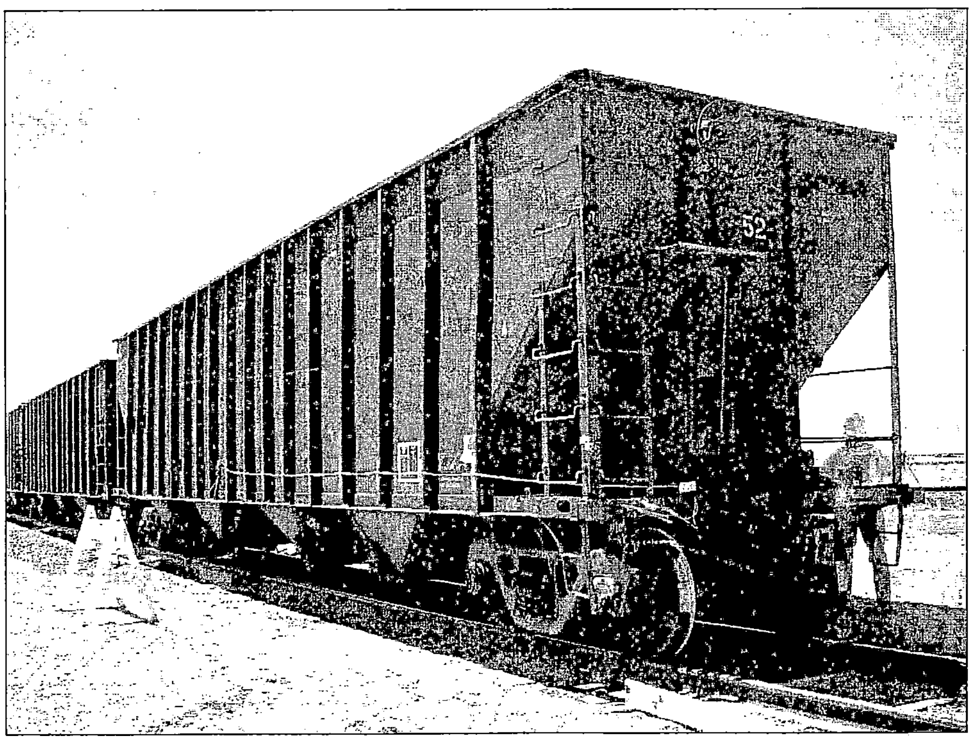

Figure 6. Stationary Hopper Cars before Impact

4.2 Items Measured During The Test

The following anomalies occurred with the data acquisition system:

- Three strain gauges showed some indication of loose electrical connections during the period of data acquisition: CPLR3_2, CPRS4, and URMF.
- The data from string potentiometers TH1_CBY appeared to show the effects of a noisy potentiometer or a loose electrical connection in the wiring.
- The data from the chest x-axis accelerometer showed a possible electrical failure before the end of the data acquisition period.

4.2.1 Speed

The test cars were accelerated from the test train by a locomotive and released at a point 1,500 feet from the front of the stationary locomotive. The speed of the consist just before impact, as measured by the laser based speed trap, was:

Laser 1	47.04 ft/s
Laser 2	47.05 ft/s
Average	47.045 ft/s = 32.1 mph

4.2.2 Strains

The Data Bricks measuring strain were set for a sampling rate of 12,800 Hz, a pre-trigger of 1 s and post-trigger of 4 s. Positive values show tension and negative values show compression.

For the rosette strain gauges on the collision post the following convention is used:

Right collision post:	Direction 1 = Vertical
	Direction 2 = Diagonal
	Direction 3 = Longitudinal
Left collision post:	Direction 1 = Longitudinal
	Direction 2 = Diagonal
	Direction 3 = Vertical

Figures 7 and 8 show the locations of the strain gages on the left and right cornerpost respectively. The highest magnitude strain measured in the test is shown next each strain gage.

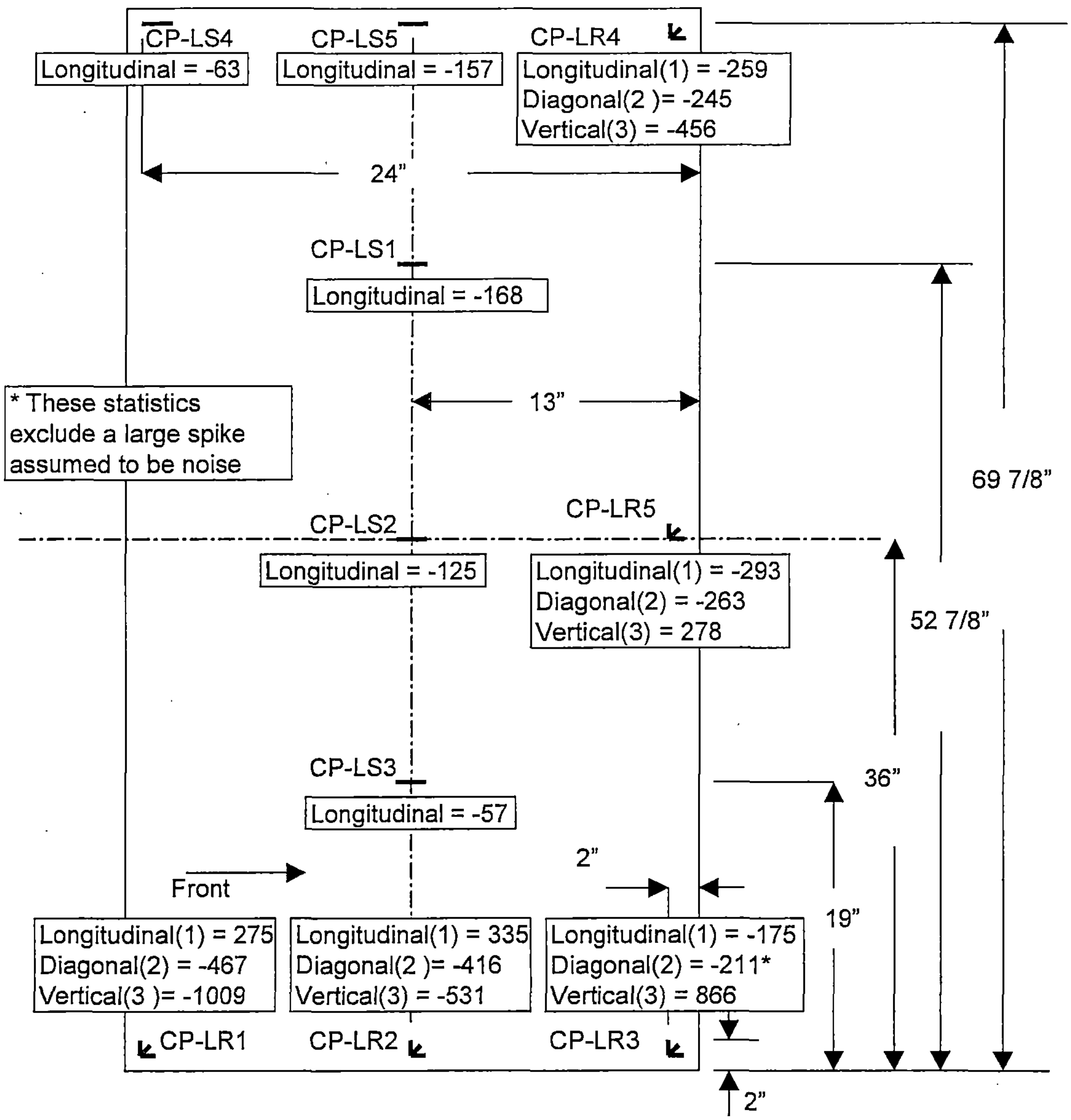

Figure 7. Left Collision Post, Location of Strain Gages and Largest Amplitude Strain (ustr)

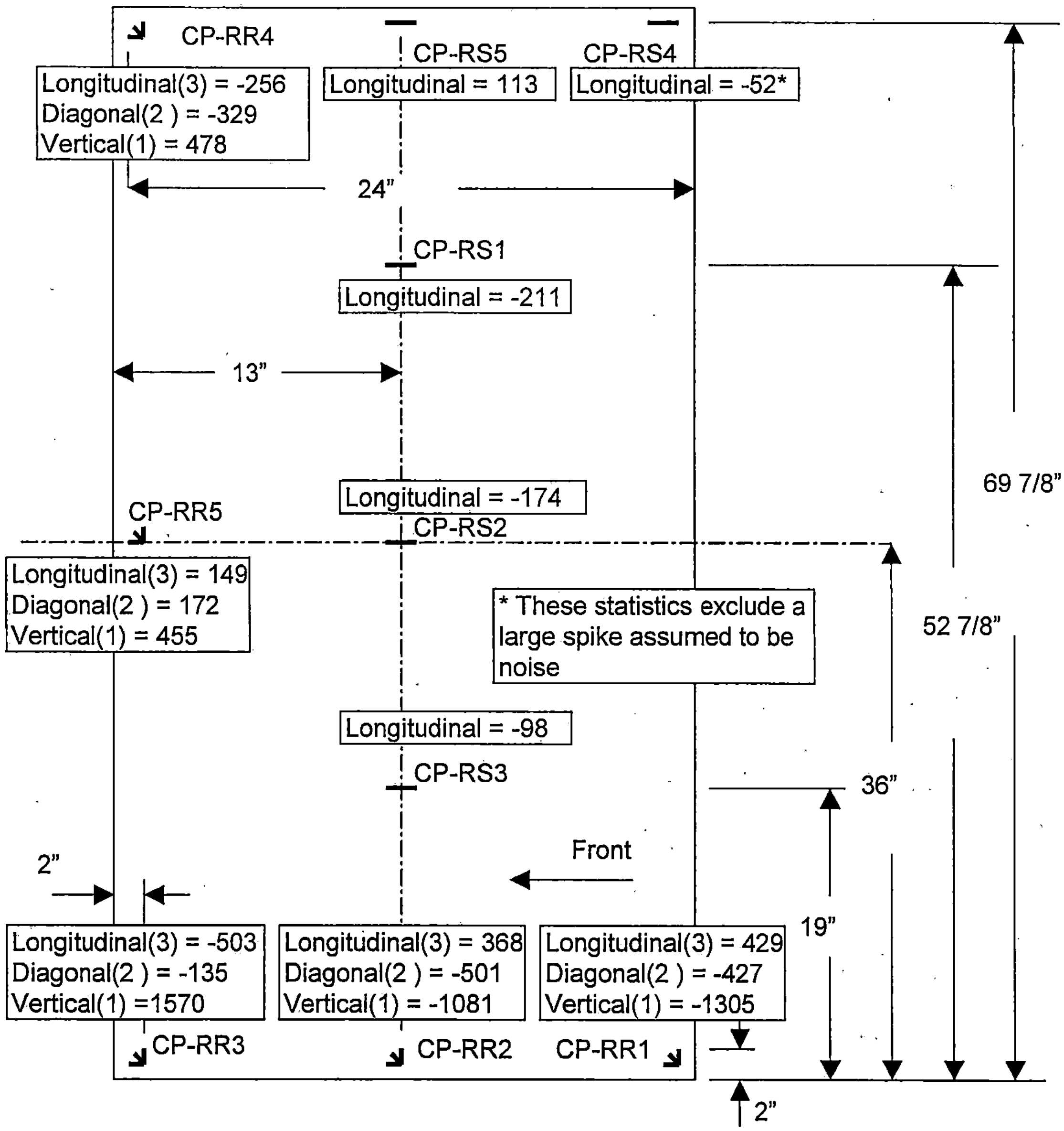

Figure 8. Right Collision Post, Location of Strain Gages and Largest Amplitude Strain (ustr)

The largest strain on the collision posts was 1,570 microstrain on the vertical leg of the bottom front rosette on the right collision post.

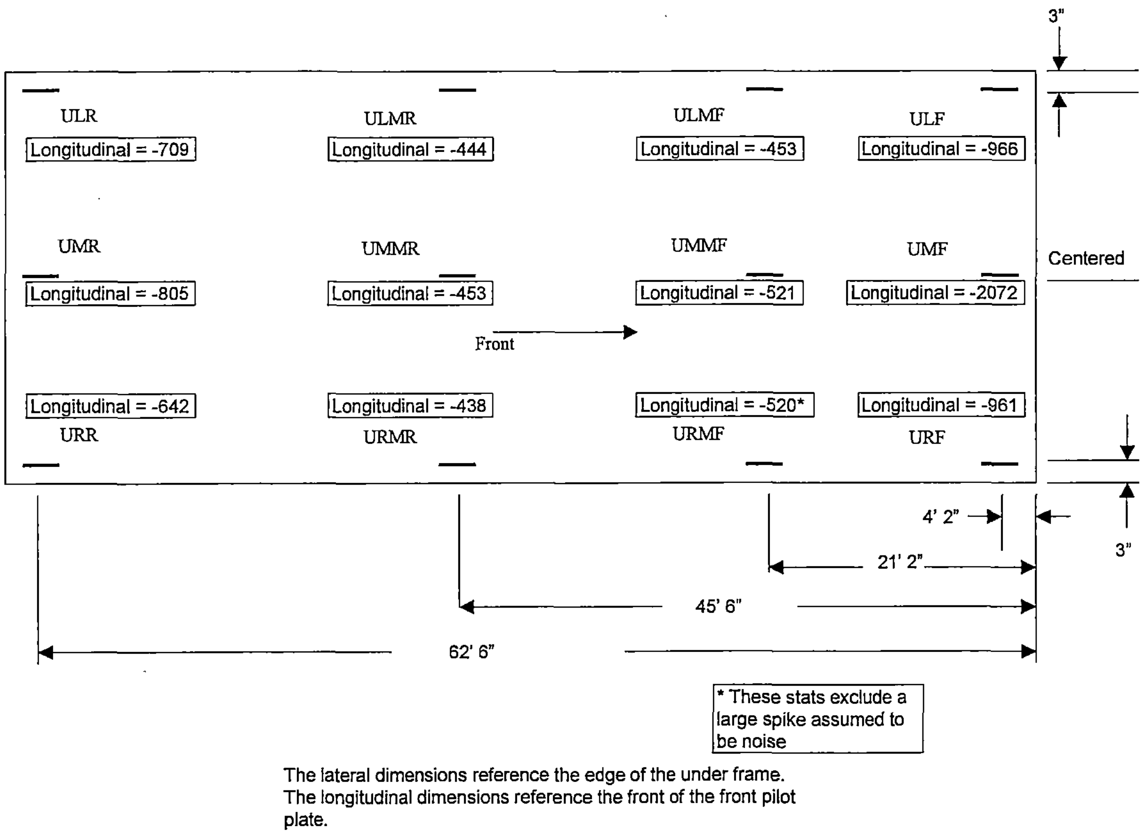

Figure 9. Underframe of Locomotive, Location of Strain Gages and Largest Amplitude Strain (ustr)

The largest magnitude strain on the underframe was –2,072 microstrain in the center of the leading row of gages (channel UMF). This gage was directly behind the leading draft pocket.

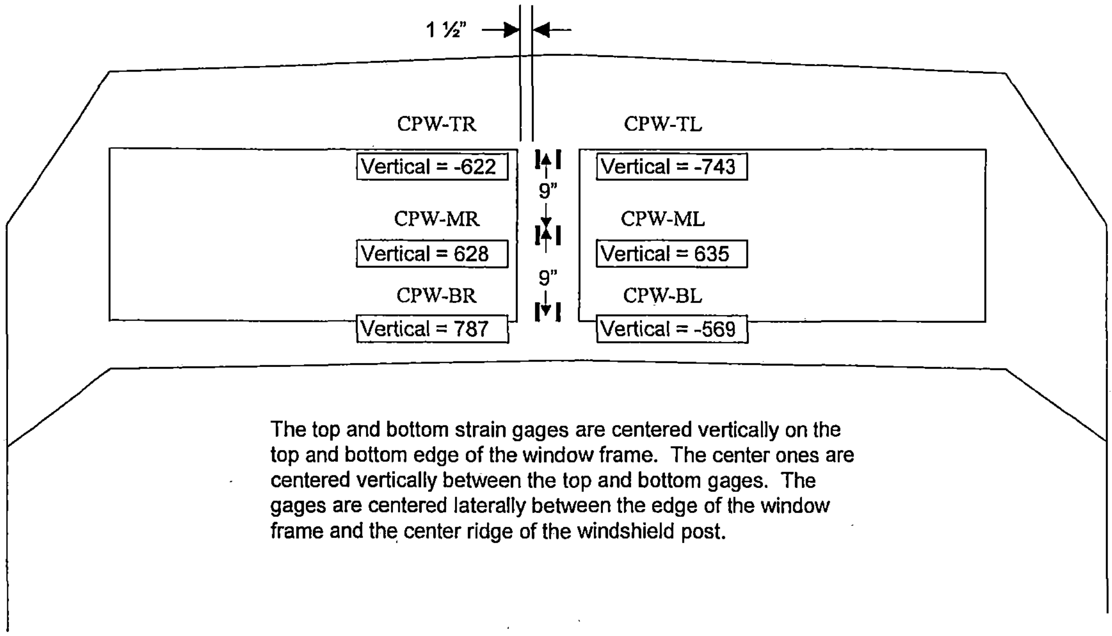

Figure 10. Window Frame, Location of Strain Gages and Largest Amplitude Strain (ustr)

The largest magnitude strain on the window center post was 787 microstrain. This occurred on the bottom right hand gage.

Strain-gauge time histories are included in Appendix F.

4.2.3 Accelerations

Acceleration channels were filtered at 1,735 Hz and sampled at 12,800 Hz. Data was digitally filtered with a phase-less 4-pole Butterworth filter as specified in SAE J211 Appendix C. Digital filer frequencies were CFC=1000Hz (Fc=1667Hz), Fc=100Hz, and Fc=25Hz. The sign convention for accelerometers is:

- Longitudinal, positive is forward acceleration
- Lateral, positive is rightward acceleration
- Vertical, positive is downward acceleration

The highest amplitude acceleration at each location is shown in Table 1. These statistics were computed from –0.5s to 3.5s for all locations except the target hopper 1 data. The accelerometers on target hopper 1 saturated at 651 milliseconds so those statistics were computed between –0.5s and 0.6s. Time plots of each channel are shown in:

- Appendix B for 1000Hz data
- Appendix C for 100Hz data
- Appendix D for 25Hz data

The Test Implementation Plan, Appendix A, shows the positions of the individual accelerometers.

Table 1. Largest Amplitude Accelerations at each Location

Direction	Locomotive Cab Floor	Event Recorder	Bullet Hopper 1	Bullet Hopper 2	Target Hopper 1	Target Hopper 2
X CFC=1000Hz	197.6	-163.7	-75.7	-42.0	-195.9	33.3
X F_c =100	-40.2	-33.8	-9.1	-13.6	-25.1	-10.3
X F_c =25	-3.9	-5.3	-7.4	-6.9	-7.1	-8.0
Y CFC=1000Hz	118.3	-139.8	-33.4	-19.6	-106.1	-33.2
Y F_c =100	-17.3	-14.3	-1.9	-2.0	-15.4	2.2
Y F_c =25	1.8	-7.0	0.3	-0.3	-7.3	0.4
Z CFC=1000Hz	251	-150.1	72.6	-44.5	-79.1	37.0
Z F_c =100	-54.7	22.7	3.2	-11.0	11.4	5.1
Z F_c =25	-5.5	7.2	-1.7	-3.6	6.1	-3.0

It is apparent that the magnitude of the accelerations is very dependant on the filter frequency. Use of the time plots in the appendices to compare this data with other test or model results is suggested.

4.2.4 Displacements

The relative displacements (in each direction) between the locomotive and its trailing-end coupler, the leading-end coupler of the first hopper car, and the hopper car body were measured using string potentiometers. The sign convention for the stringpots is:

- Locomotive Longitudinal, + = Coupler extending, (BL_CBX)
- Locomotive Lateral, + = Coupler moving right in pocket (forward facing), (BL_CBY)
- Locomotive Vertical, + = Coupler drooping downward, (BL_CBZ)
- Bullet Hopper 1 Longitudinal, + = Coupler extending, (BH1_CAX)
- Bullet Hopper 1 Lateral, + = Coupler moving left in pocket (forward facing), (BH1_CAY)
- Buller Hopper 1 Vertical, + = Coupler drooping downward, (BH1_CAZ)
- Target Hopper 1 Longitudinal, + = Coupler extending, (TH1_CBX)
- Target Hopper 1 Lateral, + = Coupler moving right in pocket (forward facing), (TH1_CBY)
- Target Hopper 1 Vertical, + = Coupler drooping downward, (TH1_CBZ)
- Target Hopper 2 Longitudinal, + = Coupler extending, (TH2_CBX)
- Target Hopper 2 Lateral, + = Coupler moving left in pocket (forward facing), (TH2_CBY)
- Target Hopper 2 Vertical, + = Coupler drooping downward, (TH2_CBZ)

The relative displacements (in each direction) between the couplers of the first two stationary hopper cars were also measured using string potentiometers. The largest amplitude displacements for each channel are shown in Table 2.

Table 2. Largest Amplitude Coupler Displacements

Direction	Locomotive	Bullet Hopper	Target Hopper 1	Target Hopper 2
Longitudinal	-2.6	-3.8	-3.2	-2.9
Lateral	-1.0	0.5	Cable Failure	-0.3
Vertical	-1.6	3.5	2.6	0.7

The couplers all bottomed out longitudinally during the impact. There was very little lateral coupler displacement. The large vertical displacement of the coupler on the bullet hopper which trailed the locomotive is likely due to the failure of the centersill, which was bent downward about 3 inches during the test.

Time plots of each displacement channel are shown in Appendix E.

4.2.5 Longitudinal Force In Coupler

The Data Bricks were set for a sampling rate of 12,800 Hz. The coupler at the leading end of the first moving hopper car was strain gauged and calibrated so that the longitudinal force could be measured. The coupler force saturated at 1,700 kips. After the test the strain gages had a permanent offset indicating that there was yielding of the coupler. A time plot of the coupler force channel is shown in Appendix E.

4.2.6 Anthropomorphic Test Device

An anthropomorphic test device was placed in the locomotive engineer's seat during the test. Tri-axial accelerometers were placed in the head and chest, a six-axis load cell measured neck forces, and two uniaxial load cells measured femur loads. Data was filtered at 1,734 Hz and sampled at 12,800 Hz. Data was digitally filtered with a four-pole Butterworth filter as specified in SAE J211 Appendix C as follows.

- Head Accelerations – Unfiltered
- Chest Accelerations – CFC 180Hz
- Neck Forces – Unfiltered
- Neck Moments – CFC 600Hz
- Femur Loads – CFC 600Hz

The magnitude of the vector sum accelerations was computed for the head and chest. Head accelerations were used to compute the Head Injury Criterion (HIC) described in reference 1. The neck injury criteria described in reference 1 was computed using the neck loads and moments. The ATD data is compared to the NHTSA proposed criteria in Table 3.

Table 3. Comparison of ATD data to NHTSA Proposed Criteria

Criteria	Criteria for Hybrid III Dummy 50% Male	Test Results
Head Criteria (HIC 15msec)	700	11
Neck Criteria: Nij In Position Critical Intercept Values Tension (N) Compression (N) Flexion (Nm) Extension (Nm) Peak Tension (N) Peak Compression (N)	1.0 6806 6160 310 135 4170 4000	0.26 253 427
Thoracic Criteria Chest Acceleration Chest Deflection	 60 63	 14.5 Not Measured
Lower Ext. Criteria Femur Load (kN)	 10.0	 4.6

All of the test results were considerably below the NHTSA proposed criteria. Time plots of the data are shown in Appendix G.

4.2.7 Photography

The Impact Test was visually recorded with five high-speed film cameras and six video cameras. Camera coverage was selected to provide views of both the left and right sides of the vehicles, overhead views, an overall view of the impact, and included a video camera in the cab of the locomotive.

The film and video camera positions are shown in Figure 4 of Appendix A.

4.3 Items Measured After The Test

The second hopper car in the target train moved approximately 195 inches from its starting location. The last hopper car in the target train moved about 102 inches from its starting location. The locomotive came to rest with its lead truck inside the hopper car at an angle of about 7 degrees. Figures 4.3.1 through 4.3.3 show the locomotive just after impact. Figure 4.3.4 shows the ATD after impact. The data recorder is shown in Figure 4.3.4. Figures 4.3.5 through 4.3.7 show the locomotive and trucks as they are being removed from the hopper car.

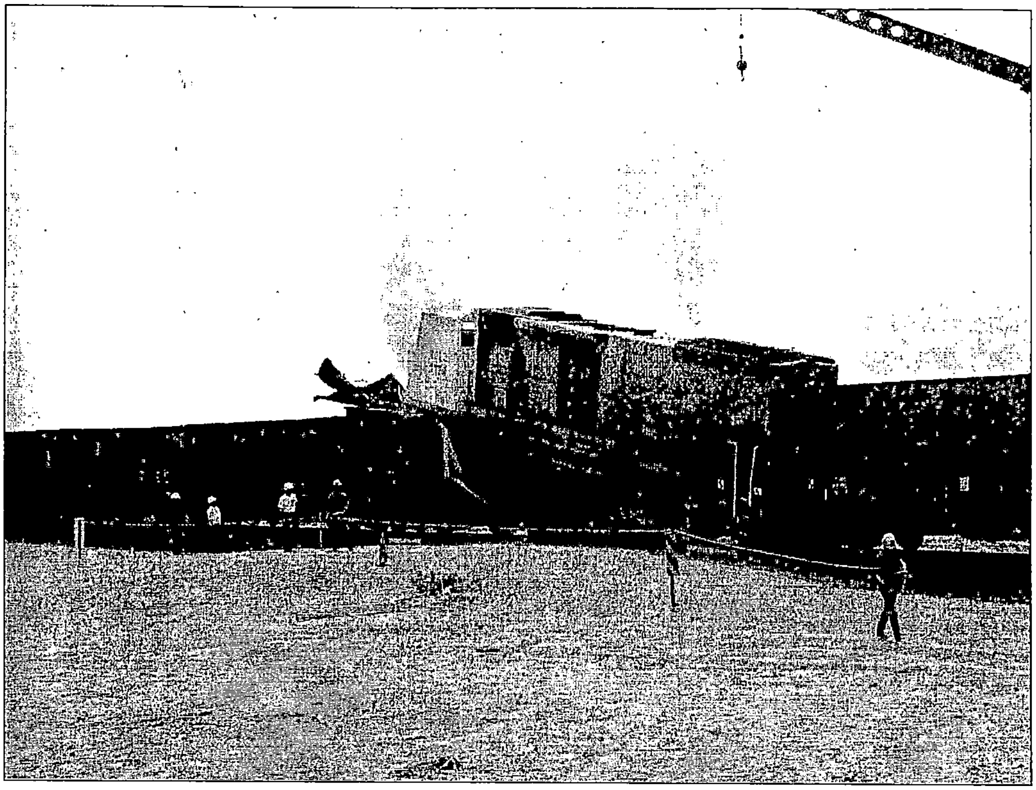

Figure 11 Locomotive after Impact

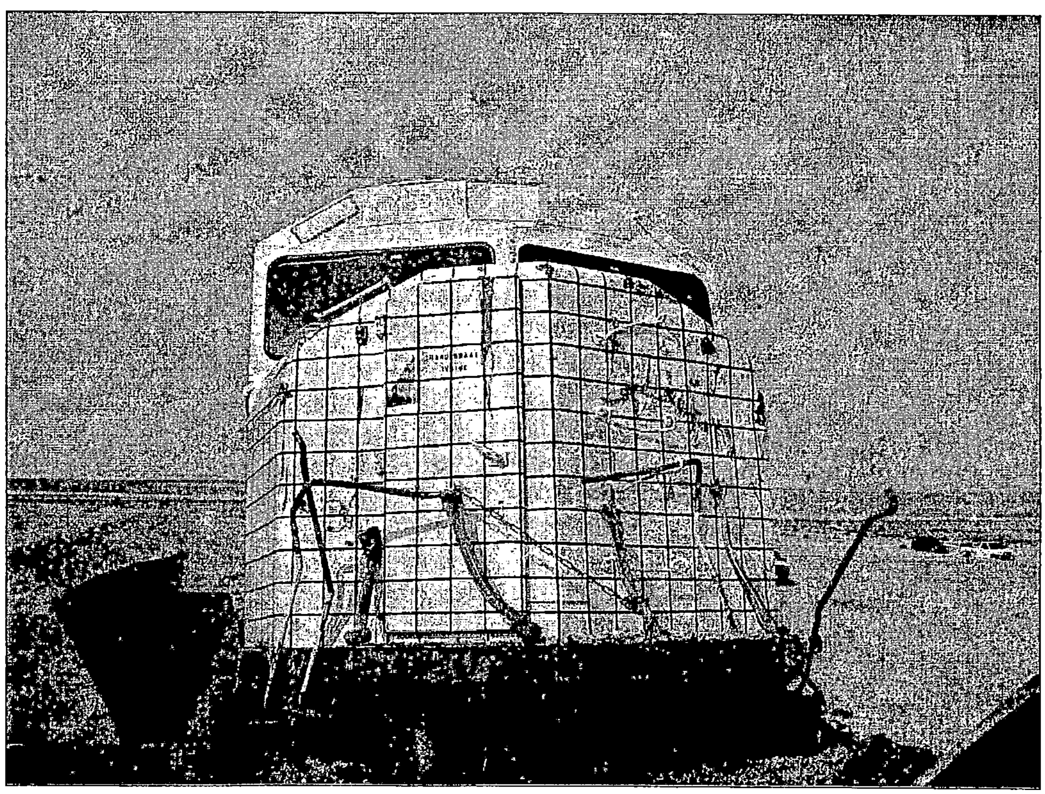

Figure 12 Nose of Locomotive after Impact

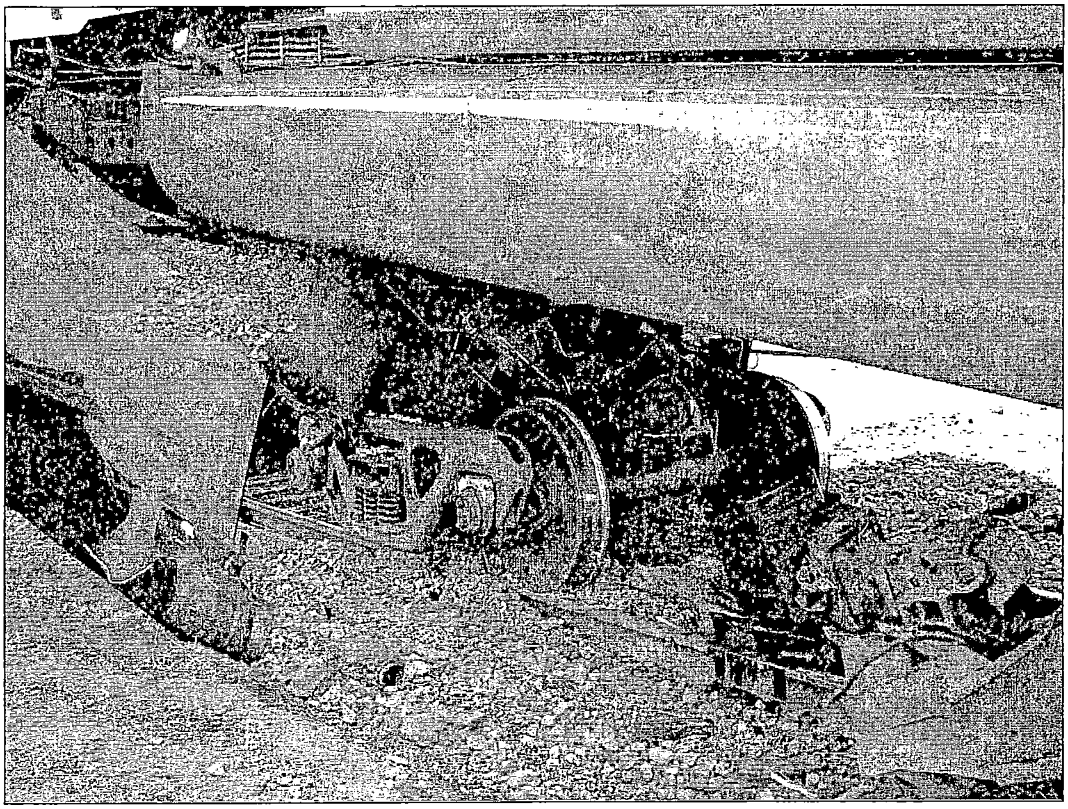

Figure 13 Fuel Tank of Locomotive after Impact

Figure 14 ATD after Impact

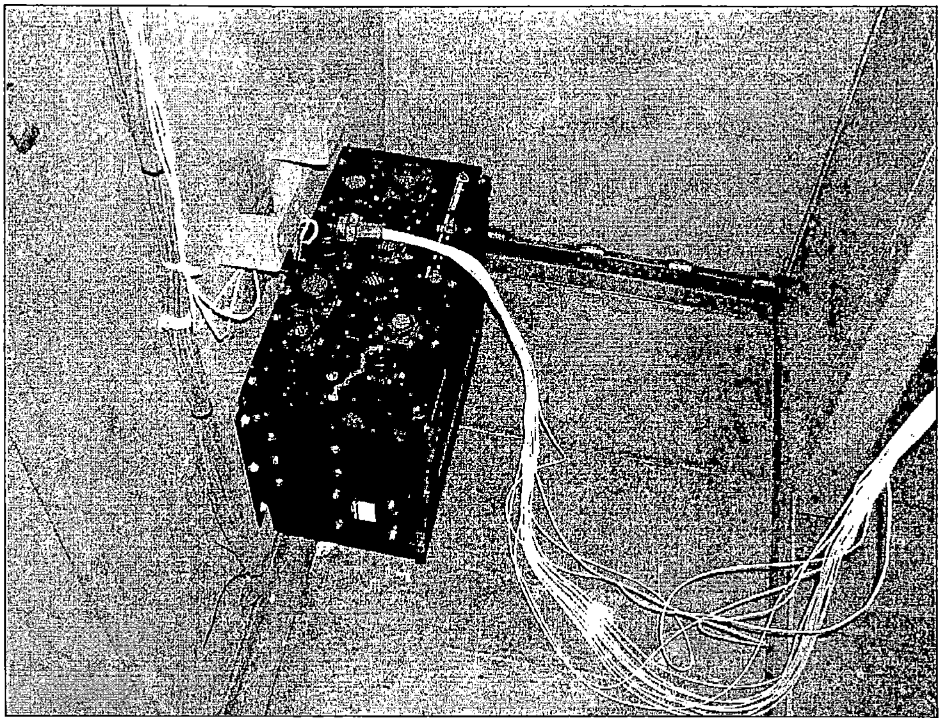

Figure 15 Event Recorder after Impact

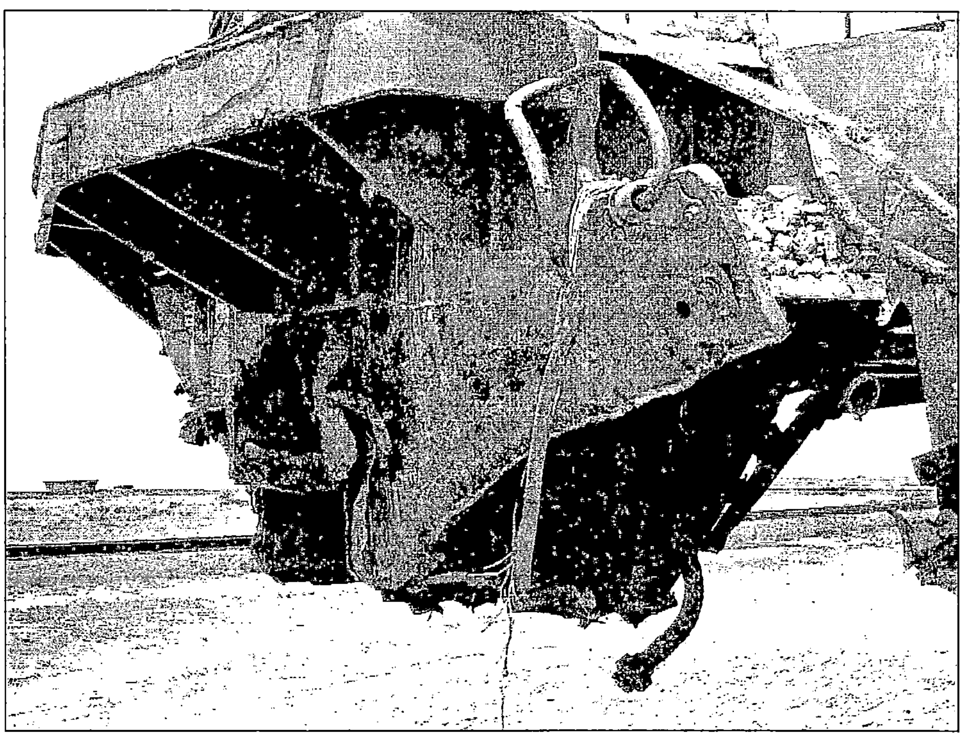

Figure 16 Locomotive Anti-climber after Removal from Hopper Car

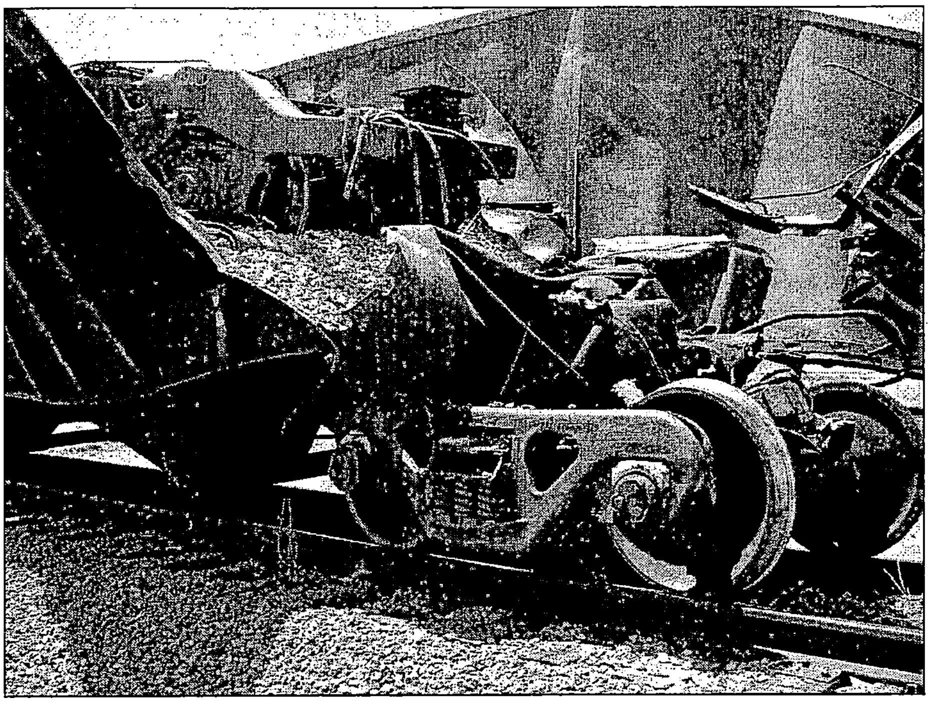

Figure 17 Hopper Car after Removal of Locomotive

5.0 DISCUSSION CONCLUSIONS

The results of the test show that the locomotive cab did not allow intrusion of foreign objects into the cab that could cause injury to the crew. The ATD results are well below NHTSA proposed criteria. The measured strain on the under frame of the locomotive directly behind the coupler was high and showed significant residual strain indicating some plastic deformation.

Although the test was carefully planned, several comments regarding the test condition were made that deserve consideration in future tests:

- Rear end collisions are often foreseen by the train crew, and the crew will often take up positions in the locomotive cab that they feel offer more protection than sitting in the engineer's seat. Options for placing ATDs in the cab should be considered.

- Although the struck hopper was loaded to its gross rail load, the load was relatively dense granite ballast. This resulted in the load level being lower in the car than is typical. Since there was no material behind the upper portion of the end sheet as the locomotive entered the car, the loads on the collision posts were likely lower than would have been experienced in a collision with a cubed out car.

- A collision into a car with a more substantial end structure, such as a tank car, would likely produce higher loads on the collision posts.

APPENDIX A

Test Implementation Plan for Locomotive Crashworthiness Testing

TO 137

(Contract No. DTFR53-93-C-00001)

June 2002

Presented by:
Transportation Technology Center, Inc.
55500 DOT Road
P.O. Box 11130
Pueblo, Colorado, USA, 81001

1.0 Purpose

Evaluation of freight locomotive structural crashworthiness by carrying out a series of full-scale impact tests based on historical accidents. Each locomotive will be instrumented to measure material strains and structural accelerations, in sufficient quantity, to allow correlation with analytical predictions. In all cases the acceleration levels in the crew compartment and the dynamic forces transmitted to critical components of the locomotive will be measured. An anthropomorphic test device (ATD) will be positioned in the seat of the locomotive for each test.

2.0 Requirements

Carry out the following full-scale impact tests involving a current AAR Specification S-580 compliant (SD-70 MAC) locomotive pulling three loaded hopper cars at:

1. 30 mph impacting a stationary consist of loaded hopper cars.
2. 50 mph impacting a stationary log truck on a railroad grade crossing.
3. 50 mph impacting a stationary truck/flatbed carrying two steel coils on a railroad grade crossing.

3.0 Test Vehicles and Site

The impact tests will be conducted using a locomotive structure built to comply with AAR Specification S-580 and provided by another contractor.

The loaded hopper cars will be provided by TTCI.

The log truck, trailer and logs will be provided by TTCI.

The flatbed trailer and steel coils will be provided by TTCI.

Test #1 will be conducted on tangent track at TTC.

Test #2 and #3 will be conducted on a grade crossing at TTC.

4.0 Test Method

The impact tests will be performed at TTC by pushing the consist of test locomotive and three loaded hopper cars with another locomotive, to a pre-defined speed and then released allowing the consist to roll along the track and into the stationary consist (Test #1), stationary log truck on a railroad grade crossing (Test #2) or stationary truck/flatbed carrying two steel coils on a railroad grade crossing (Test #3).

The release distance, and the speed of the locomotive at the release point, will be determined from a series of speed calibration runs carried out before each test.
A radar speed measuring system will be used for the speed calibration tests. Calculations will be performed using TOES to estimate the speed versus distance for the test

locomotive and freight cars, using the measured track profile. The ambient temperature and wind speed will be measured during the calibration tests and during the actual test. A laser speed trap will be used on the actual test to measure the speed of the test consist just before impact.

On-board instrumentation will record accelerations, displacements and strains at various points on the locomotive and hopper cars during and after the impact. Five high-speed film cameras and six video cameras will be used to record each impact test.

5.0 Measured Items

The weight of the test locomotive and hopper cars, and the position of all the transducers will be measured before each test. The weights of the logs, steel coils and trailers will also be measured before each test. Strains and accelerations will be measured during the test using a battery powered on-board data acquisition system which will provide excitation to the strain gauges and accelerometers, analog anti-aliasing filtering of the signals, analog-to-digital conversion and recording. Data acquisition will be in accordance with SAE J211/1,Instrumentation for Impact Tests (revised March 1995). Data from each channel will be recorded at a sample rate of 12,800 Hz. All data will be synchronized with a time reference applied to all systems simultaneously at the time of impact. The time reference will come from a closure of a tape switch on the front of the impacting cab-car. The following items will be measured during each test :

1. The speed of the test locomotive just before impact using a laser based speed trap
2. Strains at each Collision Post of the locomotive as shown in Figure 1 (5 3-axis rosette and 5 uniaxial strain gauges (longitudinal))(2x20=40 channels).
3. Longitudinal strains on the Under-frame of the Locomotive as shown in Figure 2 (12 uniaxial strain gauges)(12 channels).
4. Longitudinal strains at the Center Post of the Windshield as shown in Figure 3 (3 uniaxial strain gauges (vertical) on either side of centerline)(6 channels).
5. A tri-axial accelerometer on the floor of the cab of the locomotive, near the driver's seat (3 channels). A second tri-axial accelerometer will also be located on the floor of the cab near the driver's seat (3 channels). This accelerometer will be connected to a different Data Brick so that it offers a separate redundant system.
6. Longitudinal strain of coupler between locomotive and first hopper car. (1 channel).
7. The ATD in the driver's seat of the locomotive will include the following instrumentation: (14 channels)
    - Head tri-axial accelerometer
    - Chest tri-axial accelerometer
    - Six-axis upper neck load cell
    - Two single-axis femur load cells

8. A tri-axial accelerometer on the first two hopper cars behind the locomotive (6 channels).
9. Three string potentiometers on each coupler between the locomotive and the first hopper car (6 channels).
10. A tri-axial accelerometer will be mounted on an Event Recorder located in an equipment bay below the locomotive cab.

In addition, the following items will also be measured on each individual test:

Test #1

1. A tri-axial accelerometer on each of the first two stationary hopper cars (6 channels).
2. Three string potentiometers on each coupler between the first two stationary hopper cars (6 channels).

Test #2

1. Targets will be attached to each of the logs on the log trailer and an attempt will be made to color code the logs.

Test #3

1. A tri-axial accelerometer will be mounted in the center of each of the two steel coils (6 channels).

In summary, 106 channels are required for Test #1, 94 channels for Test #2 and 100 channels for Test #3.

For Test #1, this will require a Data Brick on each of the first two hopper cars behind the locomotive (2 Data Bricks), each of the first two stationary hopper cars (2 Data Bricks), and 11 Data Bricks on the locomotive. A total of 15 Data Bricks.
For Test #2, this will require a Data Brick on each of the first two hopper cars behind the locomotive (2 Data Bricks) and 11 Data Bricks on the locomotive. A total of 13

Data Bricks.
For Test #3, this will require a Data Brick on each of the first two hopper cars behind the locomotive (2 Data Bricks) and 11 Data Bricks on the locomotive. A Data Brick will also be required in each steel coil (2 Data Bricks). A total of 15 Data Bricks.
Each Data Brick will be set at a sampling rate of 12,800 Hz and timing of 1 second pre-trigger data collection and 7 seconds of post-trigger data collection.
Five high-speed film cameras and six video cameras will be used to record the impact for each test. A reference signal will be placed on the film so that analysis of the film after the event will give the velocity and displacement of each vehicle during impact. The placement of the high-speed film and video cameras are shown in Figure 4.

6.0 Instrumentation

6.1 Strain measurements, Locomotive

Figures 1, 2 and 3 show the general arrangement of strain gauges on the collision post, underframe and central post of the windshield respectively. Table 1 lists the locations and strain gauge types for the collision post, Table 2 lists the locations and strain gauge types for the underframe and Table 3 lists the locations and strain gauge types for the central post of the windshield.

Table 1 Strain gauge location and type on collision post

Location	Strain Gauge	Channels
SG-CP-RR1	Rosette	1,2,3
SG-CP-RR2	Rosette	4,5,6
SG-CP-RR3	Rosette	7,8,9
SG-CP-RR4	Rosette	10,11,12
SG-CP-RR5	Rosette	13,14,15
SG-CP-RS1	Standard	16
SG-CP-RS2	Standard	17
SG-CP-RS3	Standard	18
SG-CP-RS4	Standard	19
SG-CP-RS5	Standard	20
SG-CP-LR1	Rosette	21,22,23
SG-CP-LR2	Rosette	24,25,26
SG-CP-LR3	Rosette	27,28,29
SG-CP-LR4	Rosette	30,31,32
SG-CP-LR5	Rosette	33,34,35
SG-CP-LS1	Standard	36
SG-CP-LS2	Standard	37
SG-CP-LS3	Standard	38
SG-CP-LS4	Standard	39
SG-CP-LS5	Standard	40

Table 2 Strain gauge location and type on underframe

Location	Strain Gauge	Channel
SG-U-LF	Standard	41
SG-U-MF	Standard	42
SG-U-RF	Standard	43
SG-U-LMF	Standard	44
SG-U-MMF	Standard	45
SG-U-RMF	Standard	46
SG-U-LMR	Standard	47
SG-U-MMR	Standard	48
SG-U-RMR	Standard	49
SG-U-LR	Standard	50
SG-U-MR	Standard	51
SG-U-RR	Standard	52

Table 3 Strain gauge location and type on the central post of the windshield

Location	Strain Gauge	Channel
SG-CPW-TR	Standard	53
SG-CPW-TL	Standard	54
SG-CPW-MR	Standard	55
SG-CPW-ML	Standard	56
SG-CPW-BR	Standard	57
SG-CPW-BL	Standard	58

6.2 Acceleration measurements, Locomotive and Hopper Cars

The gross and flexible motions of the floor of the cab, near the driver's seat, will be measured using a tri-axial accelerometer. The gross and flexible motions of the first two hopper cars behind the locomotive will be measured by a tri-axial accelerometer underneath each car. The gross and flexible motions of the first two stationary hopper cars will also be measured by a tri-axial accelerometer underneath each car.

All the accelerometers are critically damped. The accelerometers will be calibrated prior to installation. The accelerometers posses natural frequencies sufficiently high to meet the requirements of SAE J211/1, *Instrumentation for Impact Test (Revised MAR95)*. Class 1000, which requires that the frequency response is essentially flat to 1000 Hz

Table 4 lists the accelerometer locations, accelerometer types, and data channels.

Table 4 Locomotive and Hopper Cars accelerometers

Location	Accelerometer	Measurement		Channel	
Locomotive Floor	Three axis	Longitudinal	X	1	50g
		Lateral	Y	2	50g
		Vertical	Z	3	50g
Locomotive Floor (Redundant)	Three axis	Longitudinal	X	4	400g
		Lateral	Y	5	200g
		Vertical	Z	6	400g
Event Recorder	Three axis	Longitudinal	X	7	400g
		Lateral	Y	8	200g
		Vertical	Z	9	400g
First moving hopper car	Three axis	Longitudinal	X	10	200g
		Lateral	Y	11	50g
		Vertical	Z	12	100g
Second moving hopper car	Three axis	Longitudinal	X	13	100g
		Lateral	Y	14	50g
		Vertical	Z	15	50g
First stationary hopper car *	Three axis	Longitudinal	X	16	200g
		Lateral	Y	17	100g
		Vertical	Z	18	100g
Second stationary hopper car*	Three axis	Longitudinal	X	19	200g
		Lateral	Y	20	100g
		Vertical	Z	21	100g

Note: * accelerometers only required for Test #1

6.3 String Potentiometers

Three string potentiometers will be attached to each coupler between the locomotive and first hopper car to measure the displacement of the coupler relative to the car body. Three string potentiometers will also be attached to each coupler between the first two stationary hopper cars, for Test #1, to measure the displacement of the coupler relative to the car bodies.

6.4 ATD

The ATD in the driver's seat of the locomotive will include the instrumentation listed in Table 5.

Table 5. ATD Instrumentation

Location	Transducer	Measurement		Channel	
Head	Three axis accel.	Longitudinal	X	1	400g
		Lateral	Y	2	200g
		Vertical	Z	3	200g
Chest	Three axis accel.	Longitudinal	X	4	400g
		Lateral	Y	5	200g
		Vertical	Z	6	200g
Upper neck	Six axis load cell	Longitudinal	X	7	
		Lateral	Y	8	
		Vertical	Z	9	
		Roll		10	
		Pitch		11	
		Yaw		12	
Femur	Two single axis load cells	Longitudinal (L)	X	13	
		Longitudinal (R)	X	14	

6.5 Acceleration measurements, Steel Coils

Tri-axial accelerometers will be mounted in each steel coil for Test #3. Table 6 lists the accelerometer locations, accelerometer types and data channels.

Table 6. Steel Coil Accelerometers

Location	Accelerometer	Measurement		Channel	
Steel coil at front of trailer	Three axis	Longitudinal	X	1	400g
		Lateral	Y	2	200g
		Vertical	Z	3	200g
Steel coil at rear of trailer	Three axis	Longitudinal	X	4	400g
		Lateral	Y	5	200g
		Vertical	Z	6	200g

6.6 High-Speed and Real-Time Photography

Five high-speed film cameras and six video cameras will document the impact test. The position of the film and video cameras is shown in Figure 4. One video camera will be located in the cab of the locomotive. All the cameras are equipped with sights that allow the photographer to view the expected image. The final siting of cameras will be carried out at the time of camera setup. Adjustments will be made, if necessary, to achieve the optimum views.

A 100 Hz reference signal will be placed on the film so that accurate frame speed can be determined for film analysis. An electronic signal generator provides the calibrated 100-Hz pulse train to light emitting diodes (LEDs) in the high-speed cameras. Illumination of the LEDs exposes a small red dot on the edge of the film, outside the normal field of view. During film analysis, the precise film speed is determined from the number of frames and fractions thereof that pass between two adjacent LED marks. Battery powered on-board lights will illuminate the on-board camera view. Battery packs use 30- v NiCad batteries.

Color negative film for the ground-based cameras will be Kodak 16-mm 7246, ISO 250, for daylight on 100-ft spools. Film speed will be pushed in processing if necessary to compensate for light conditions at test time

Targets will be placed on the vehicles and the ground to facilitate post-test film analysis to determine speed and displacement during the test. The targets are divided into four quadrants with adjacent colors contrasting to provide good visibility. At least three targets will be placed on each side of each vehicle and the ground. During film analysis, the longitudinal and vertical coordinates of the targets are determined from projections on a film analyzer on a frame-by-frame basis. The distances between the targets, which are known from pre-test measurements, provide distance reference information for the film analysis. The differences in locations between vehicle-mounted targets and ground-based targets quantify the motion of the vehicle during the test. By taking the position differences between vehicle-mounted and ground-based targets, the effects of film registration jitter in the high-speed cameras are minimized. The 100-Hz LED reference marks provide an accurate time base for the film analysis. Test vehicle position is determined directly as indicated above, and vehicle speed is determined by dividing displacement between adjacent frames by the time difference between the adjacent frames. If necessary, smoothing is applied to the displacement and speed data to compensate for digitization and other uncertainties.

The ground-based cameras will be started simultaneously from a central relay box triggered manually. The cameras will run at the determined nominal speed of 300-500 frames per second for about eight seconds before the100-ft film is entirely exposed. The appropriate nominal speed will be defined prior to the test.

6.6 Data Acquisition

Up to fifteen, 8-channel battery-powered on-board data acquisition systems will provide excitation to the strain gauges, accelerometers and displacement transducers, analog anti-aliasing filtering of the signals, analog-to-digital conversion, and recording on the locomotive.

Data acquisition will be in compliance with SAE J211. Data from each channel will be recorded at 12,800 Hz. Parallel redundant systems will be used for all accelerometer channels. Data recorded on the fifteen Data Bricks will be synchronized with a time reference applied to all systems simultaneously at the time of impact. The time reference will come from closure of the tape switches on the front of the test vehicle. The data acquisition systems are GMH Engineering Data Brick Model II. Each Data Brick is ruggedized for shock loading up to at least 100 g. On-board battery power will be provided by GMH Engineering 1.7 A-HR 14.4 volt NiCad Packs. Tape Switches, Inc., model 1201-131-A tape switches will provide event markers.

Software in the Data Brick will be used to determine zero levels and calibration factors rather than relying on set gains and expecting no zero drift. The Data Bricks will be set to record 1 seconds of pre-trigger data and 7 seconds of post-trigger data.

6.7 Speed Trap

A dual channel speed trap will accurately measure the impact speed of the locomotive when it is within 0.5 meter impact point. The speed trap is a GMH Engineering Model 400, 4 Interval Precision Speed Trap with an accuracy of 0.1%. Passage of a rod affixed to the vehicle will interrupt laser beams a fixed and known distance apart. The first interruption starts a precision counter, and the second interruption stops the counter. Speed is calculated from distance and time. Tentatively, the rod will be attached at the aft-end of the third moving hopper car. Final rod location will be determined prior to installation.

7.0 Test Procedure

- Strain gauges, accelerometers and displacement transducers will be attached to the locomotive, hopper cars and steel coils as described above.
- Speed calibration runs will be carried out using the test consist, comprising the test locomotive and three hopper cars. The test consist will be pushed by a locomotive and then the power switched off at a pre-determined point before the impact point. The speed of the consist will be measured as the consist passes the impact point, using a radar gun. Having passed the impact point, the test consist will be stopped by the pushing locomotive. A calibration chart of speed versus distance will be produced from these tests and compared with simulation results using TOES. The speed of release will be determined from these tests.
- The Data Bricks will be mounted on the locomotive and hopper cars. The transducers will be connected to the data acquisition system and tested.
- The film and video cameras will be set up.
- The weight of the locomotive, hopper cars, log truck and steel coil truck, will be measured just prior to each test.
- All instruments will be calibrated and a zero reading carried out.
- A trial low speed soft impact (less than 1 mph) of the test consist will be carried out to confirm all the instruments work properly.
- The instruments will be re-calibrated, the Tape Switches replaced and the test consist pulled back.
- The test consist will be pushed by a locomotive and released at the appropriate distance from the stationary hopper cars, or road trailer, triggering the cameras just before impact.

- The instrumentation will be triggered on impact.
- Visual inspection of all the vehicles will be carried out after impact. Still photographs will be taken.
- The data will be downloaded onto lap-top computers from the on-board data acquisition system.

A checklist based on the above tasks will be signed by key personnel as each task is completed.

8.0 Data Analysis

8.1 Data Post-Processing

Each data channel will be offset adjusted in post-processing. The procedure is to average the data collected just prior to the test locomotive's impact with the first hopper car and subtract the offset from the entire data set for each channel. It is expected that between 0.05 and 1.0 second of pre-impact data will be averaged to determine the offsets. The precise duration of the averaging period cannot be determined with certainty until the data are reviewed. The offset adjustment procedure assures that the data plotted and analyzed contains impact-related accelerations and strains but not electronic offsets or steady biases in the data. The post-test offset adjustment is independent of, and in addition to, the pre-test offset adjustment made by the data acquisition system.

Plots of all data channels recorded and combinations of data channels will be produced as described below. Post-test filtering of the data will be accomplished with a two-pass phaseless four-pole digital filter algorithm consistent with the requirements of SAE J211. In the filtering process, data are first filtered in the forward direction with a two-pole filter. The first pass of the filtering process introduces a phase lag in the data. In the next pass, the data are filtered in the reverse direction with the same filter. Because the data are filtered in the reverse direction, a phase lead is introduced into the data. The phase lead of the reverse-direction filtering cancels the phase lag from the forward-direction filtering. The net effect is to filter the data without a change in phase with a four-pole filter.

8.2 Data Presentation

Every channel as recorded (raw data) will be plotted against time (where time = 0 is defined as the impact of the locomotive with the hopper cars or road trailer).

The acceleration records during the impacts will be plotted against time. The longitudinal acceleration will be integrated and the derived velocity plotted against time. The strain gauge time histories will be presented. The displacement time histories will be presented. All data recorded by the Data Bricks, the derived values mentioned above, and plotted time histories will be presented to the FRA in digital form on a CD.

The film from each high speed camera will be analyzed frame by frame and the velocity during the impact calculated. A 100 Hz reference signal will be placed on the film so that accurate frame speed can be determined for film analysis. An electronic signal generator provides the calibrated 100-Hz pulse train to light emitting diodes (LEDs) in the high-speed cameras. Illumination of the LEDs exposes a small red dot on the edge of the film, outside the normal field of view

During film analysis, the precise film speed is determined from the number of frames and fractions thereof that pass between two adjacent LED marks.
All the data output described in this section will be presented in a report and submitted to the FRA. The report will also contain general information about the crash test and describe how it was conducted.

9.0 Safety

All Transportation Technology Center, Inc. (TTCI) safety rules will be observed during the preparation and performance of the crash tests. All personnel participating in the tests will be required to comply with these rules when visiting the TTC, including wearing appropriate personal protective equipment. A safety briefing for all test personnel and visitors will be held prior to testing.

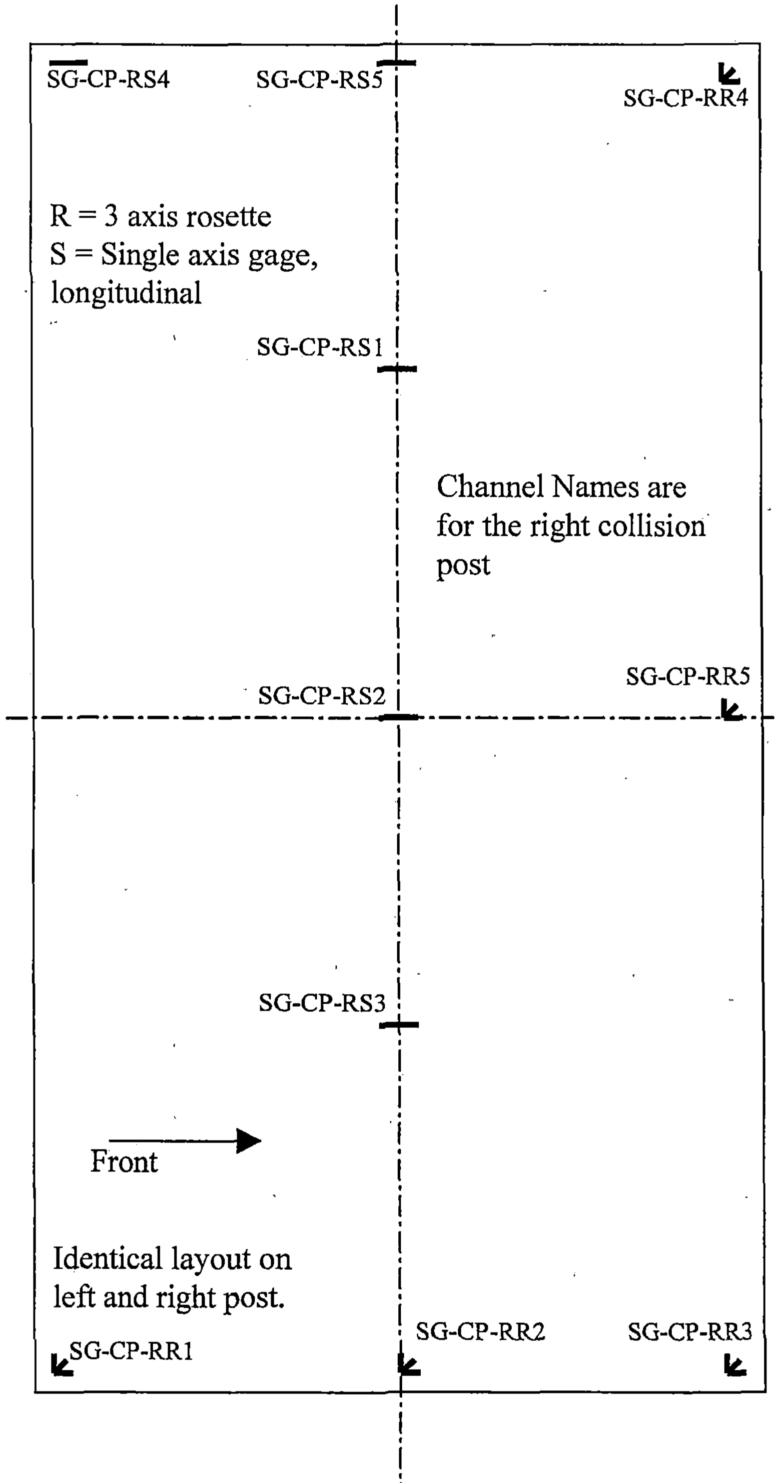

Figure 11. Location of strain gauges on the collision post

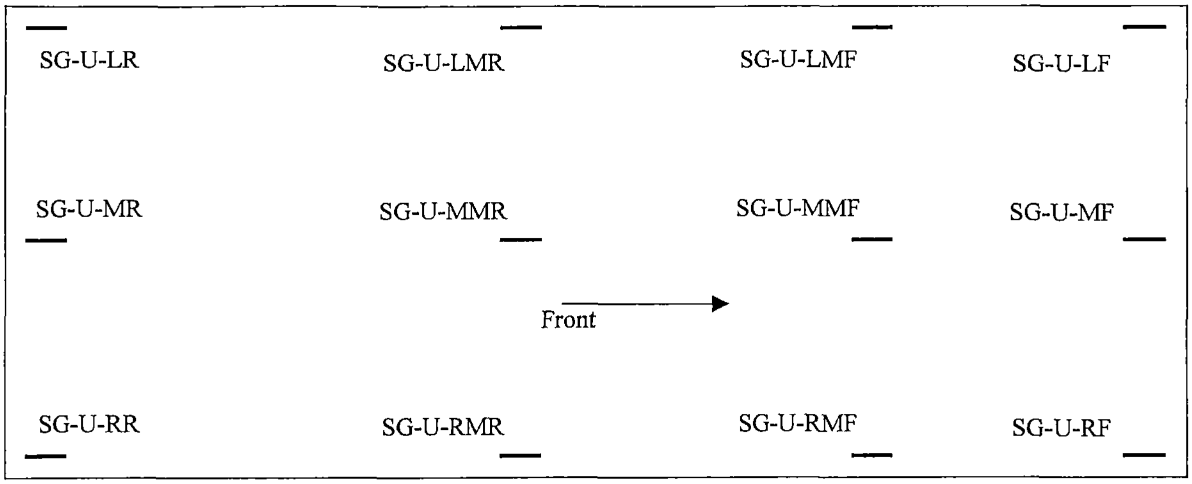

Figure 12. Location of strain gauges on locomotive under-frame

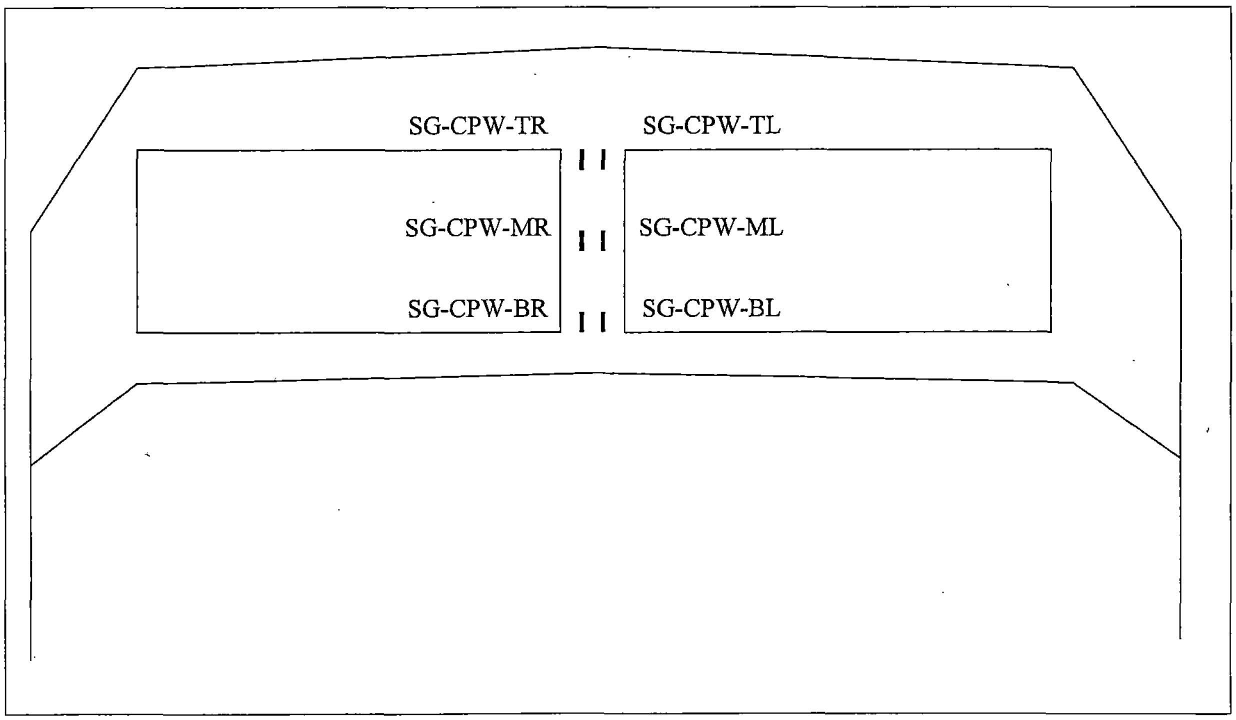

Figure 13. Location of strain gauges on windshield post

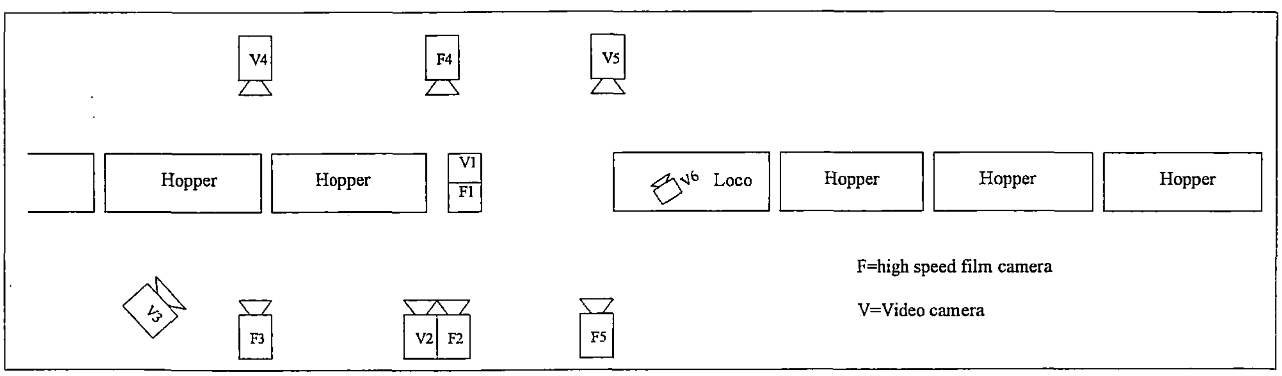

Figure 14. Location of cameras

APPENDIX B

Acceleration Data, CFC = 1000 Hz

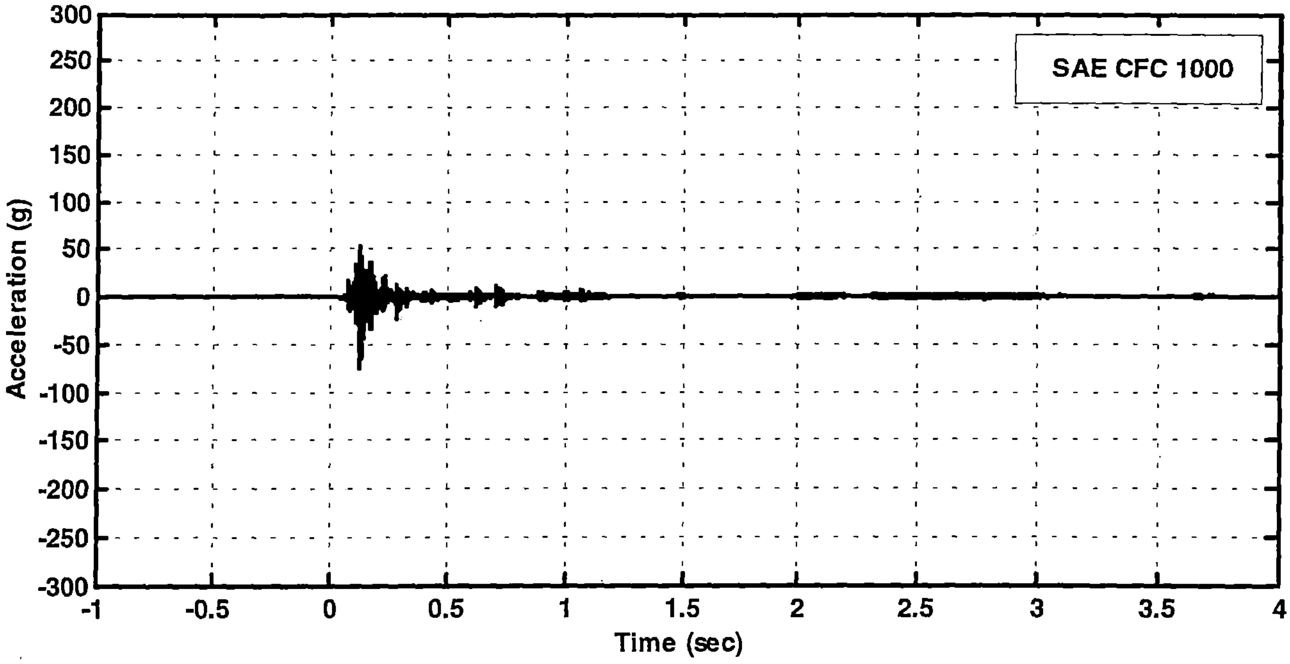

Figure B1. Bullet hopper 1, longitudinal acceleration
Channel Name: BH1_CGX

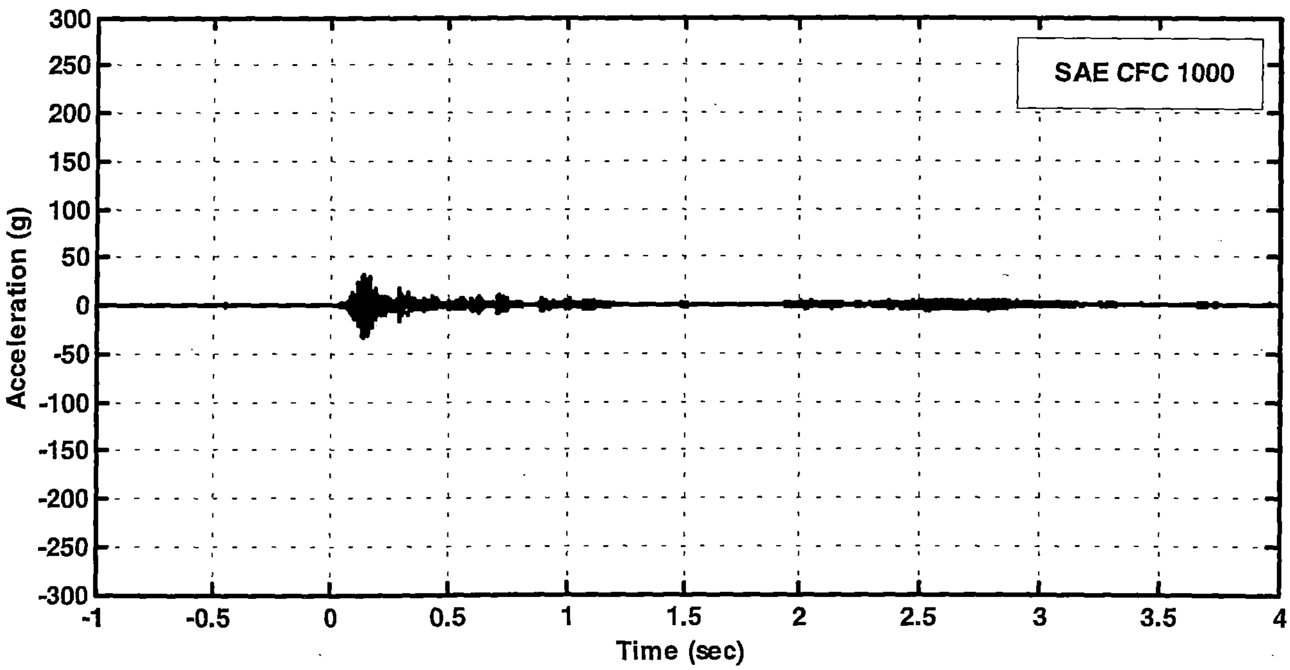

Figure B2. Bullet hopper 1, lateral acceleration
Channel Name: BH1_CGY

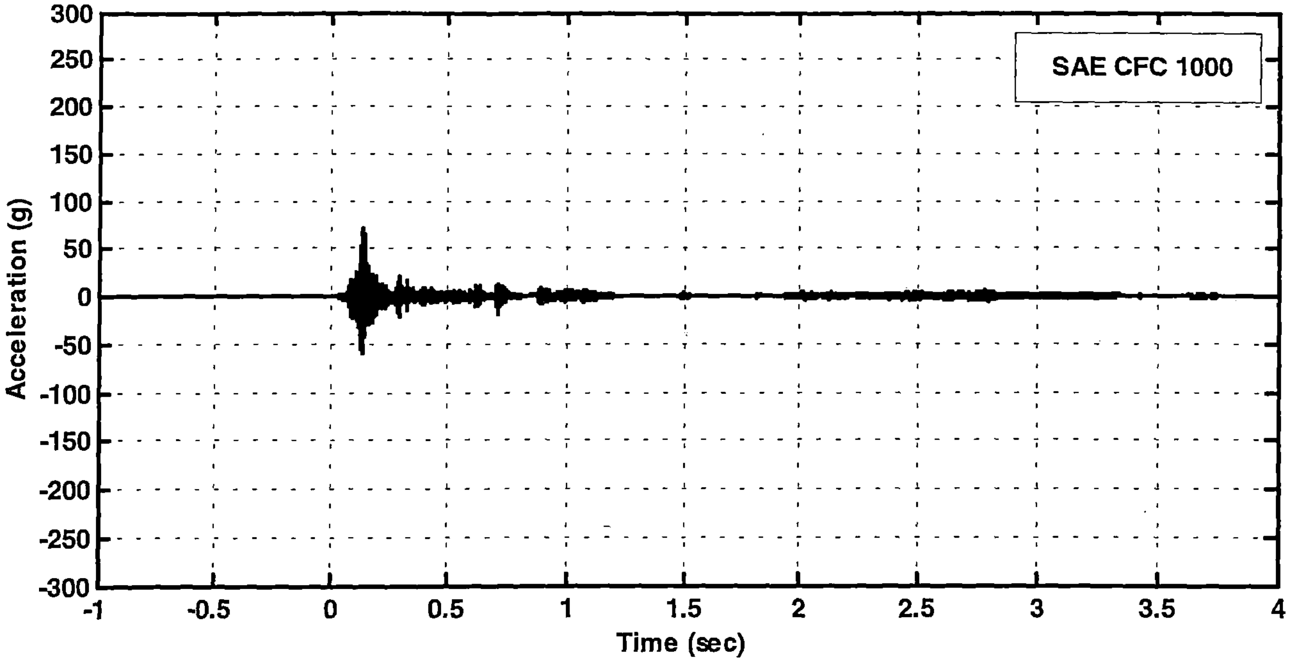

Figure B3. Bullet hopper 1, vertical acceleration
Channel Name: BH1_CGZ

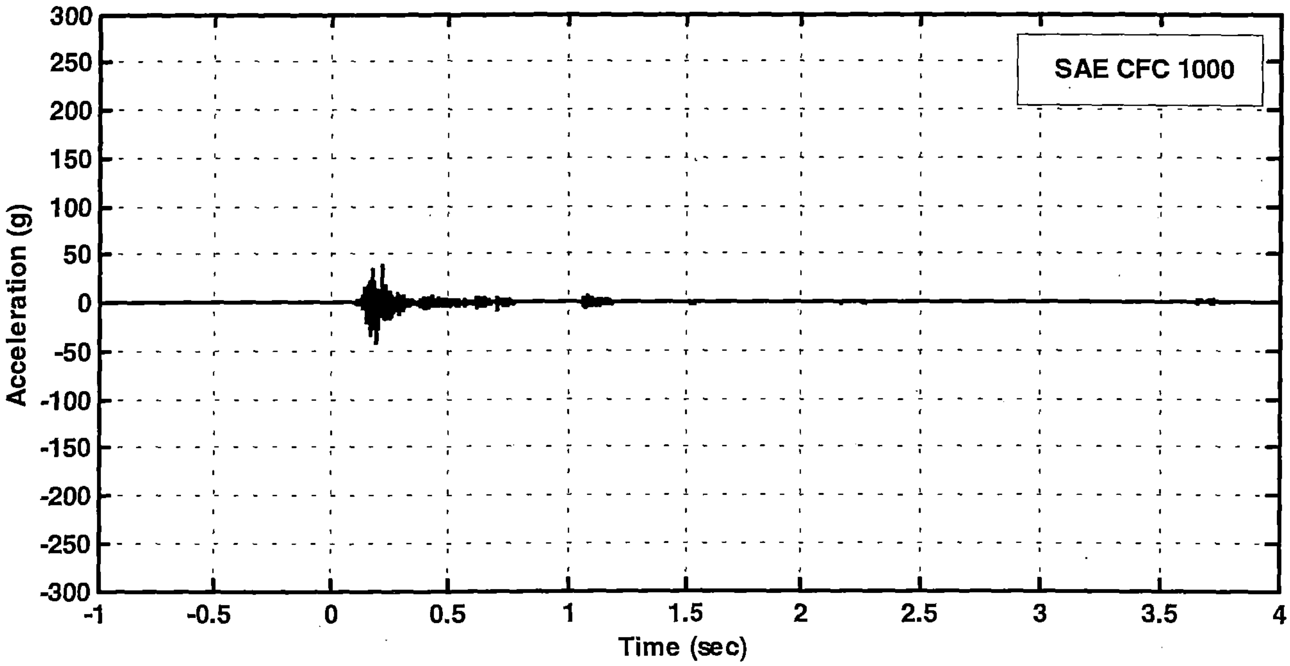

Figure B4. Bullet hopper 2, longitudinal acceleration
Channel Name: BH2_CGX

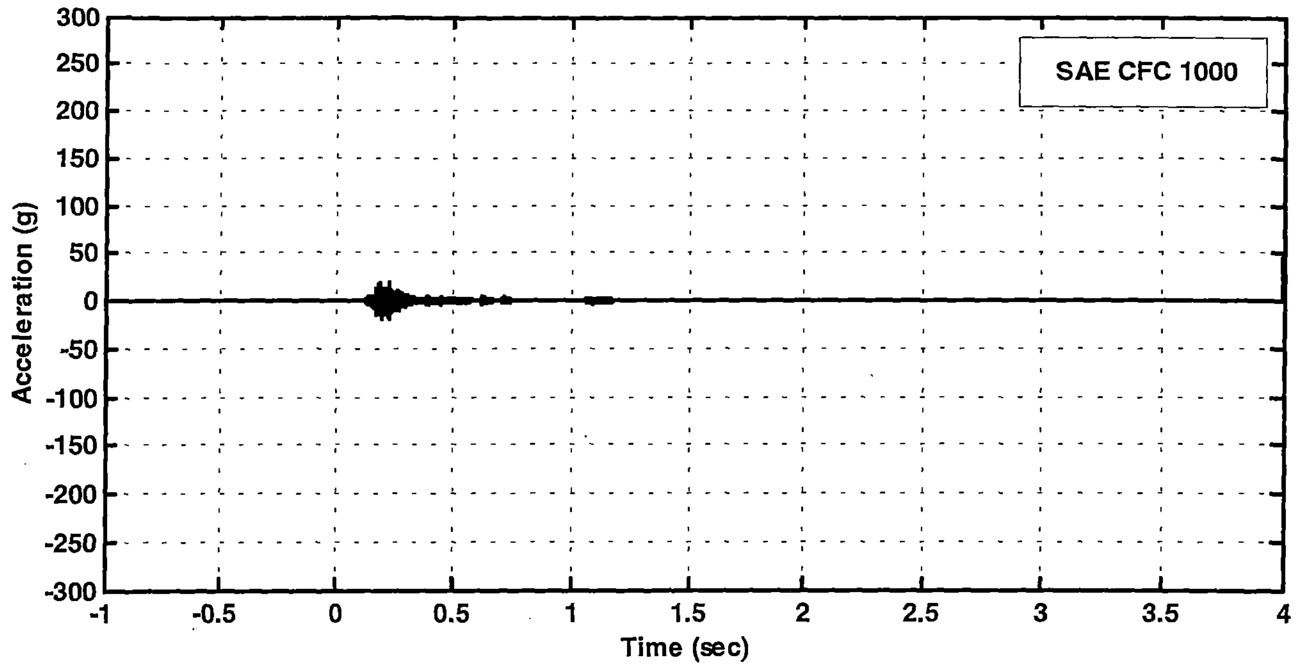

Figure B5. Bullet hopper 2, lateral acceleration
Channel Name: BH2_CGY

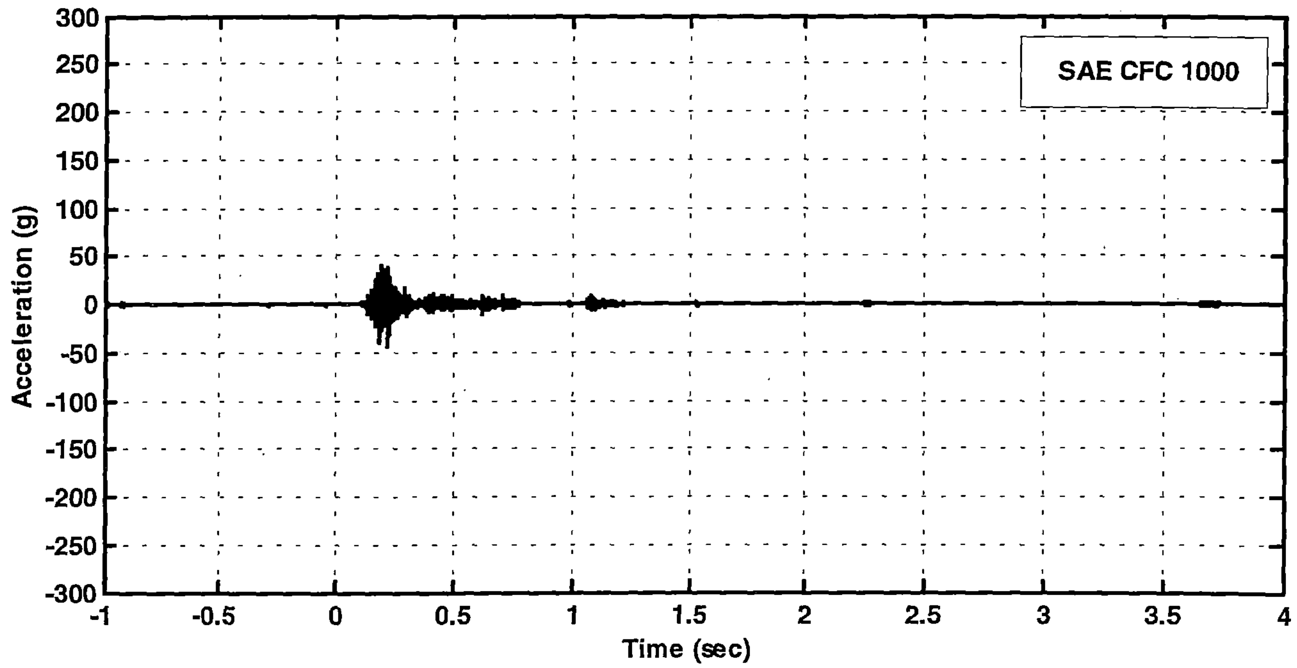

Figure B6. Bullet hopper 2, vertical acceleration
Channel Name: BH2_CGZ

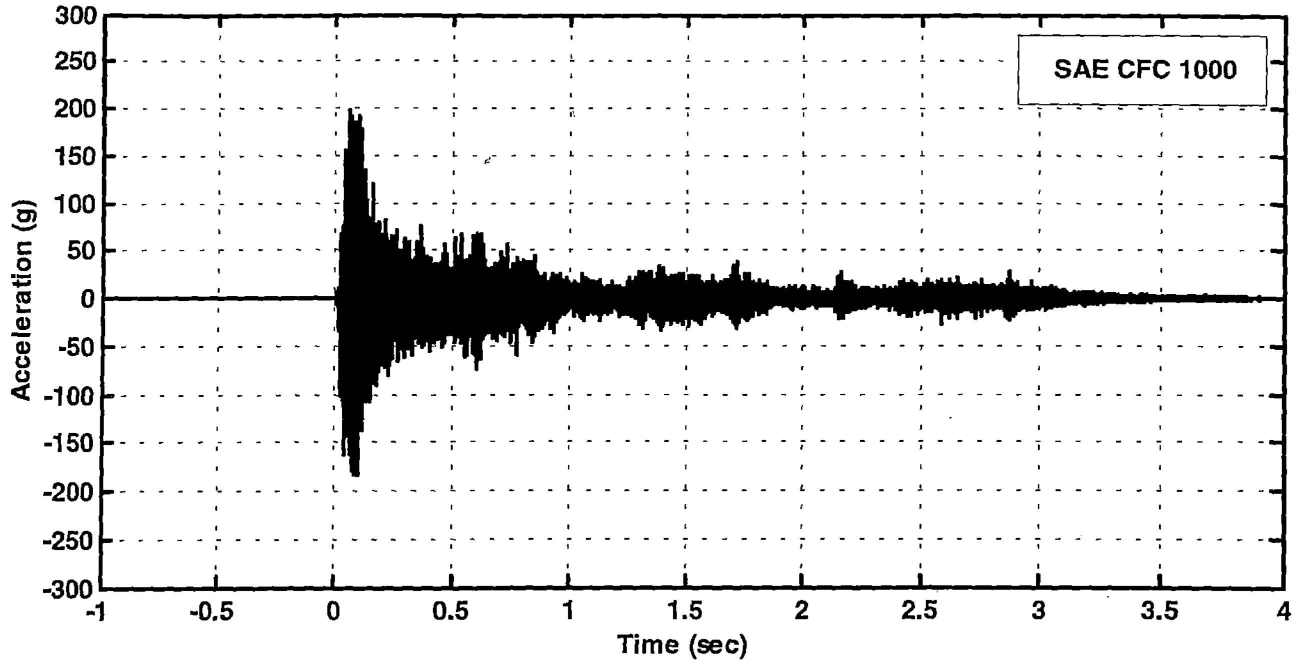

Figure B7. Locomotive floor, location 1, longitudinal acceleration
Channel Name: BL_F1X

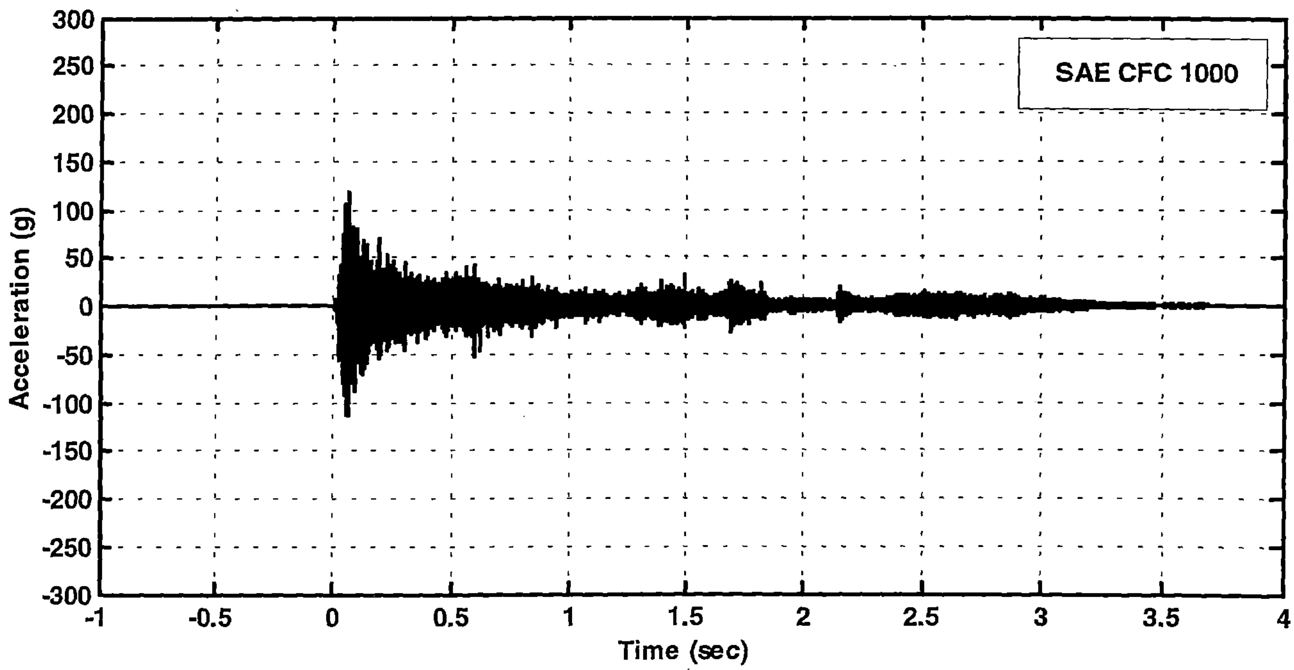

Figure B8. Locomotive floor, location 1, lateral acceleration
Channel Name: BL_F1Y

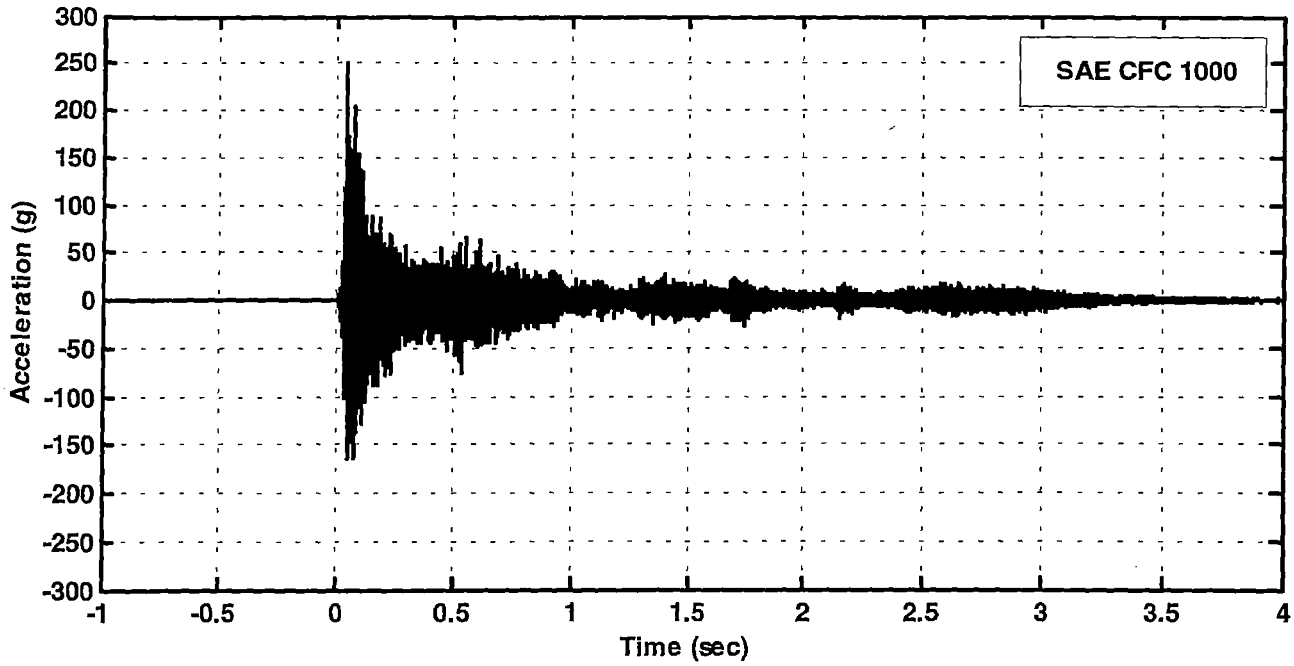

Figure B9. Locomotive floor, location 1, vertical acceleration
Channel Name: BL_F1Z

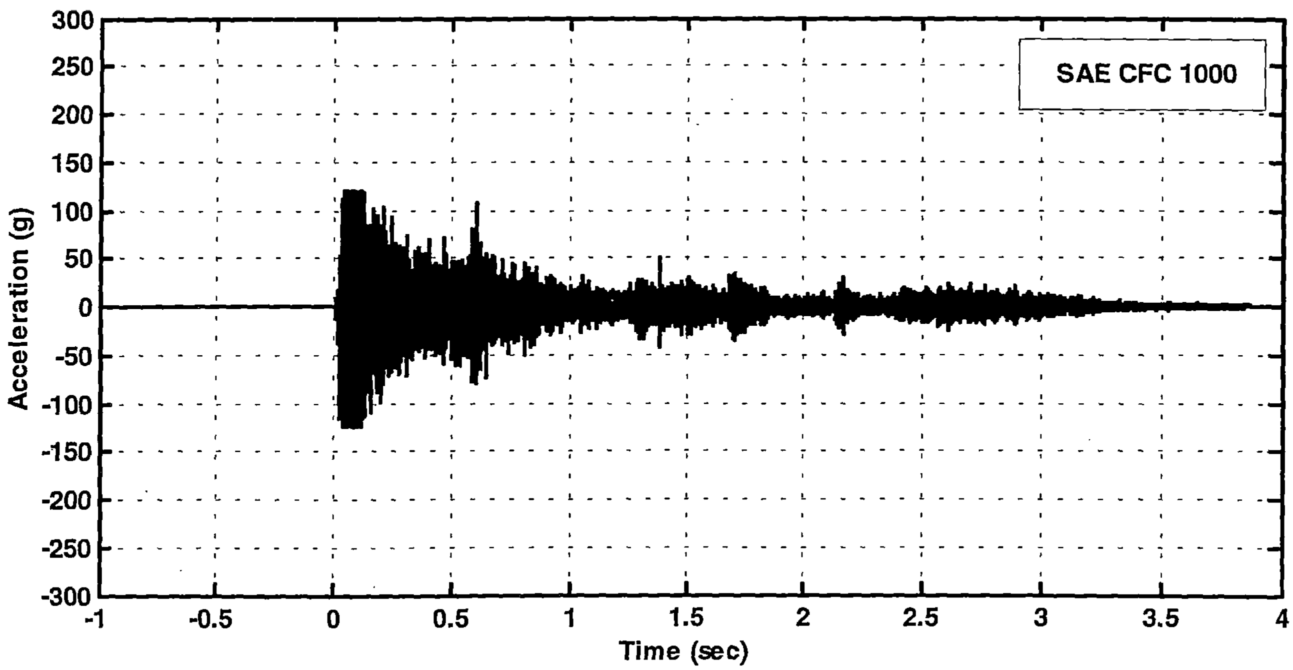

Figure B10. Locomotive floor, location 2, longitudinal acceleration
Channel Name: BL_F2X

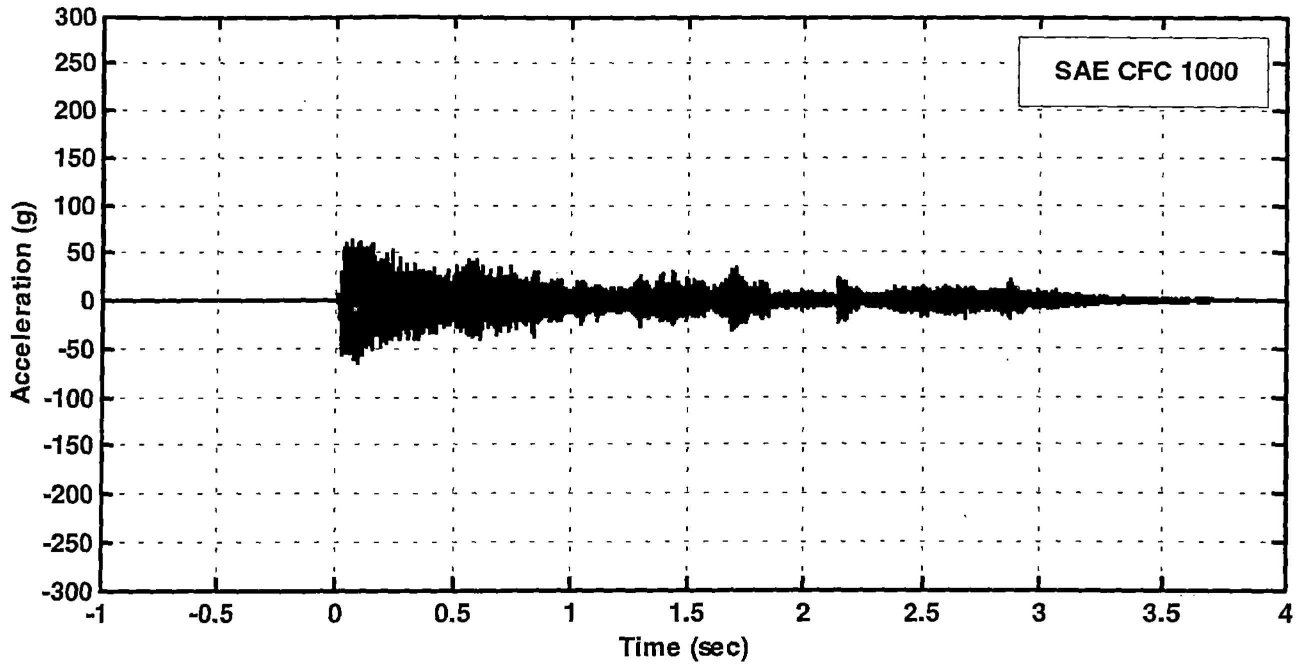

Figure B11. Locomotive floor, location 2, lateral acceleration
Channel Name: BL_F2Y

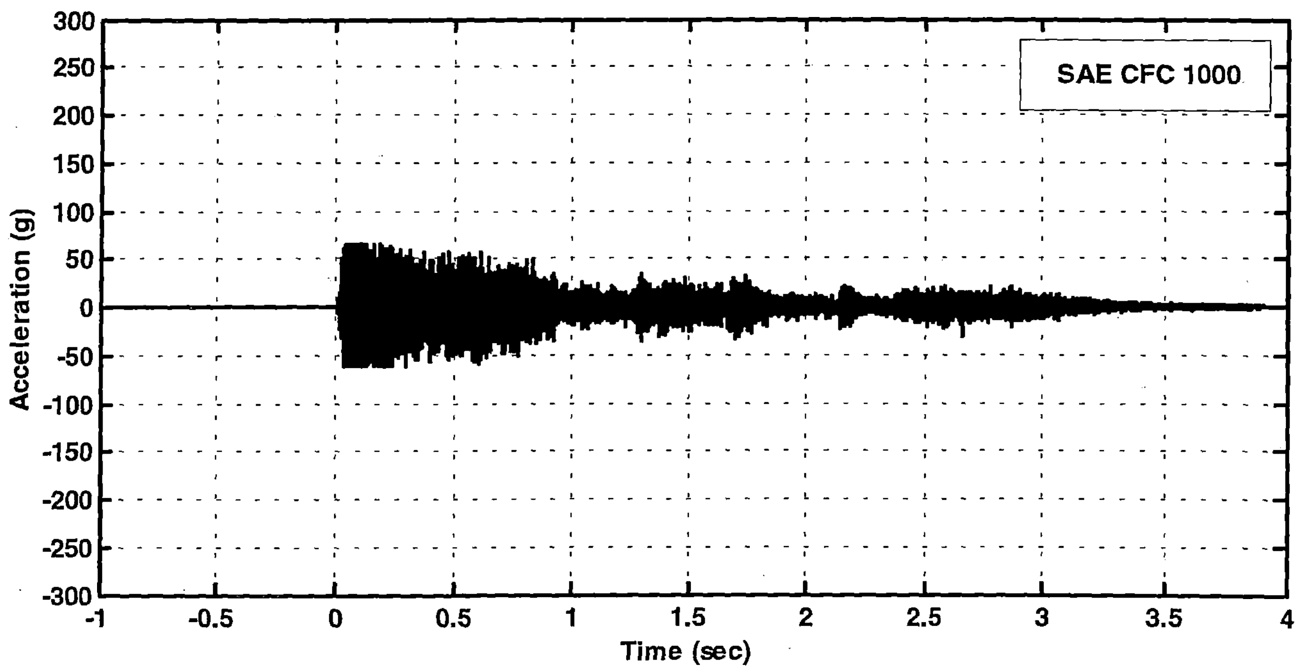

Figure B12. Locomotive floor, location 2, vertical acceleration
Channel Name: BL_F2Z

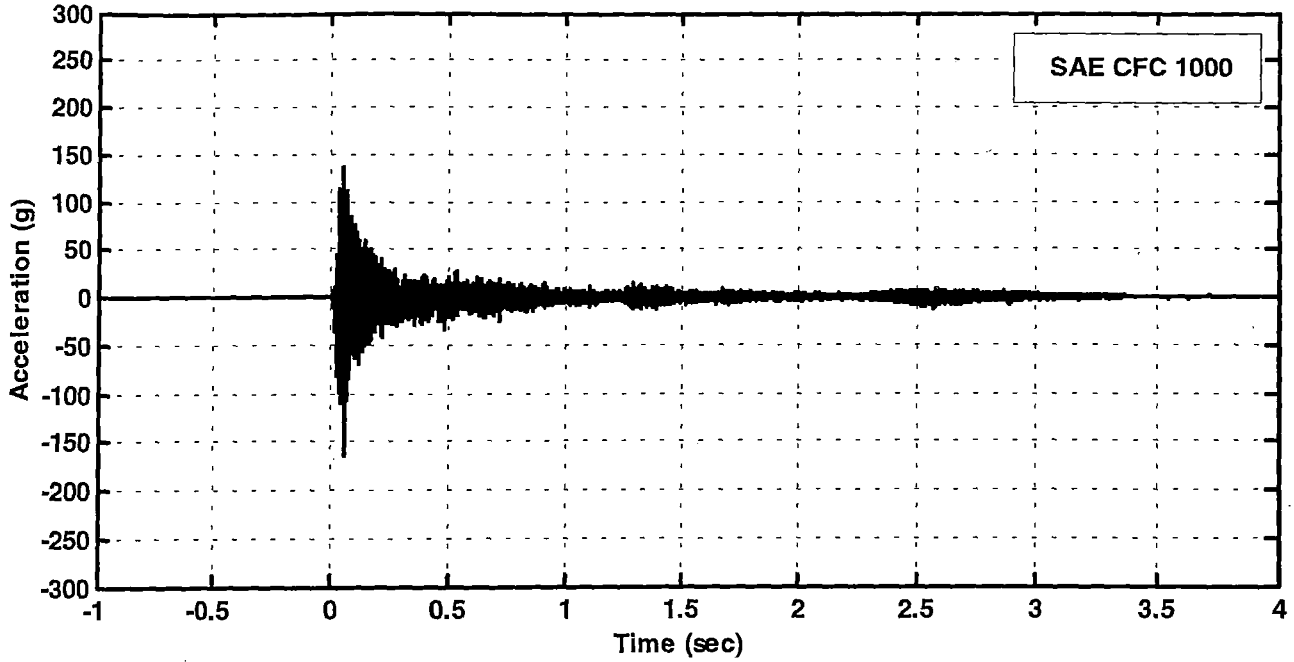

Figure B13. Locomotive event recorder, longitudinal acceleration
Channel Name: BL_RX

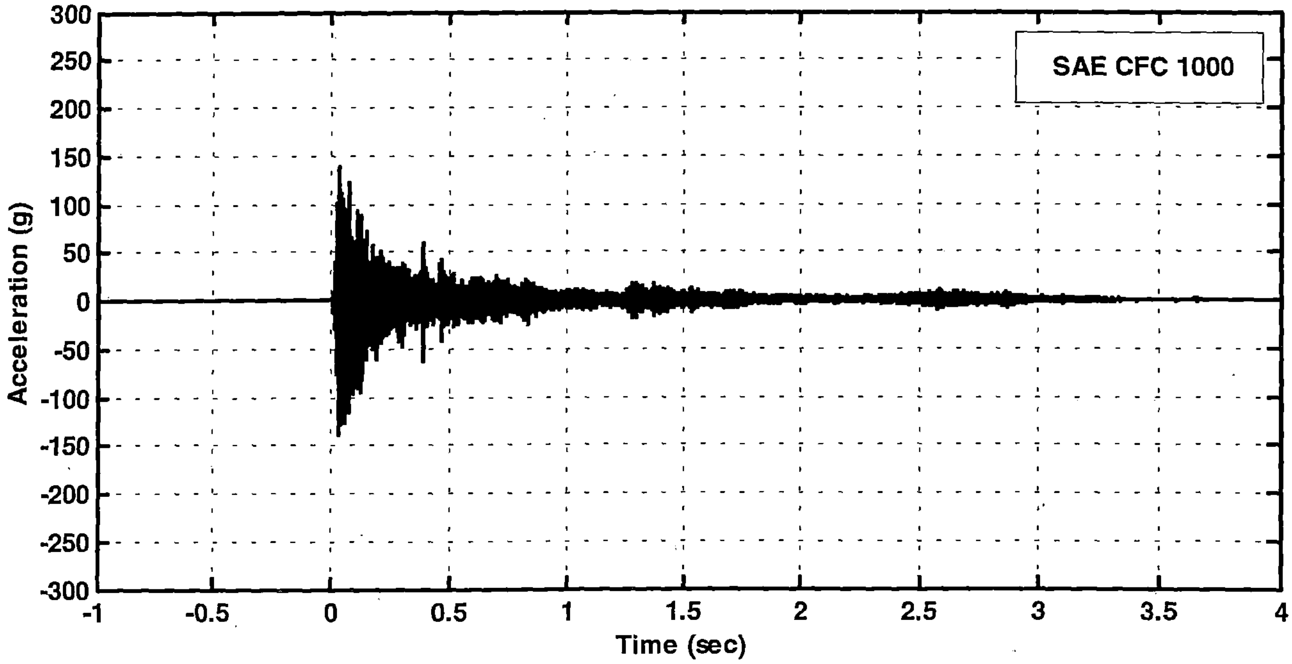

Figure B14. Locomotive event recorder, lateral acceleration
Channel Name: BL_RY

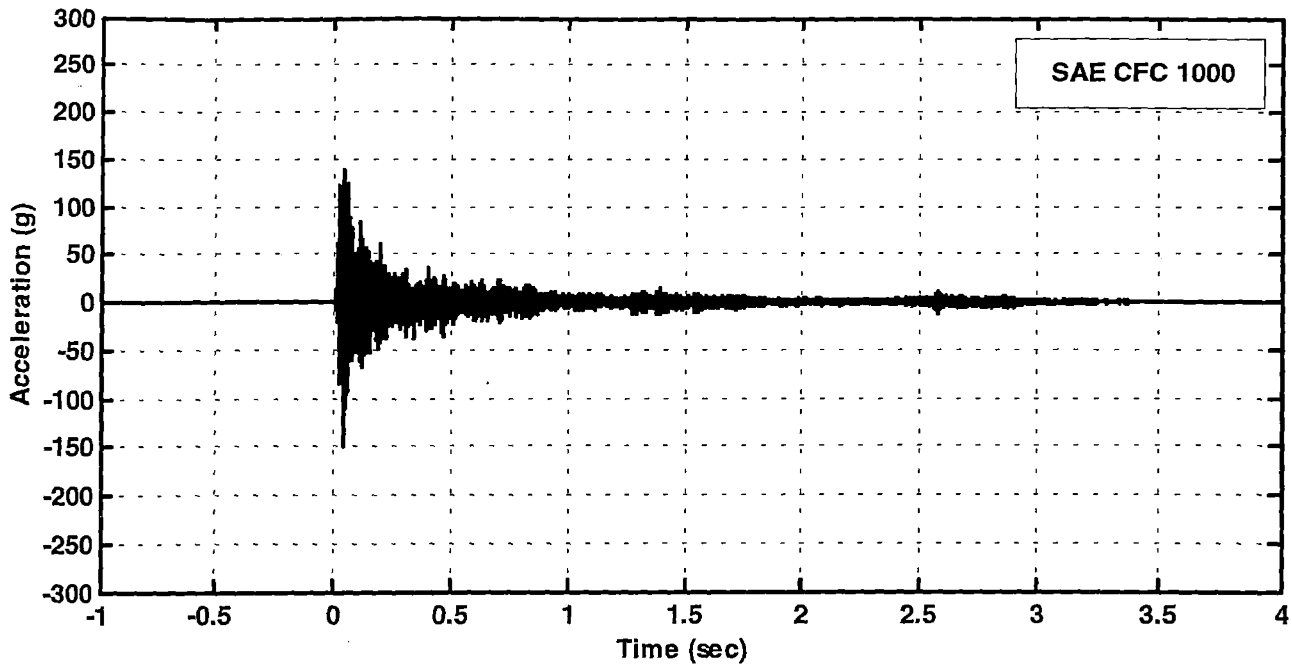

Figure B15. Locomotive event recorder, vertical acceleration
Channel Name: BL_RZ

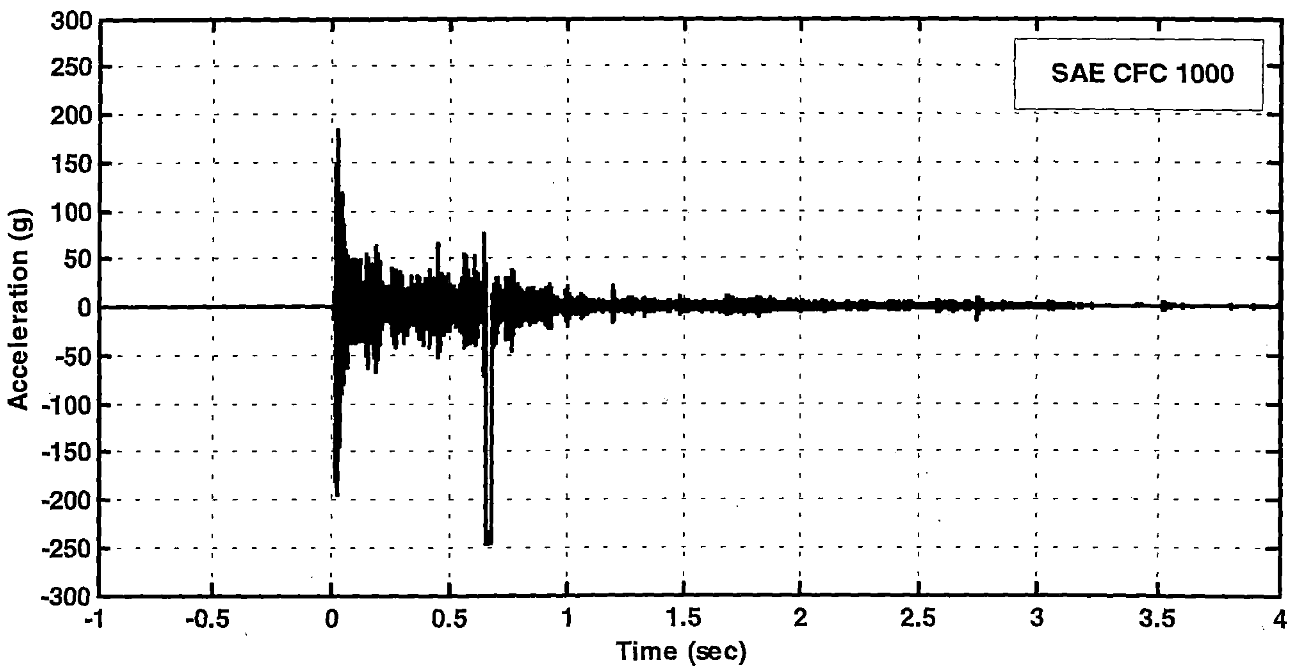

Figure B16. Target hopper 1, longitudinal acceleration
Channel Name: TH1_CGX

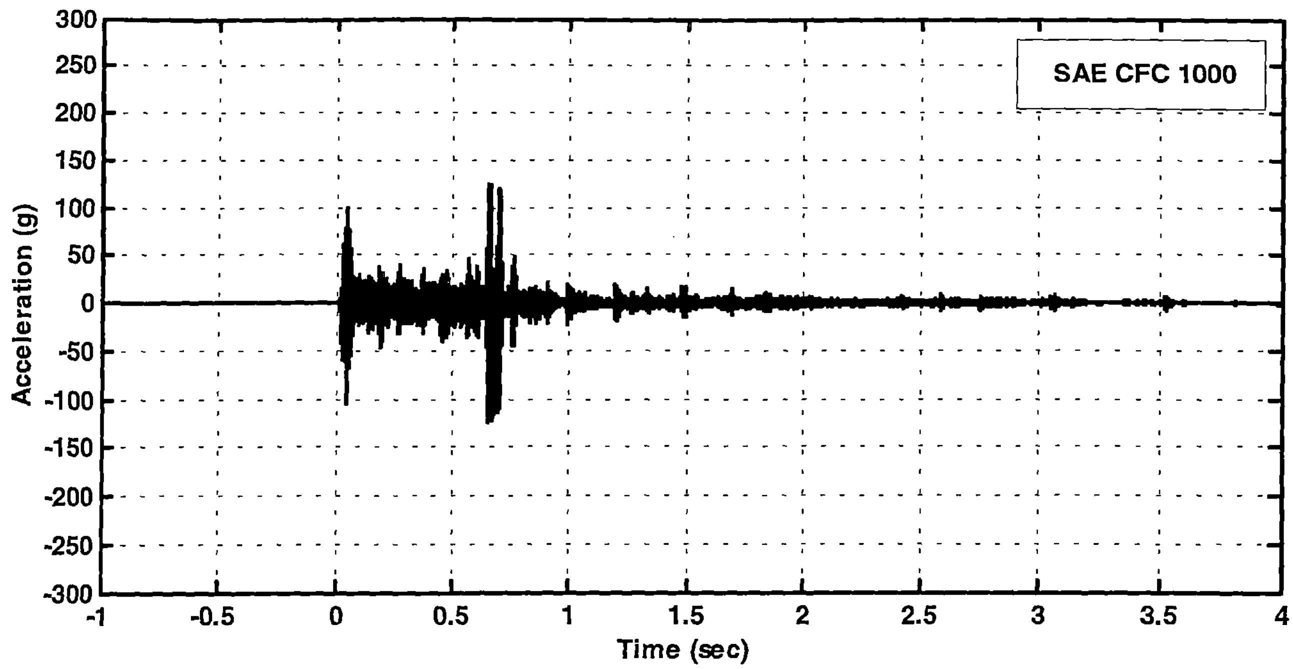

Figure B17. Target hopper 1, lateral acceleration
Channel Name: TH1_CGY

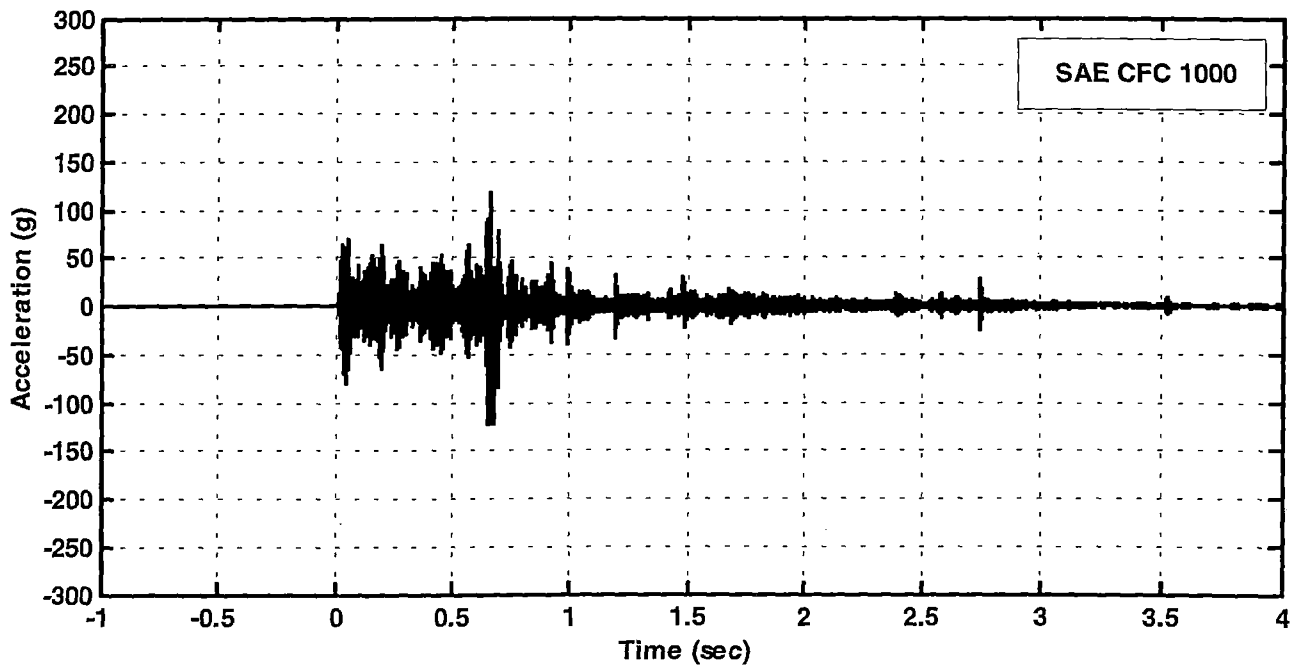

Figure B18. Target hopper 1, vertical acceleration
Channel Name: TH1_CGZ

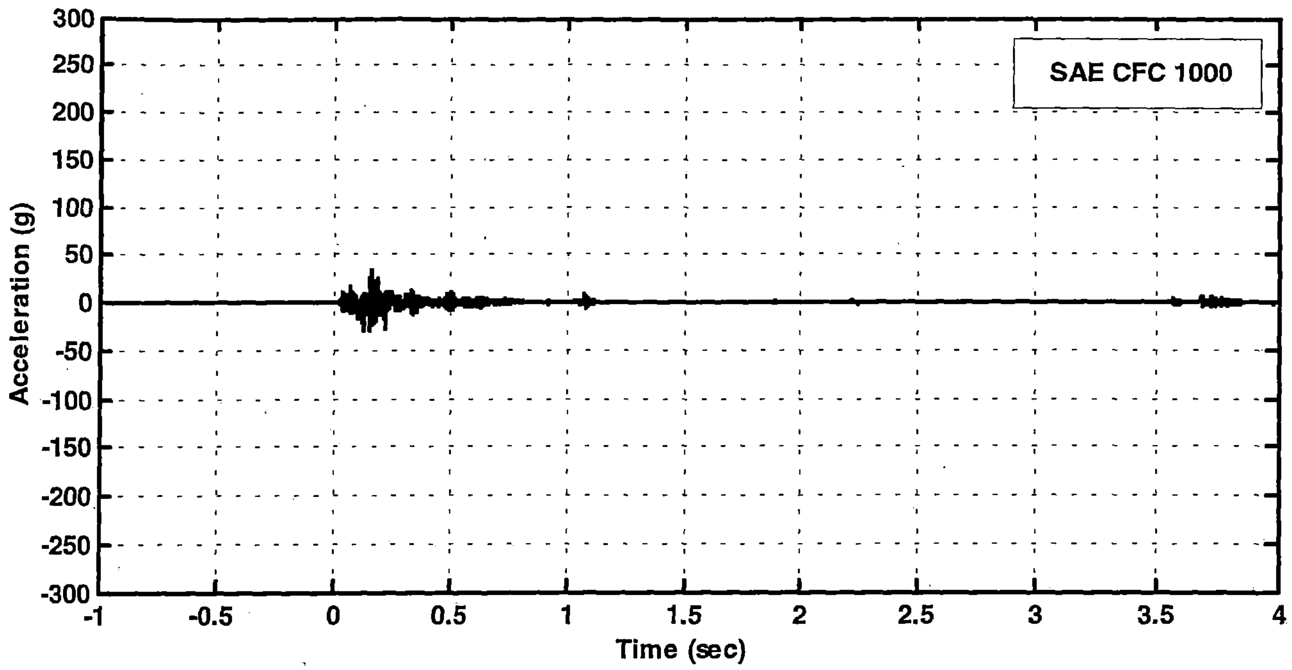

Figure B19. Target hopper 2, longitudinal acceleration
Channel Name: TH2_CGX

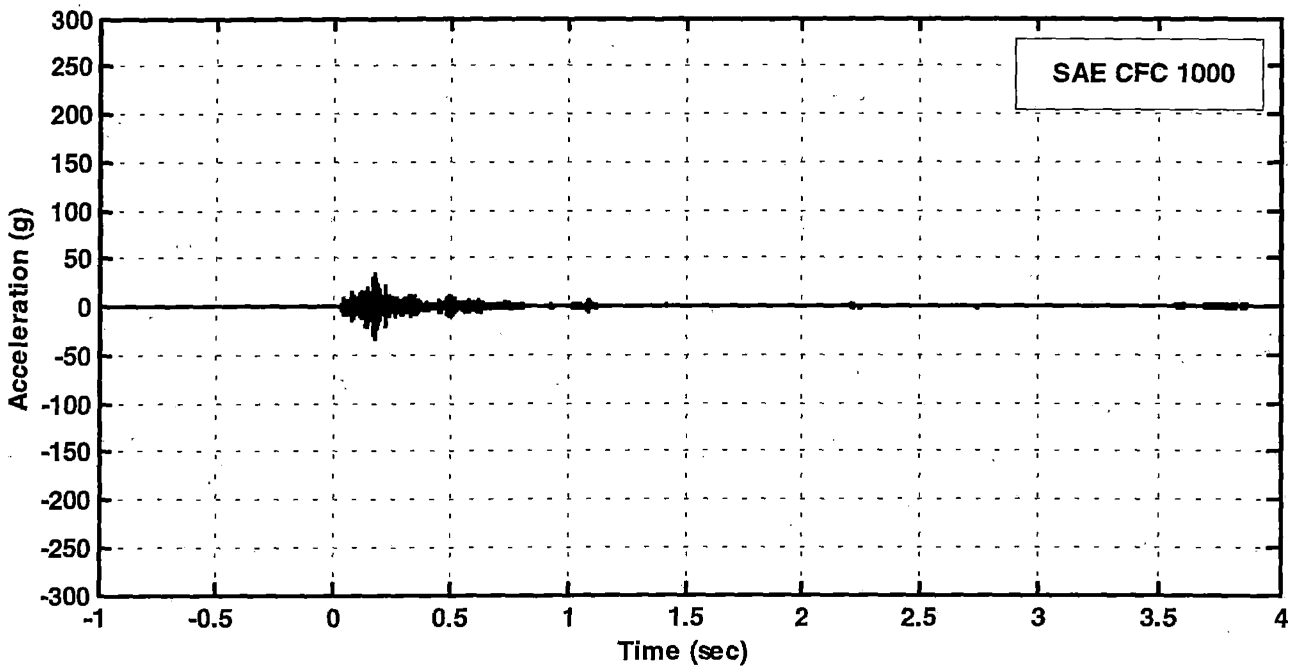

Figure B20. Target hopper 2, lateral acceleration
Channel Name: TH2_CGY

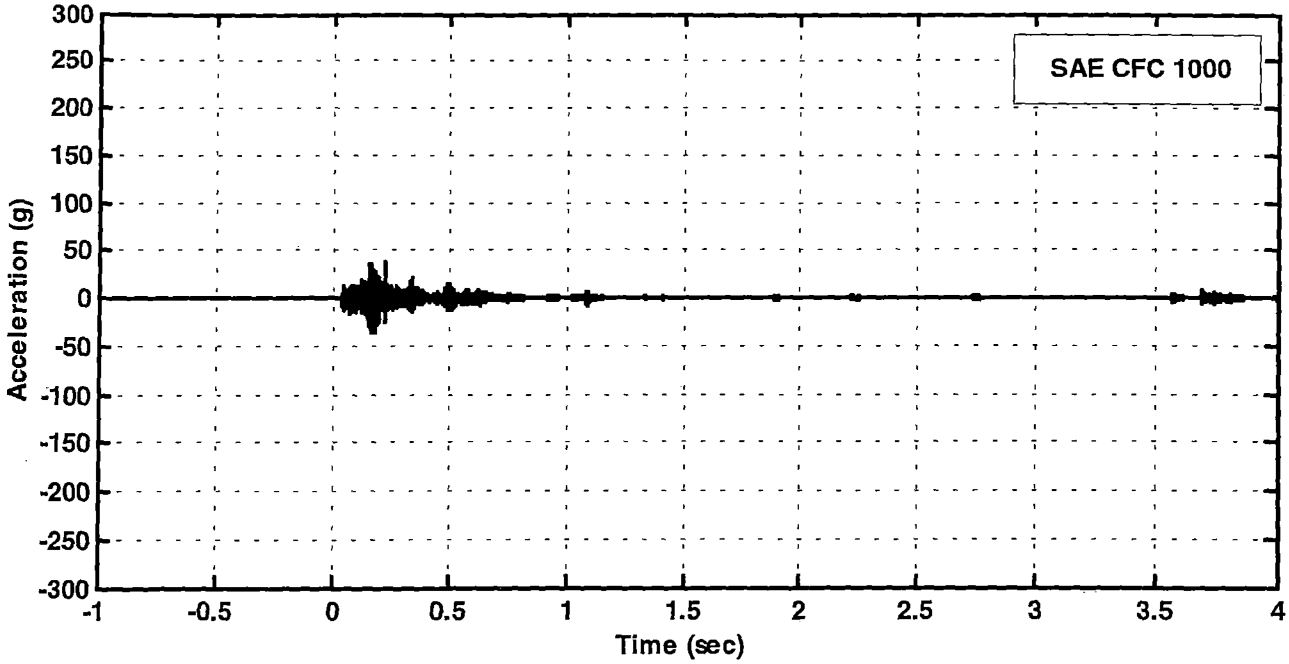

Figure B21. Target hopper 2, vertical acceleration
Channel Name: TH2_CGZ

APPENDIX C

Acceleration Data, Fc = 100 Hz

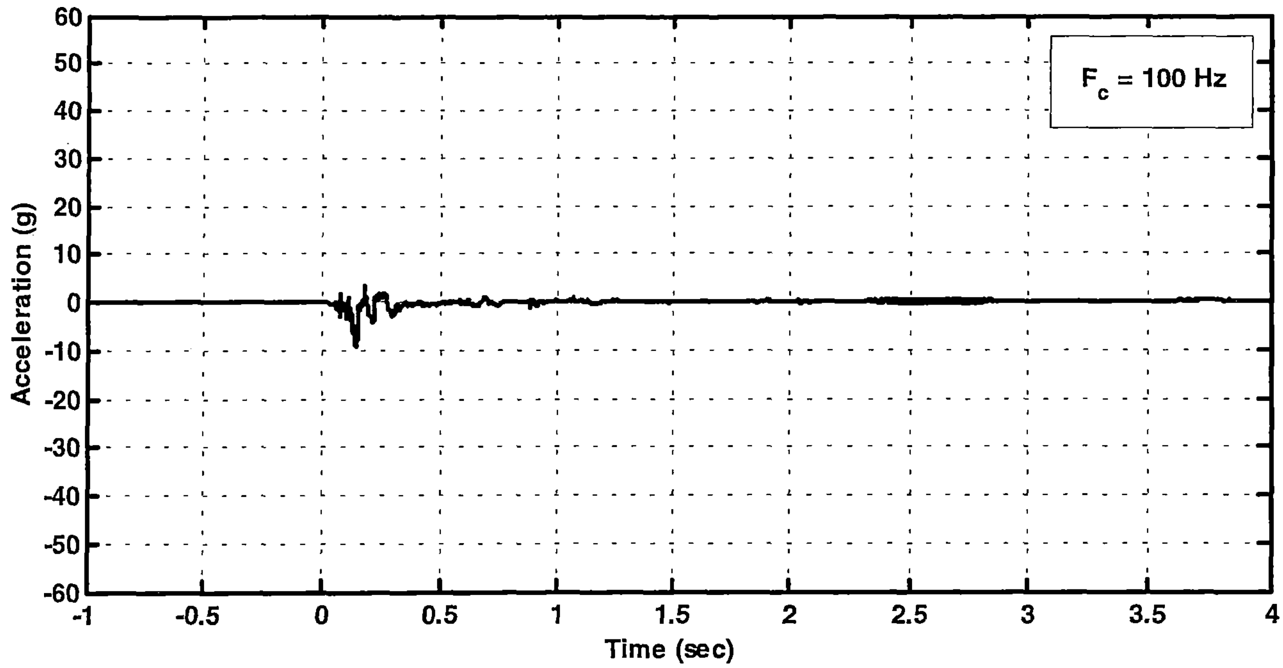

Figure C1. Bullet hopper 1, longitudinal acceleration
Channel Name: BH1_CGX

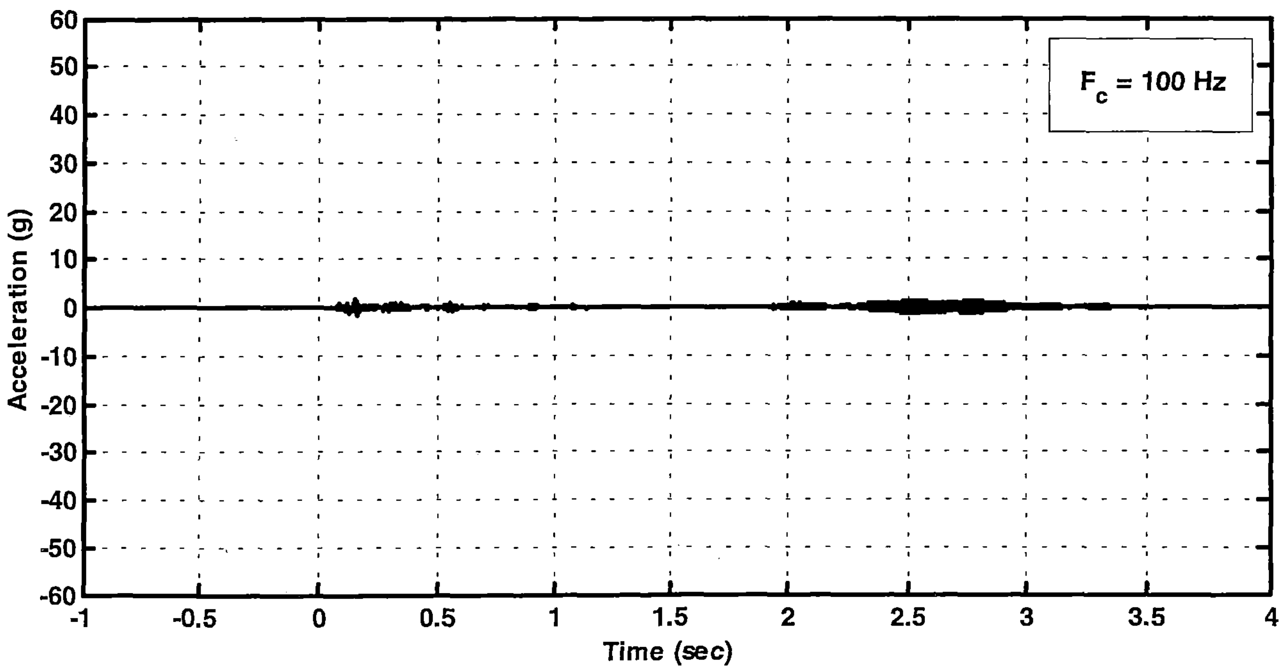

Figure C2. Bullet hopper 1, lateral acceleration
Channel Name: BH1_CGY

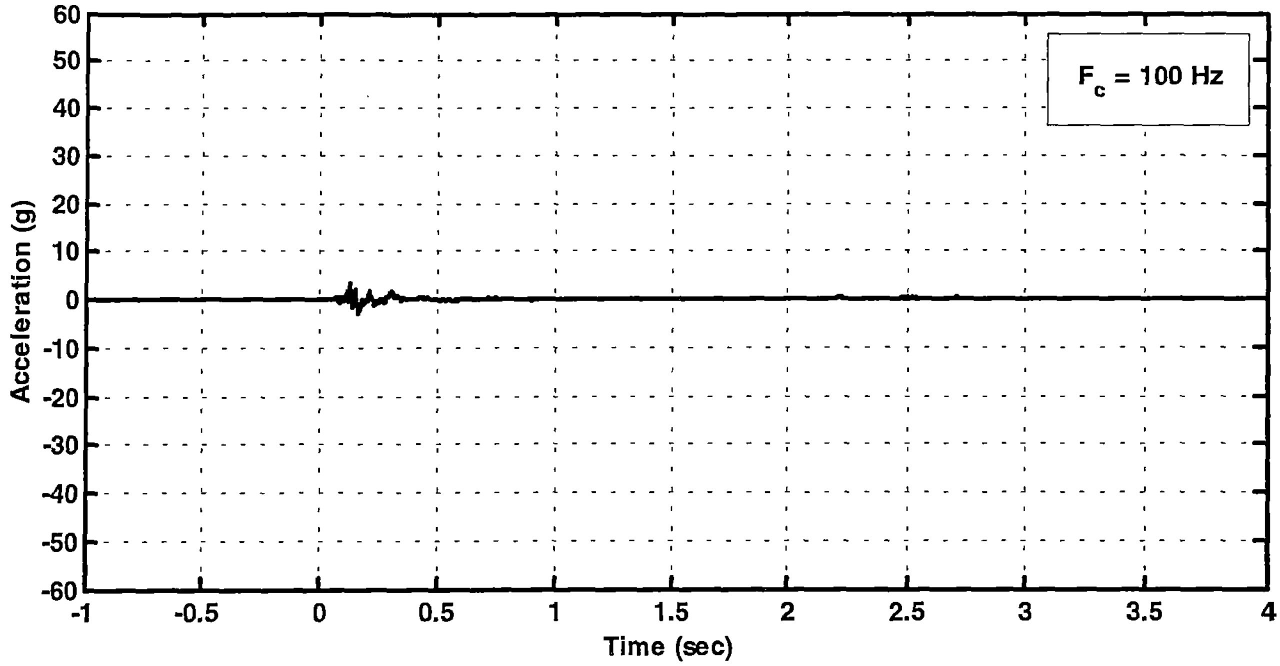

Figure C3. Bullet hopper 1, vertical acceleration
Channel Name: BH1_CGZ

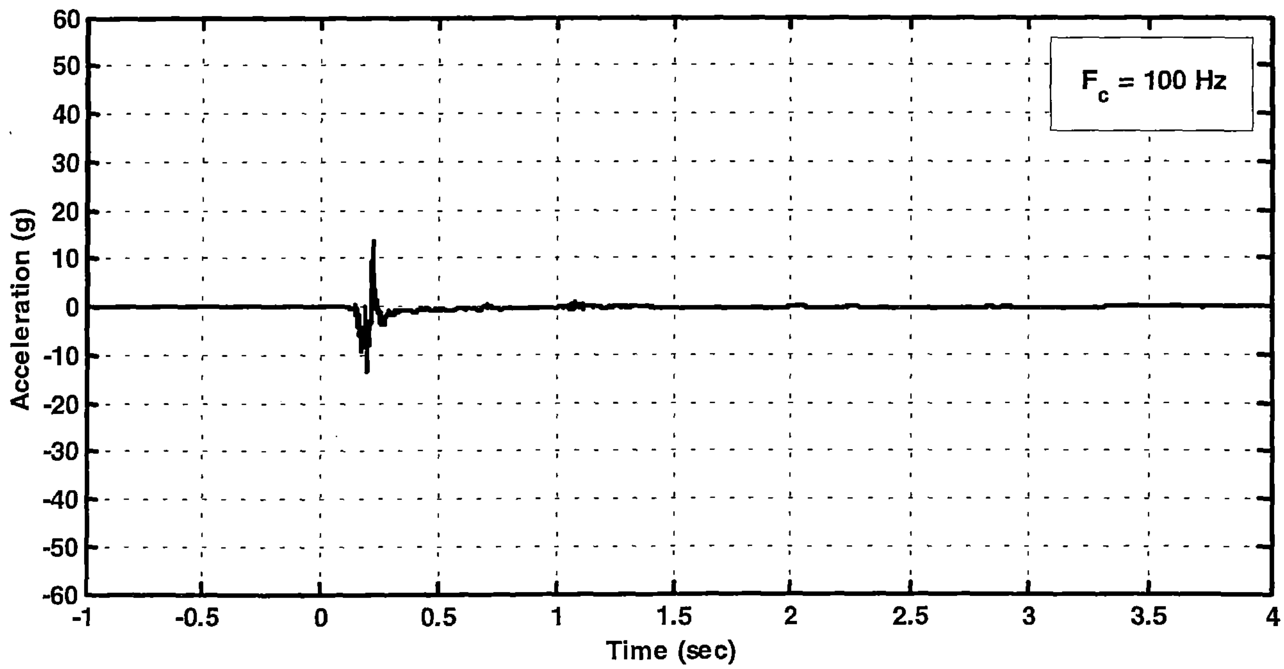

Figure C4. Bullet hopper 2, longitudinal acceleration
Channel Name: BH2_CGX

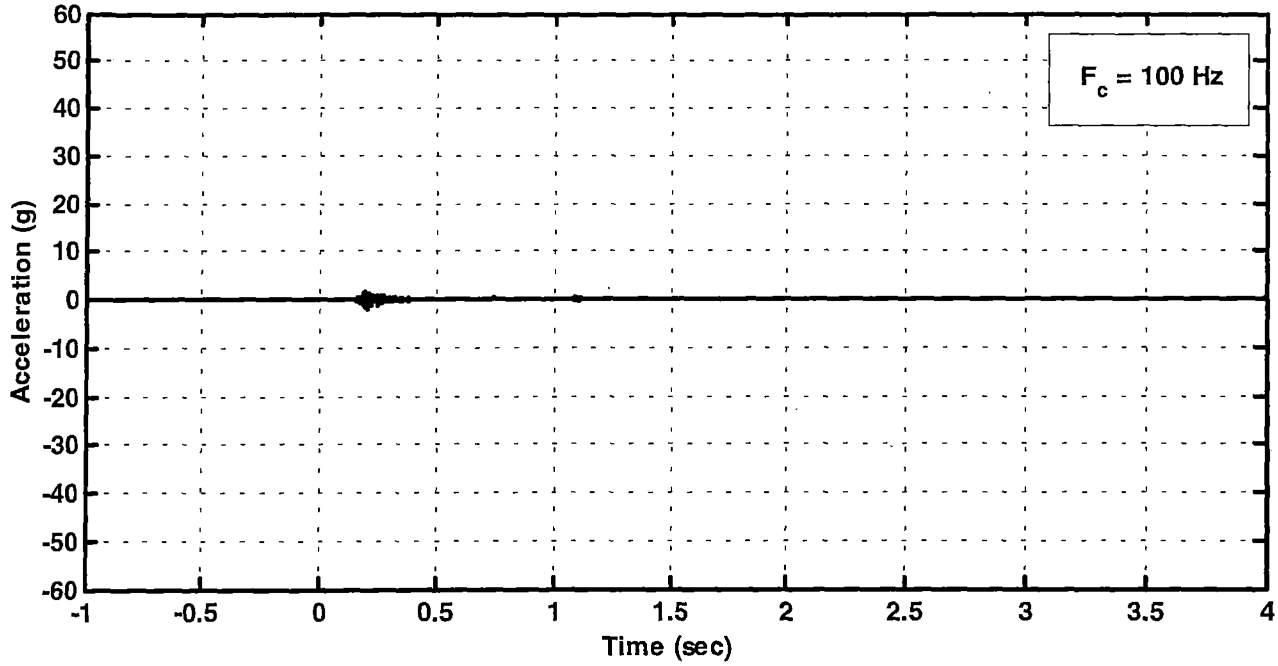

Figure C5. Bullet hopper 2, lateral acceleration
Channel Name: BH2_CGY

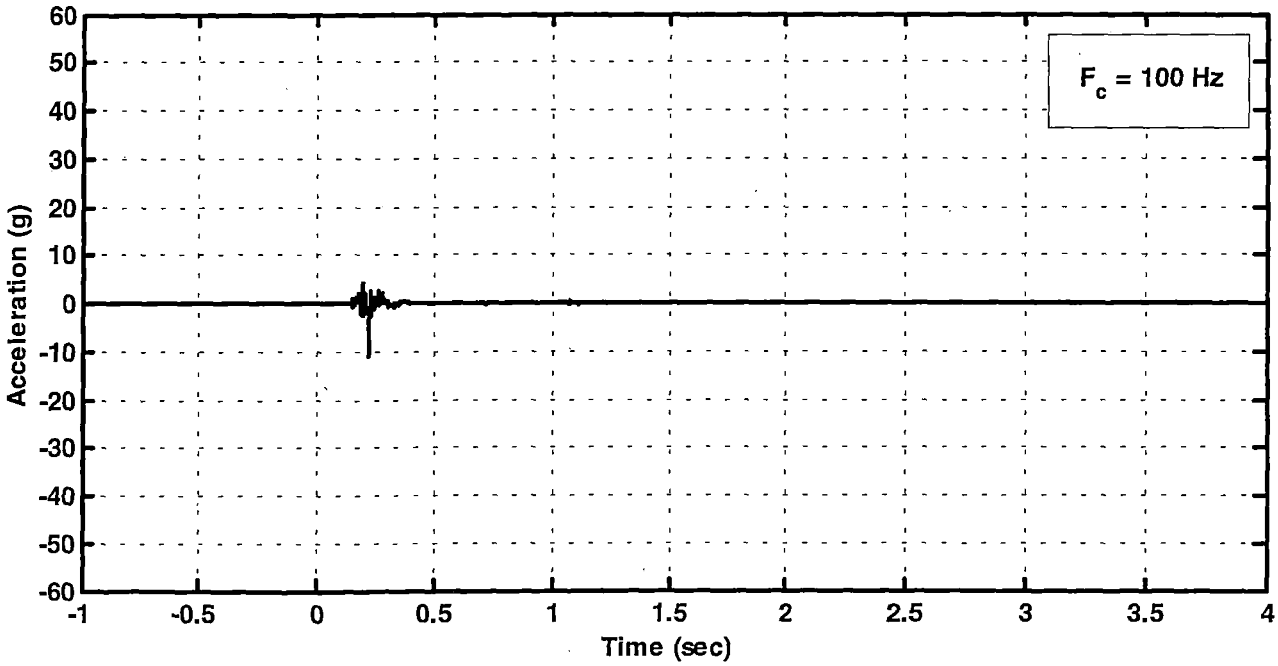

Figure C6. Bullet hopper 2, vertical acceleration
Channel Name: BH2_CGZ

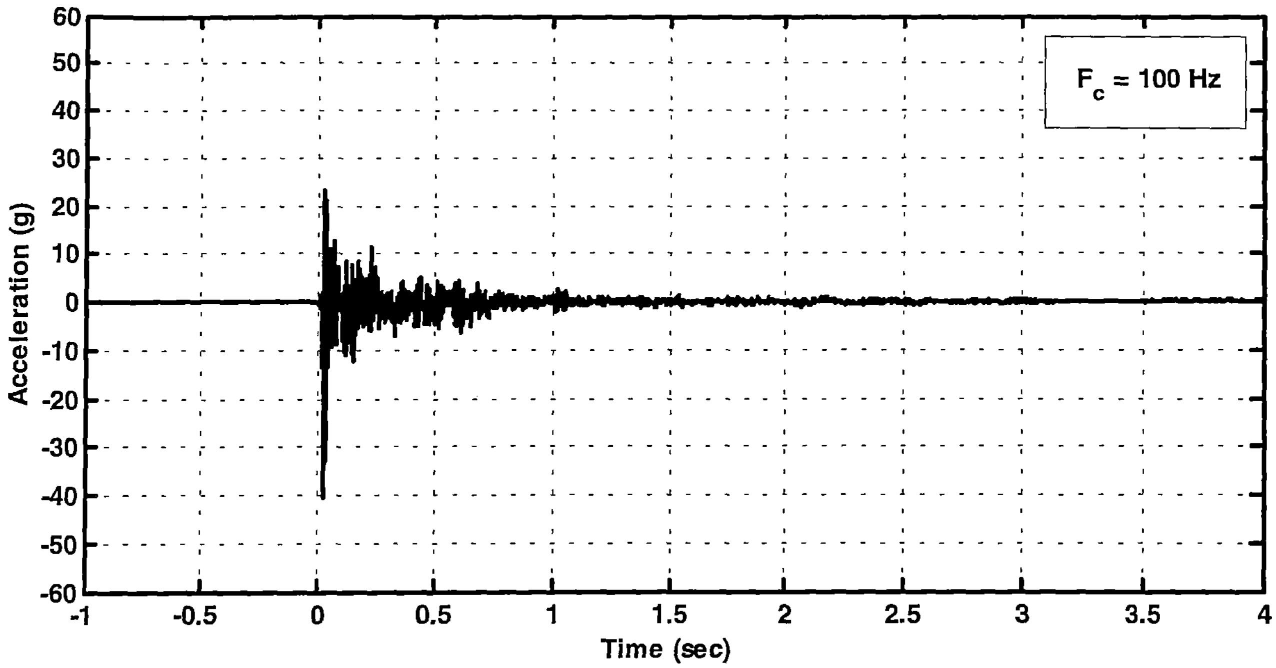

Figure C7. Locomotive floor, location 1, longitudinal acceleration
Channel Name: BL_F1X

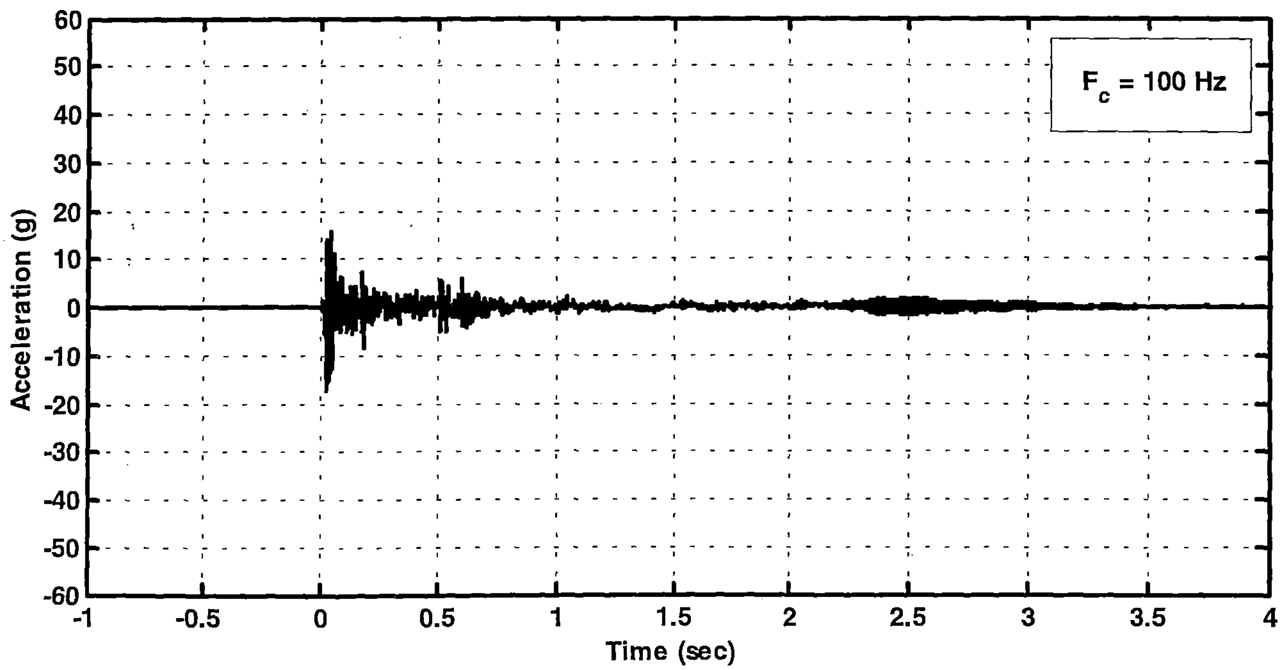

Figure C8. Locomotive floor, location 1, lateral acceleration
Channel Name: BL_F1Y

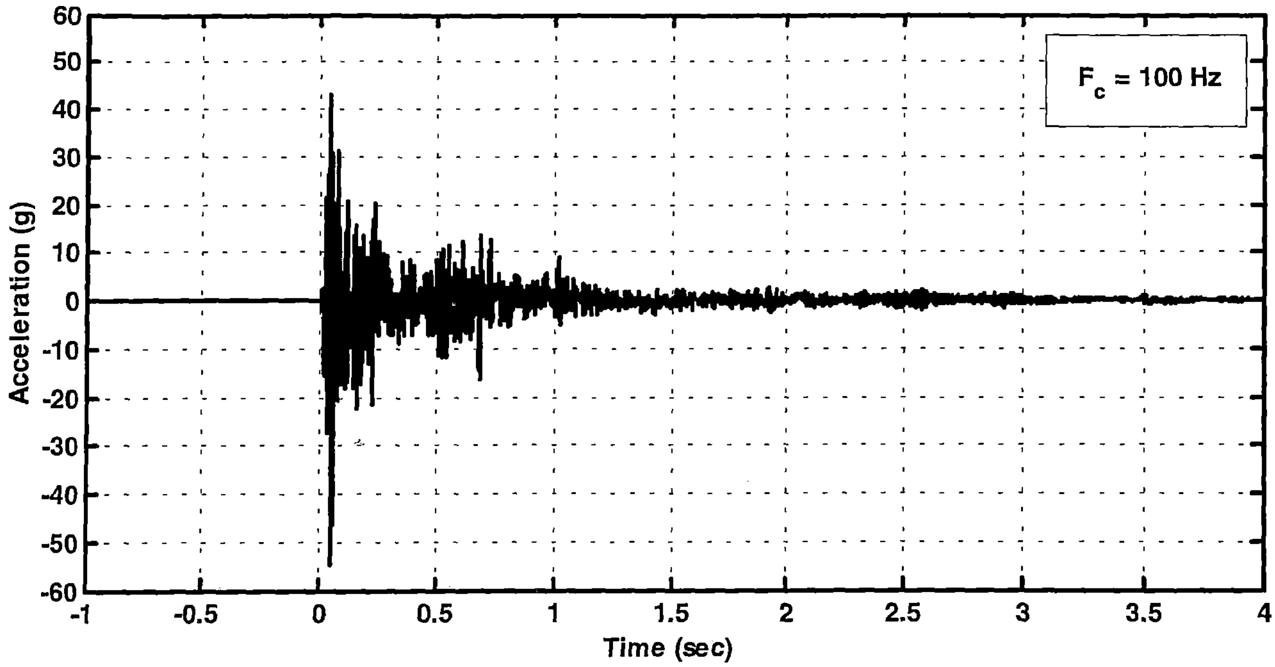

Figure C9. Locomotive floor, location 1, vertical acceleration
Channel Name: BL_F1Z

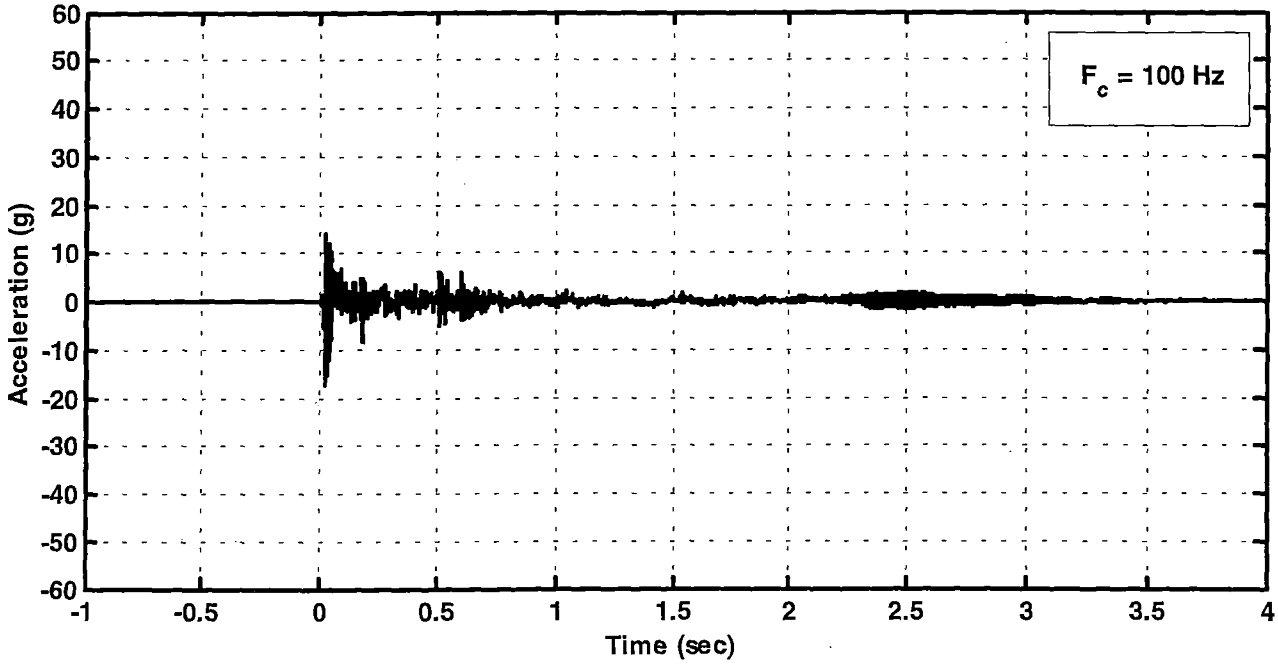

Figure C10. Locomotive floor, location 2, lateral acceleration
Channel Name: BL_F2Y

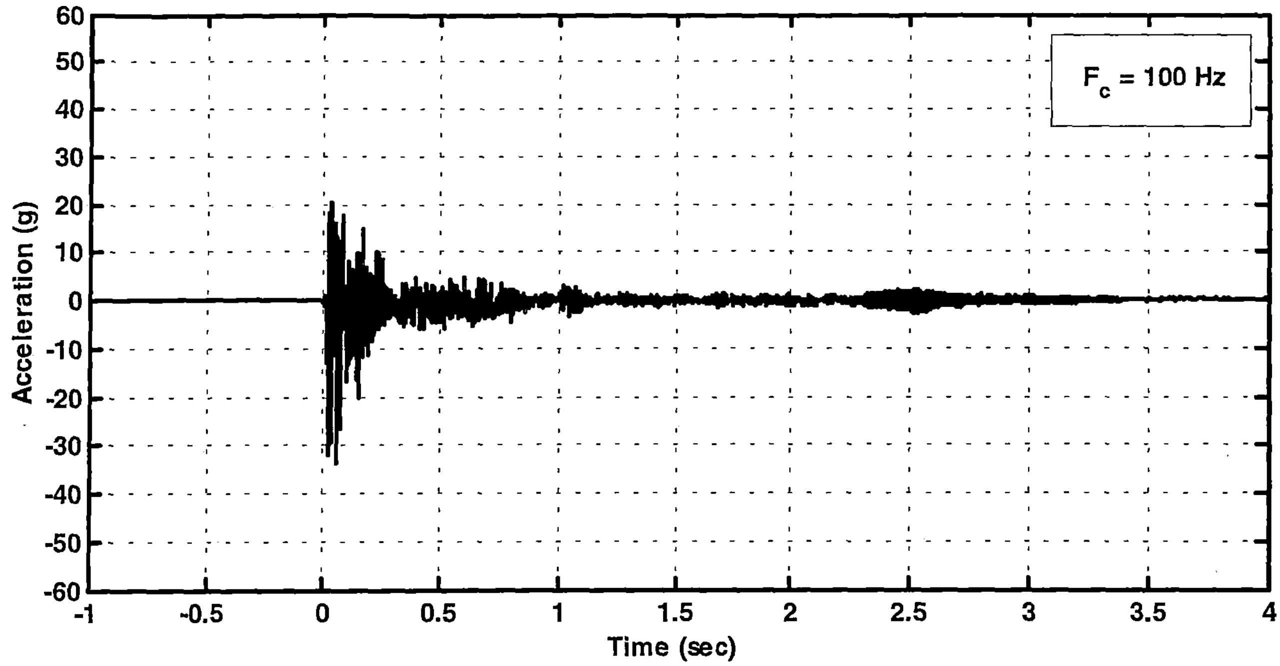

Figure C11. Locomotive event recorder, longitudinal acceleration
Channel Name: BL_RX

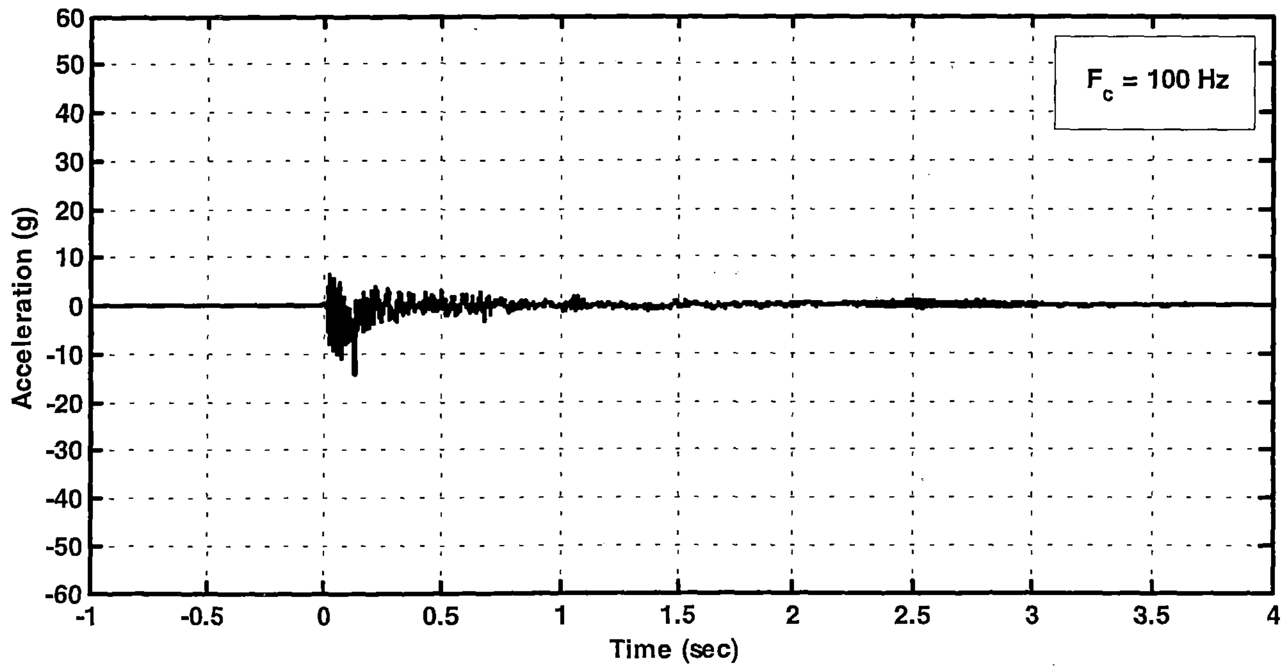

Figure C12. Locomotive event recorder, lateral acceleration
Channel Name: BL_RY

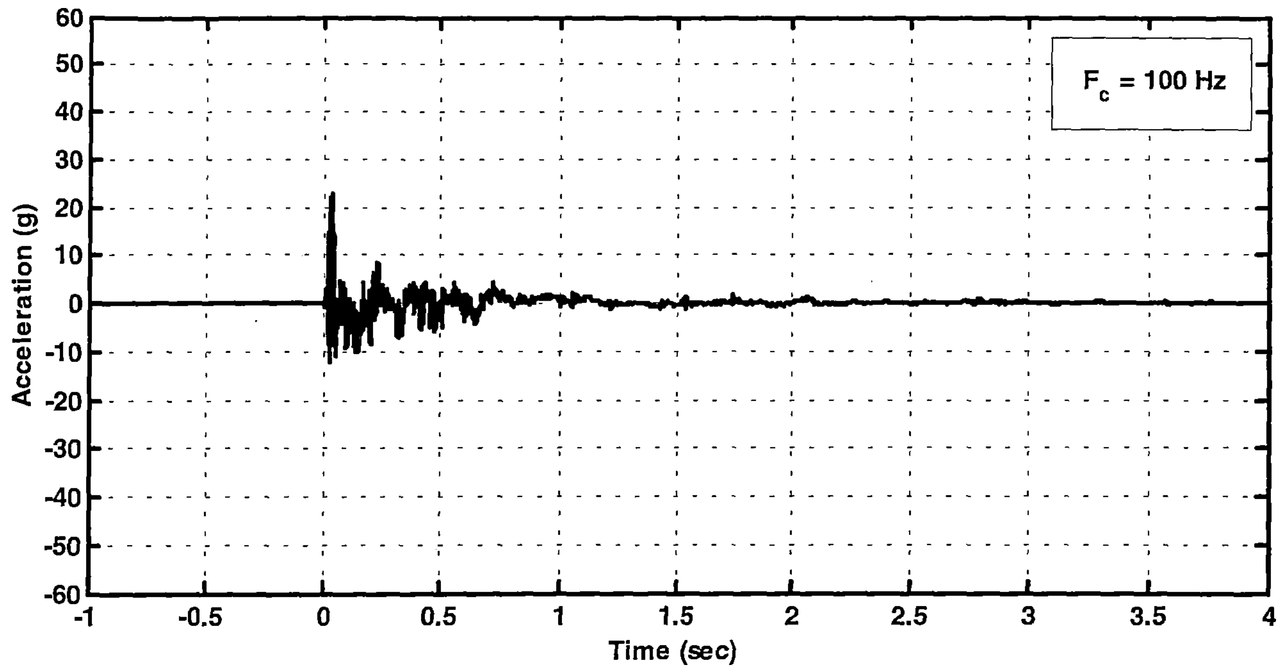

Figure C13. Locomotive event recorder, vertical acceleration
Channel Name: BL_RZ

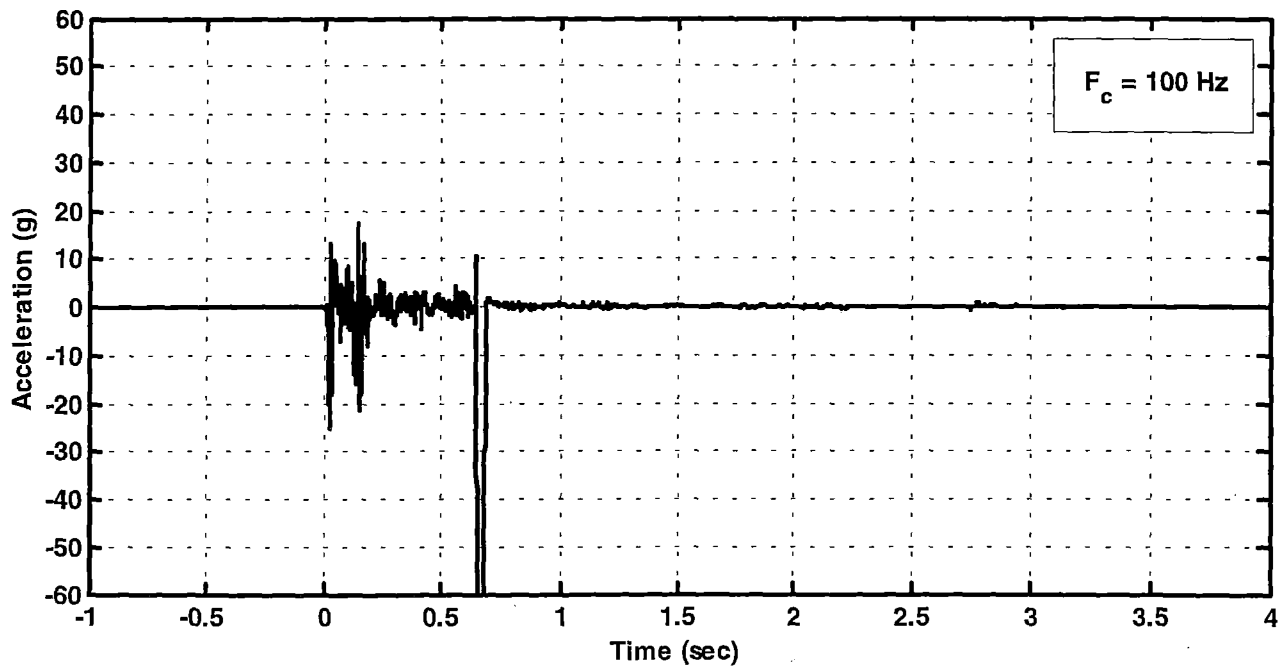

Figure C14. Target hopper 1, longitudinal acceleration
Channel Name: TH1_CGX

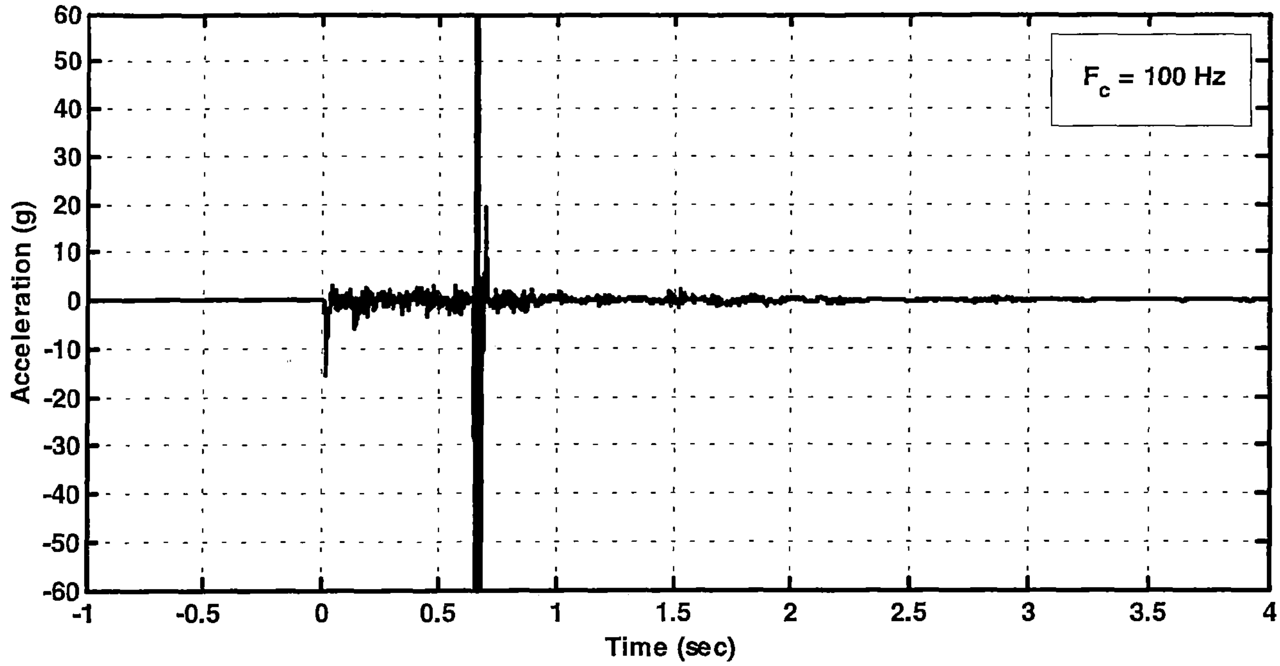

Figure C15. Target hopper 1, lateral acceleration
Channel Name: TH1_CGY

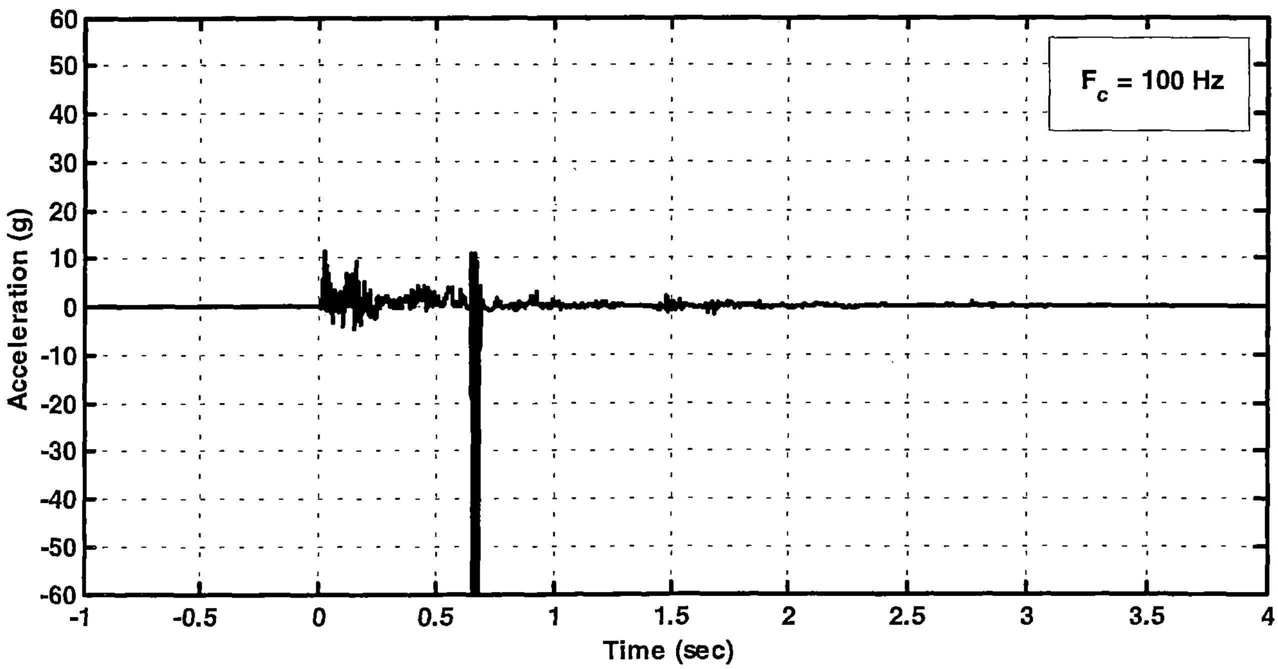

Figure C16. Target hopper 1, vertical acceleration
Channel Name: TH1_CGZ

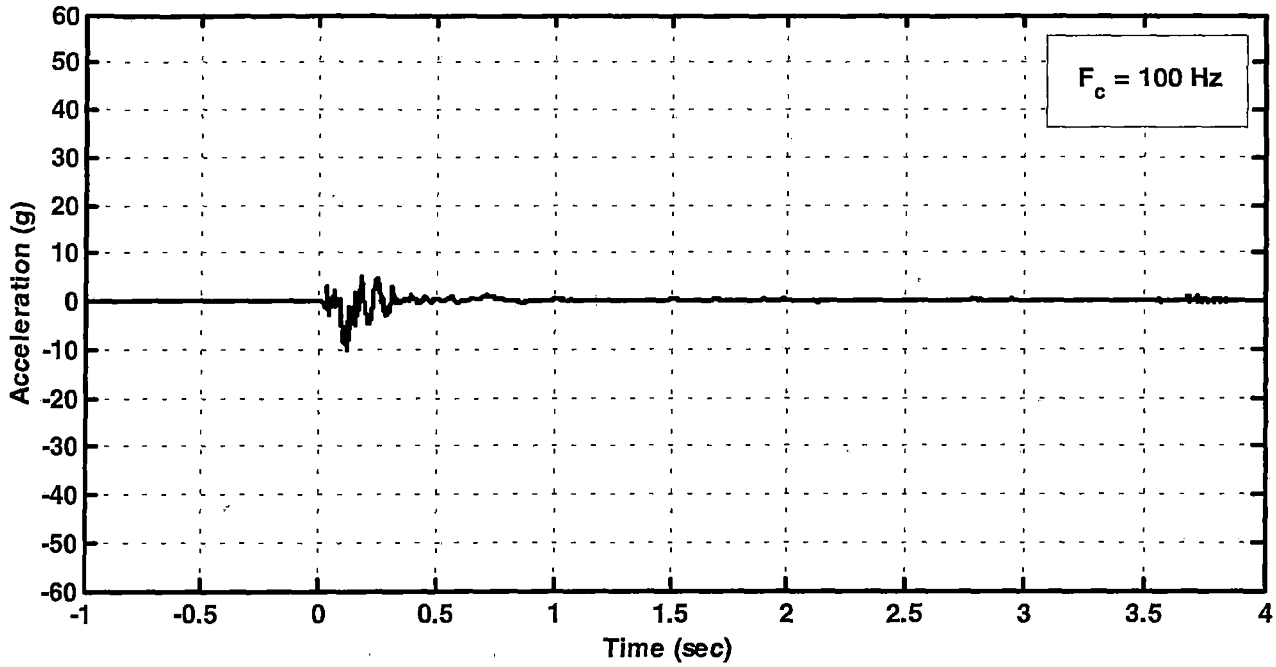

Figure C17. Target hopper 2, longitudinal acceleration
Channel Name: TH2_CGX

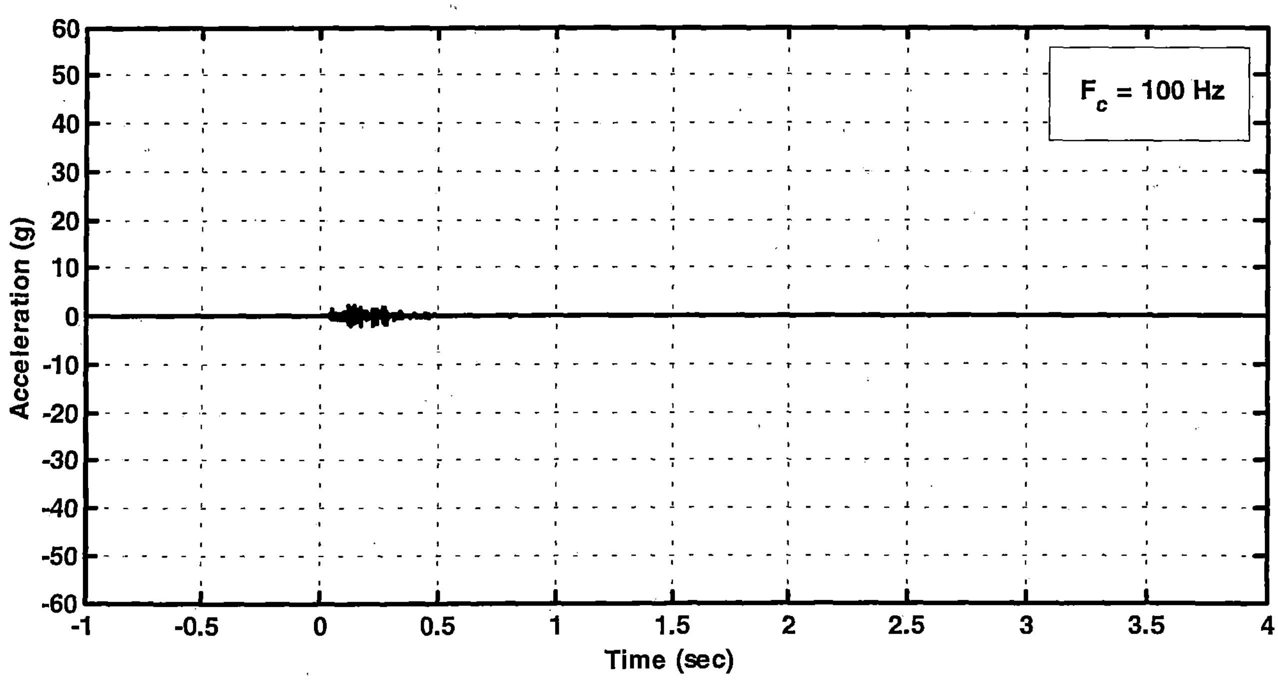

Figure C18. Target hopper 2, lateral acceleration
Channel Name: TH2_CGY

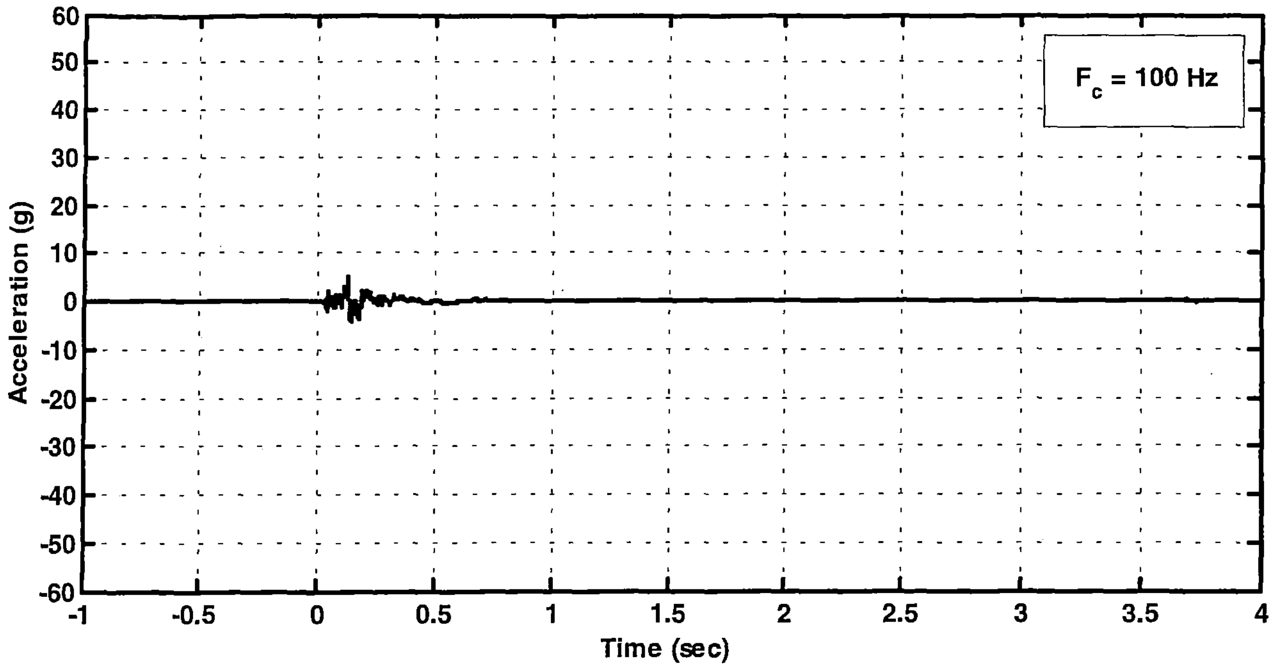

Figure C19. Target hopper 2, vertical acceleration
Channel Name: TH2_CGZ

APPENDIX D

Acceleration Data, Fc = 25 Hz

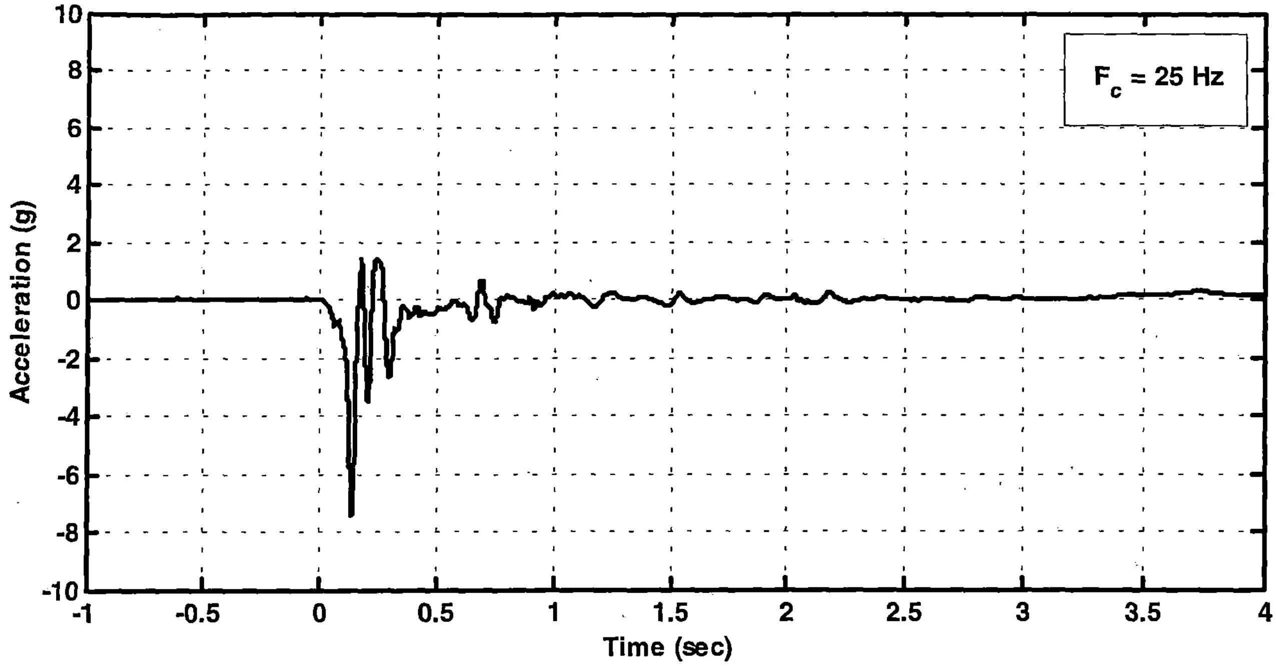

Figure D1. Bullet hopper 1, longitudinal acceleration
Channel Name: BH1_CGX

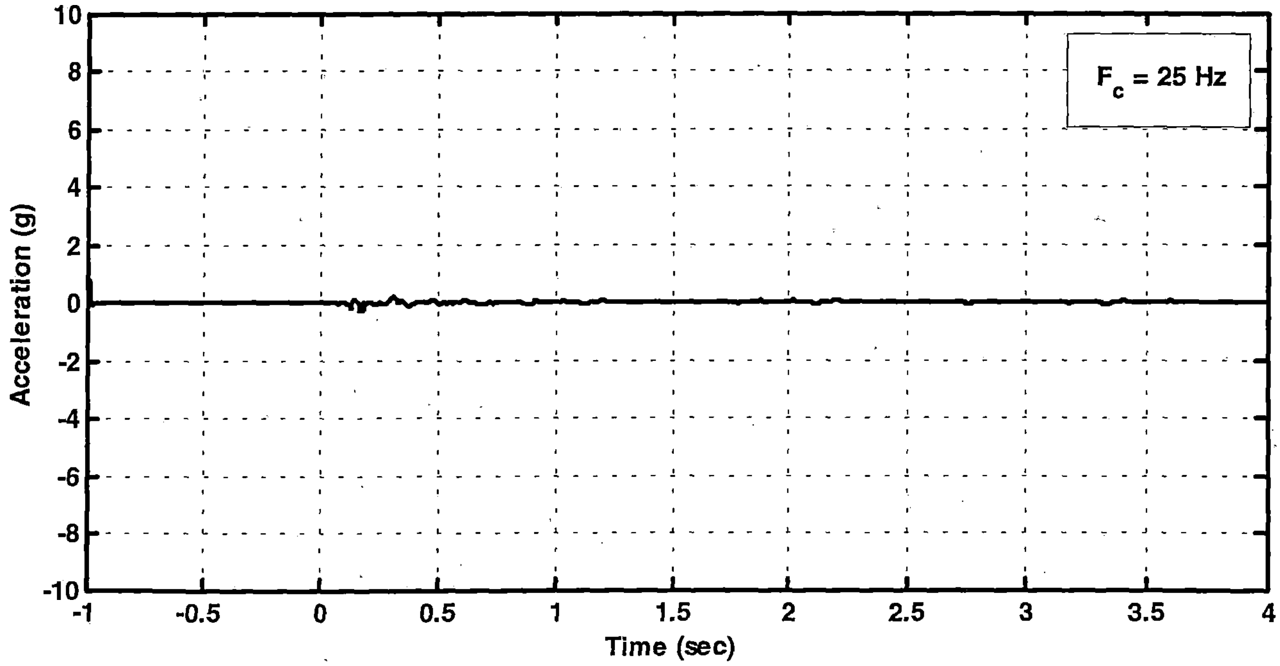

Figure D2. Bullet hopper 1, lateral acceleration
Channel Name: BH1_CGY

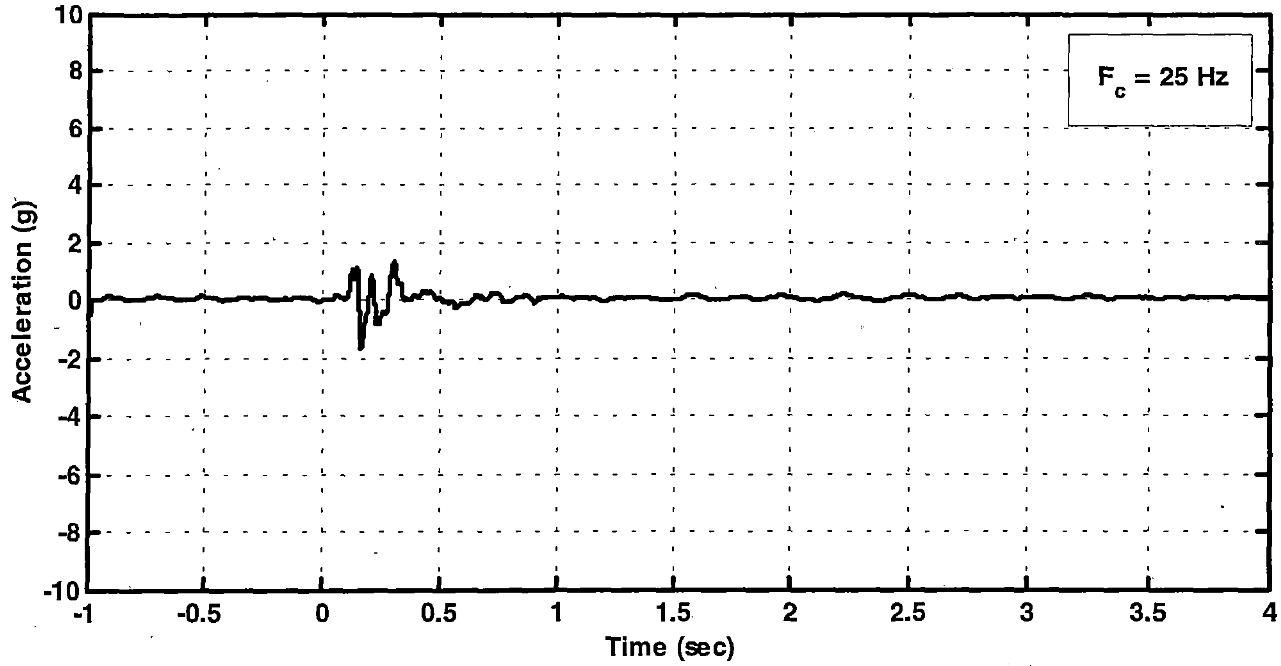

Figure D3. Bullet hopper 1, vertical acceleration
Channel Name: BH1_CGZ

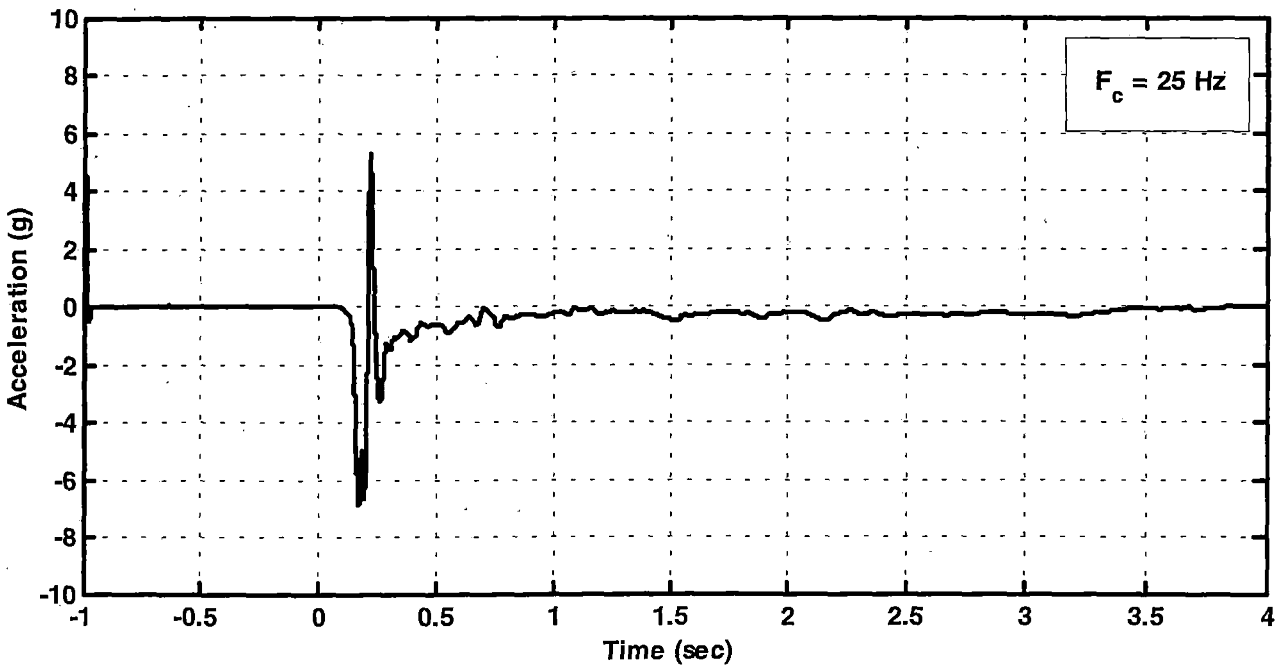

Figure D4. Bullet hopper 2, longitudinal acceleration
Channel Name: BH2_CGX

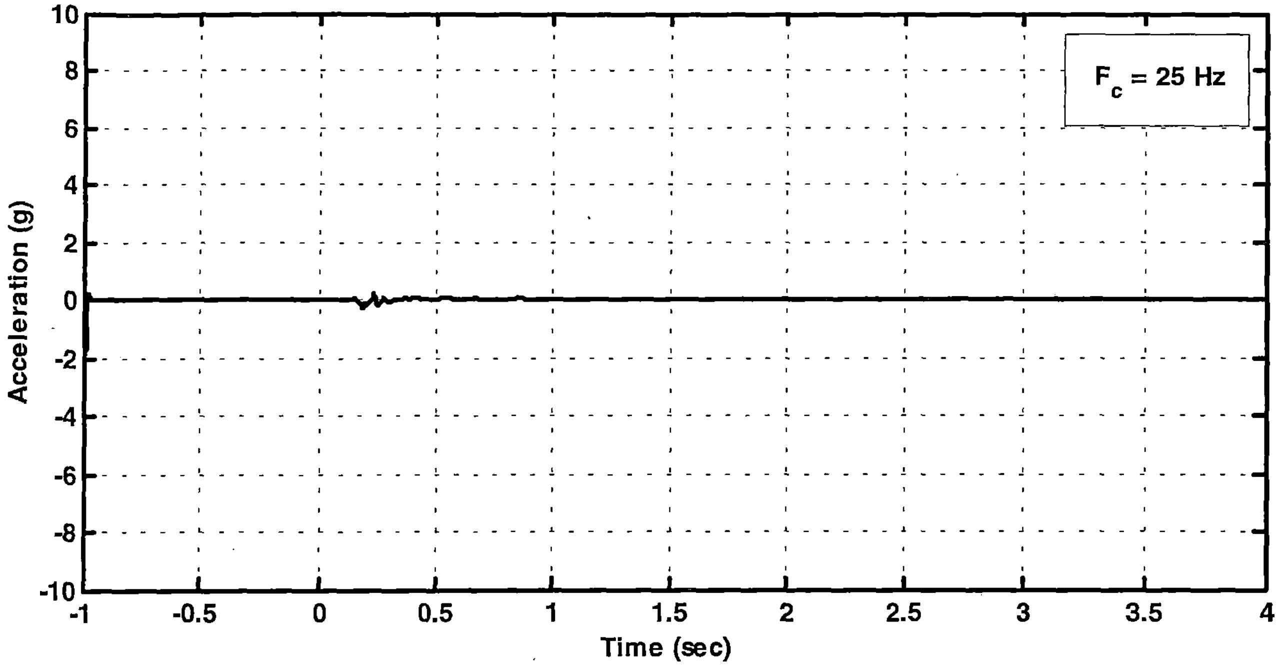

Figure D5. Bullet hopper 2, lateral acceleration
Channel Name: BH2_CGY

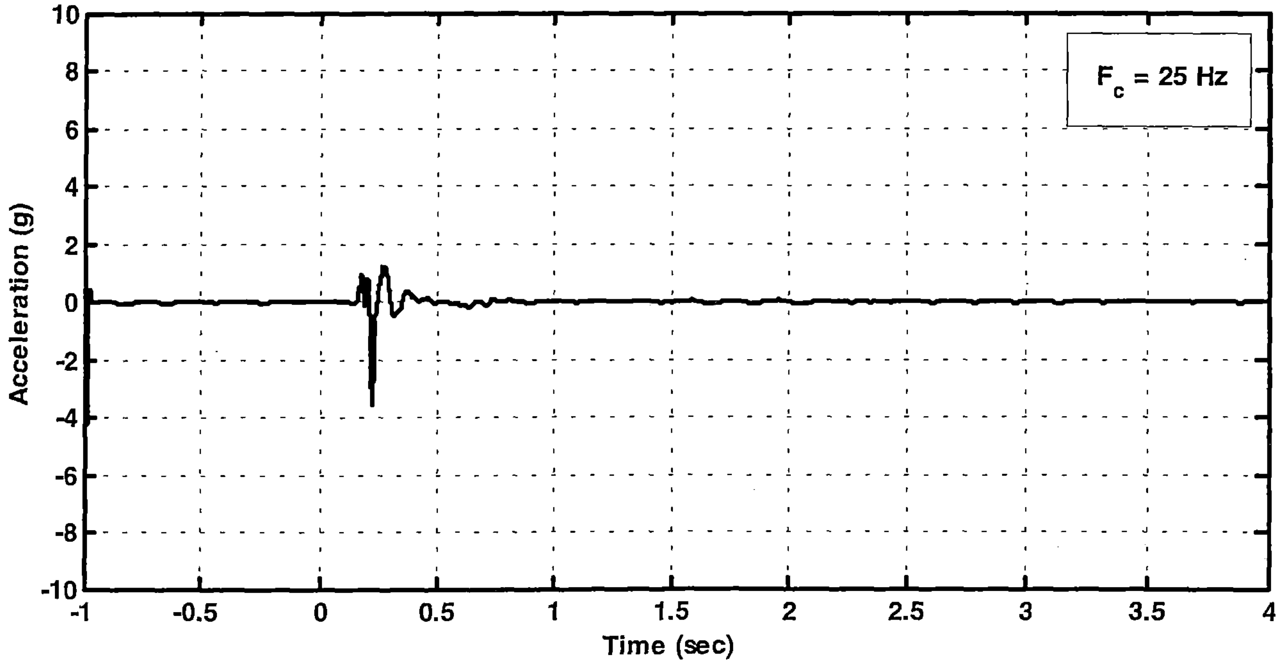

Figure D6. Bullet hopper 2, vertical acceleration
Channel Name: BH2_CGZ

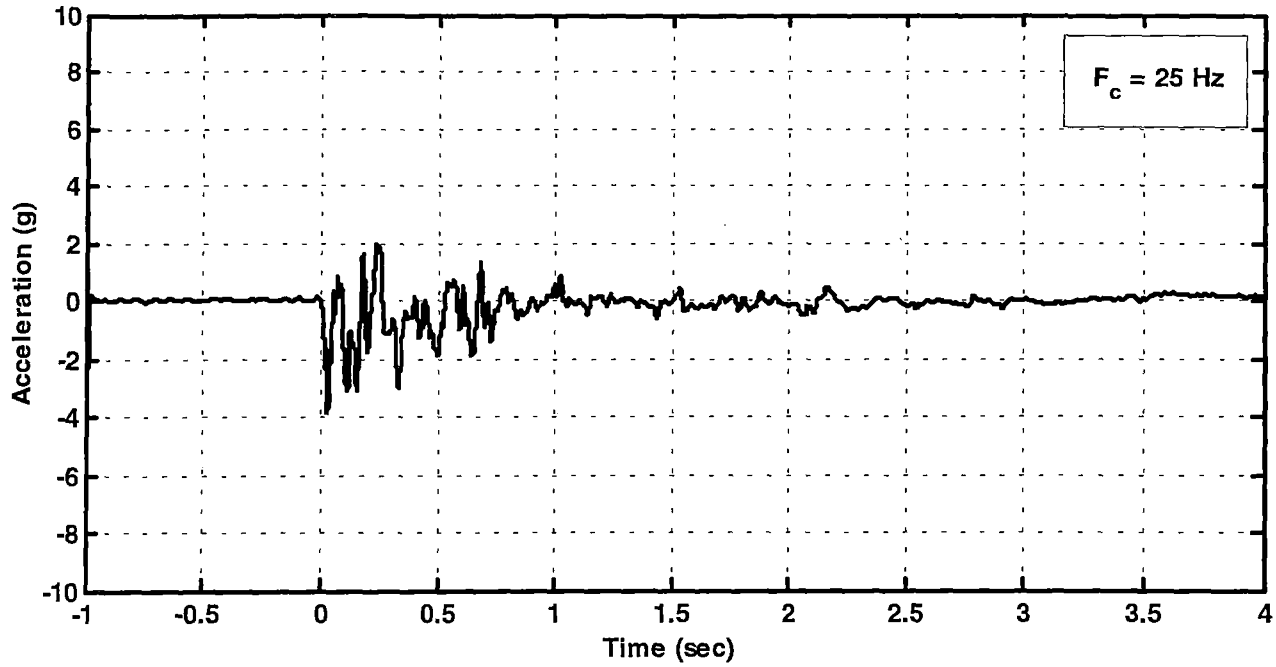

Figure D7. Locomotive floor, location 1, longitudinal acceleration
Channel Name: BL_F1X

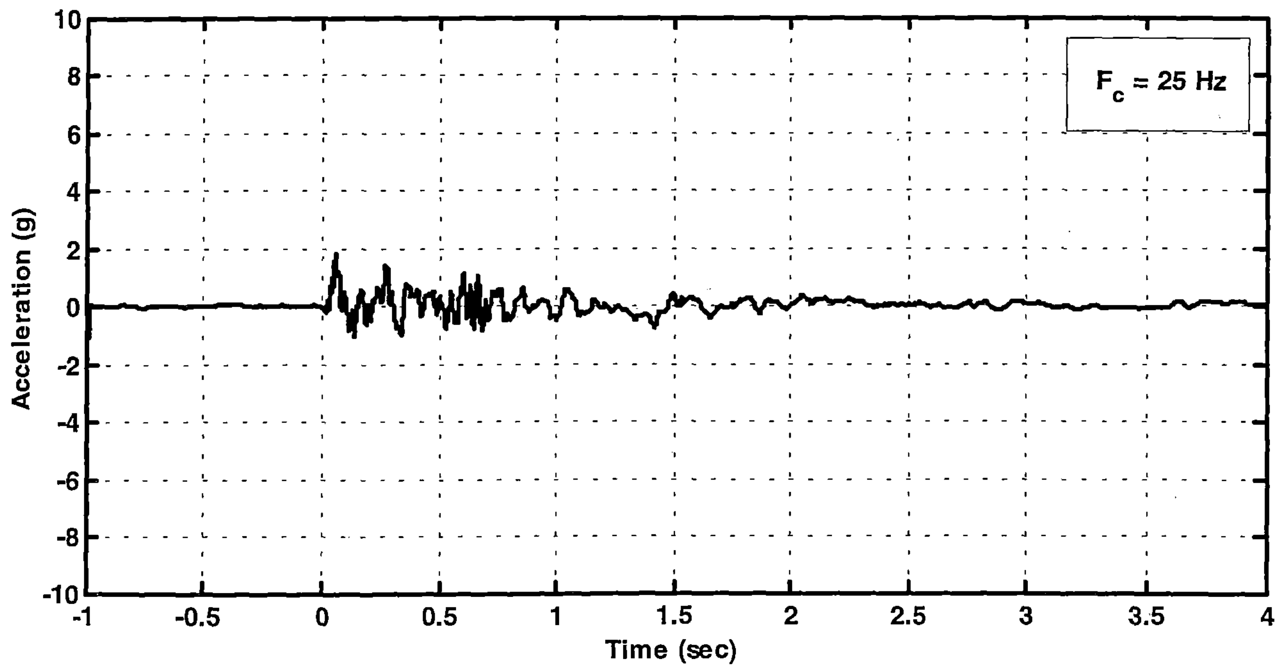

Figure D8. Locomotive floor, location 1, lateral acceleration
Channel Name: BL_F1Y

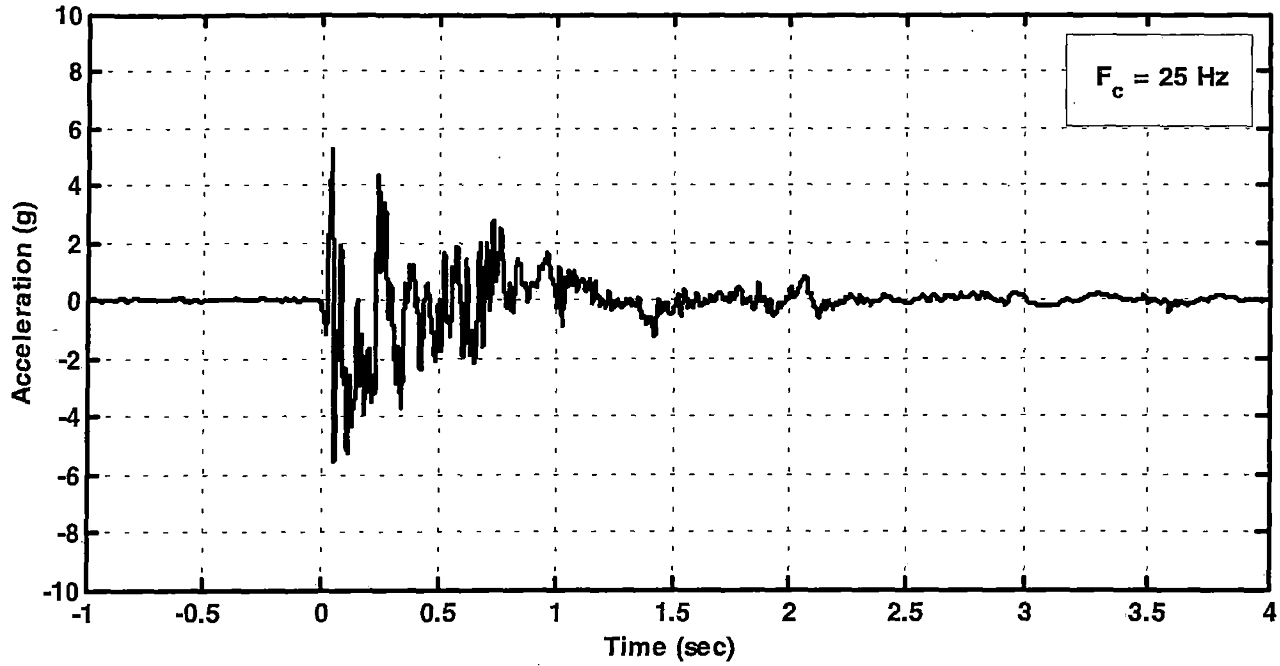

Figure D9. Locomotive floor, location 1, vertical acceleration
Channel Name: BL_F1Z

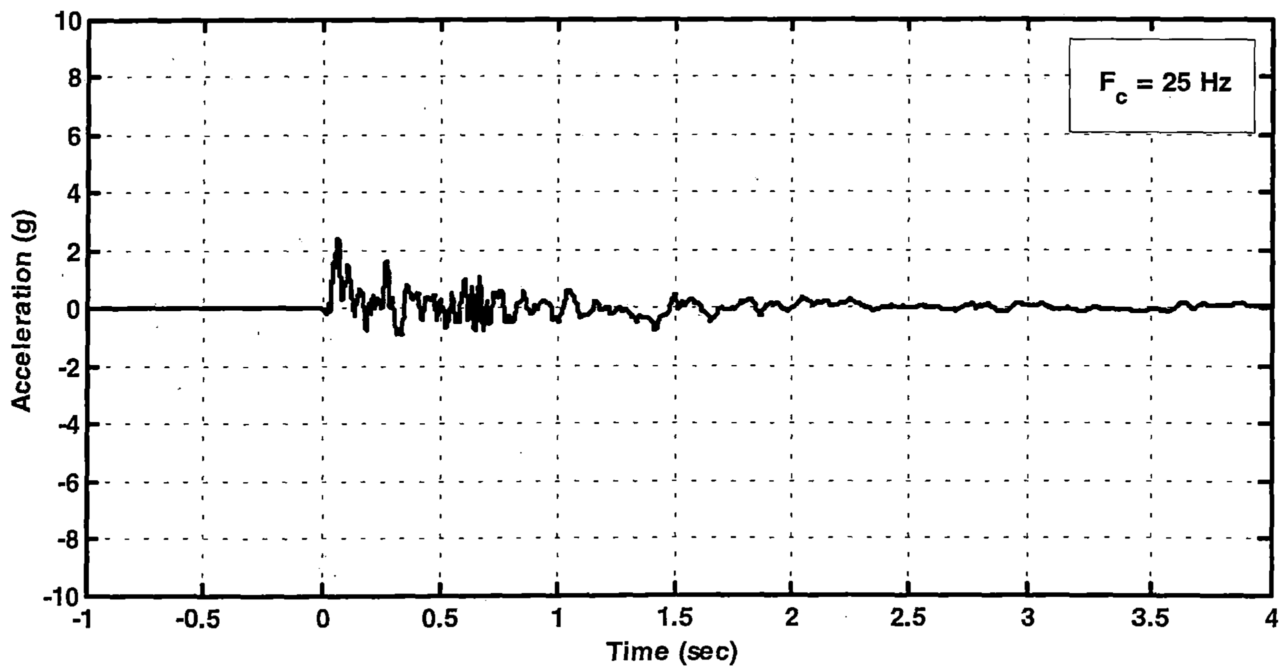

Figure D10. Locomotive floor, location 2, lateral acceleration
Channel Name: BL_F2Y

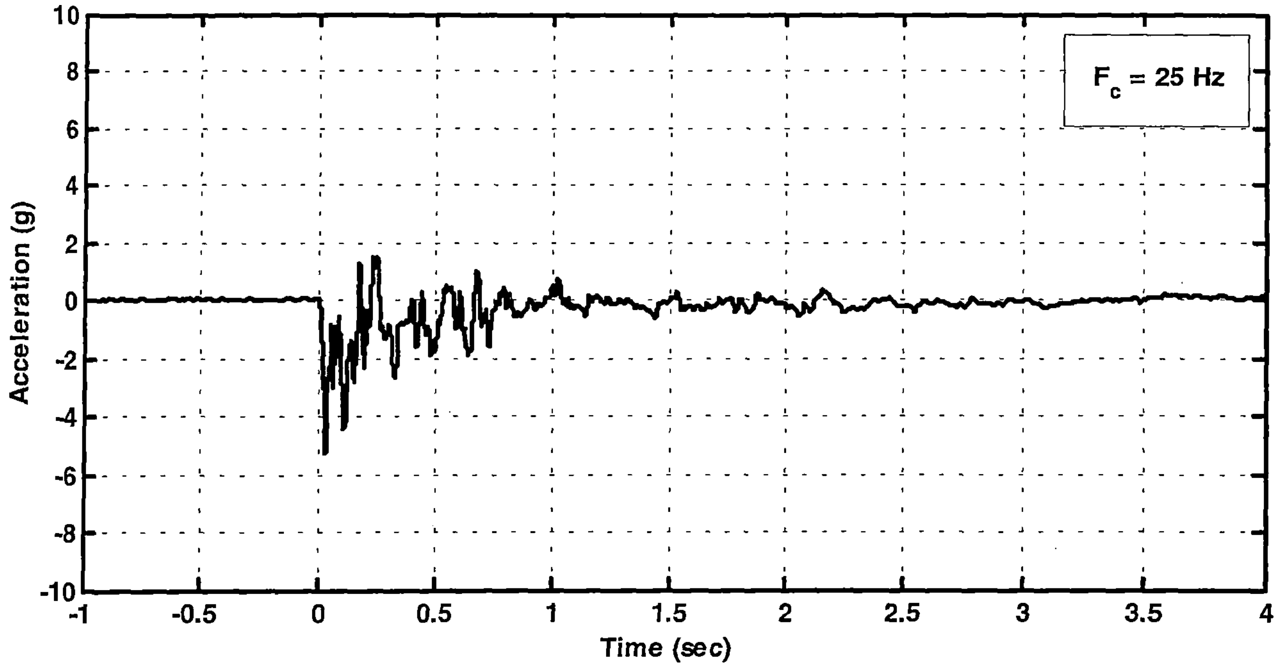

Figure D11. Locomotive event recorder, longitudinal acceleration
Channel Name: BL_RX

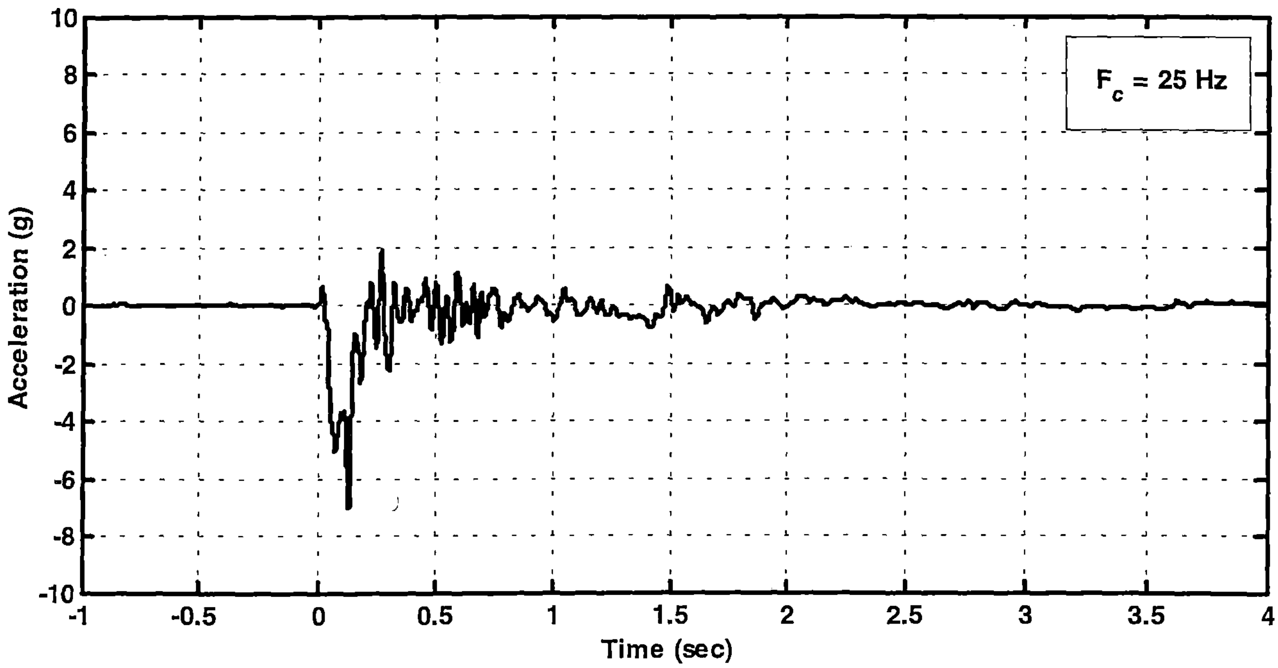

Figure D12. Locomotive event recorder, lateral acceleration
Channel Name: BL_RY

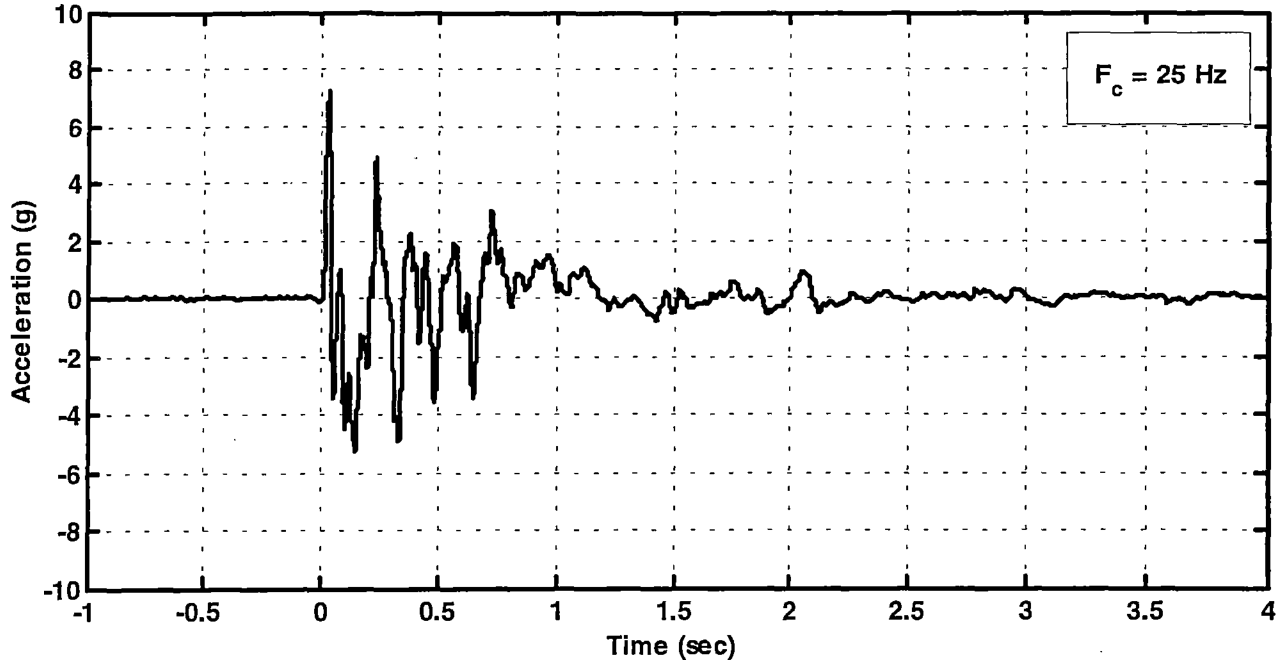

Figure D13. Locomotive event recorder, vertical acceleration
Channel Name: BL_RZ

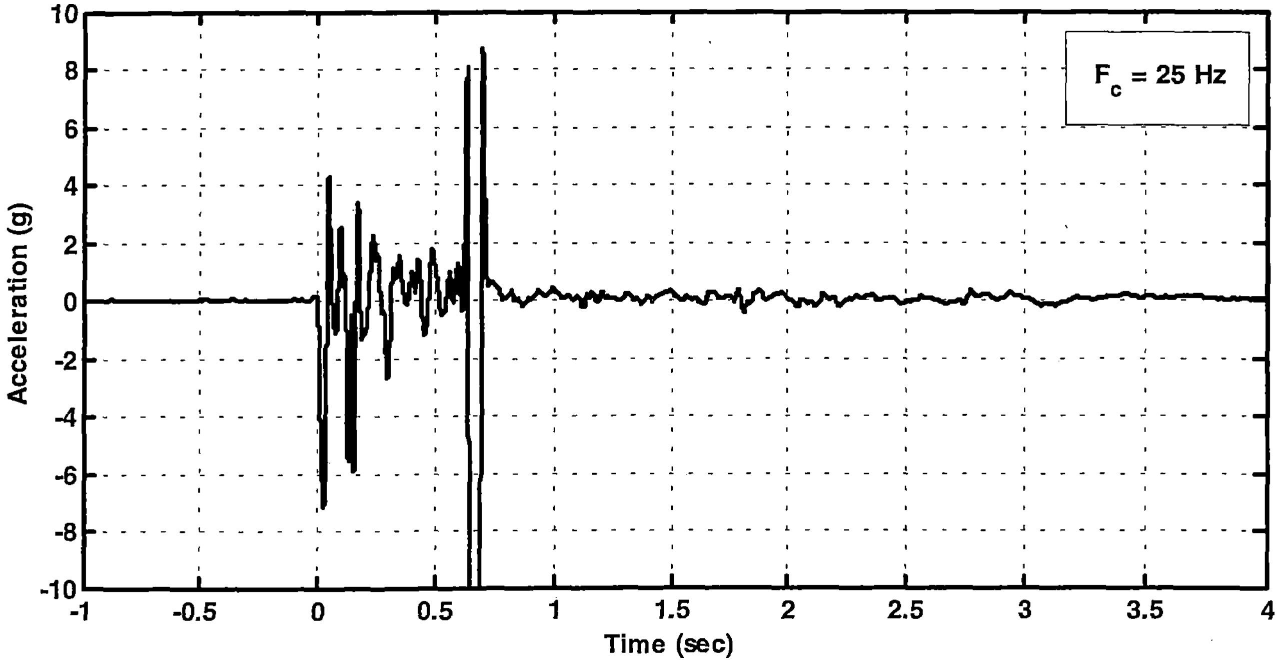

Figure D14. Target hopper 1, longitudinal acceleration
Channel Name: TH1_CGX

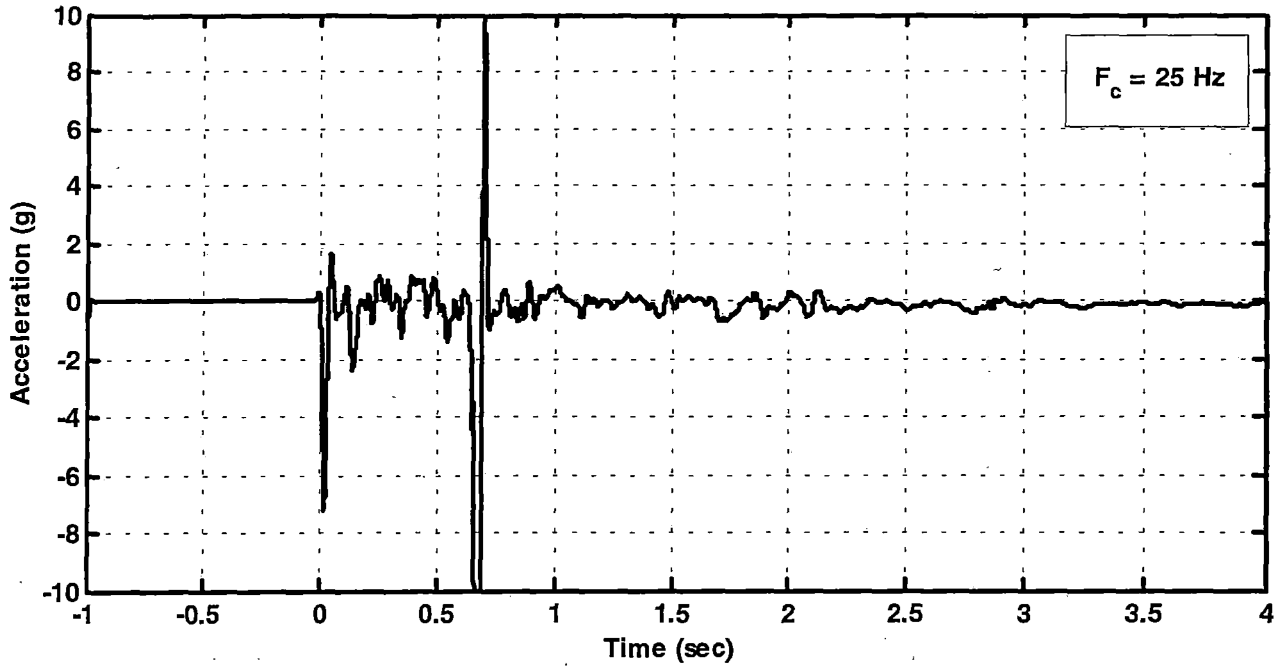

Figure D15. Target hopper 1, lateral acceleration
Channel Name: TH1_CGY

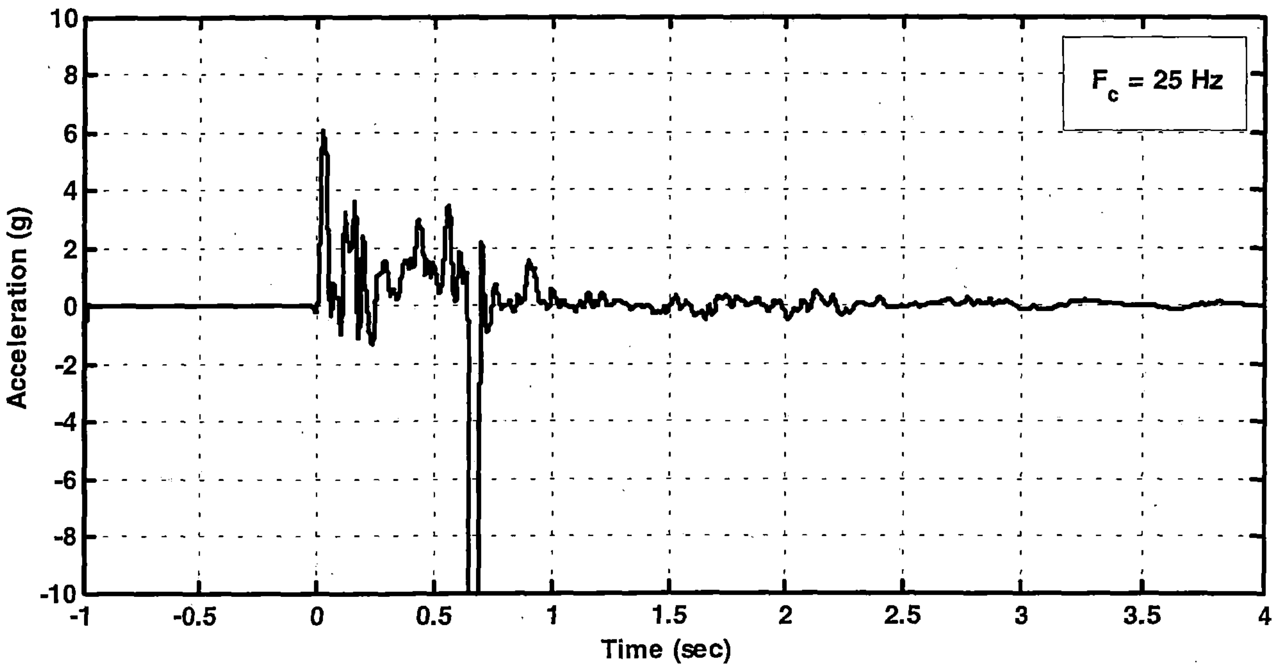

Figure D16. Target hopper 1, vertical acceleration
Channel Name: TH1_CGZ

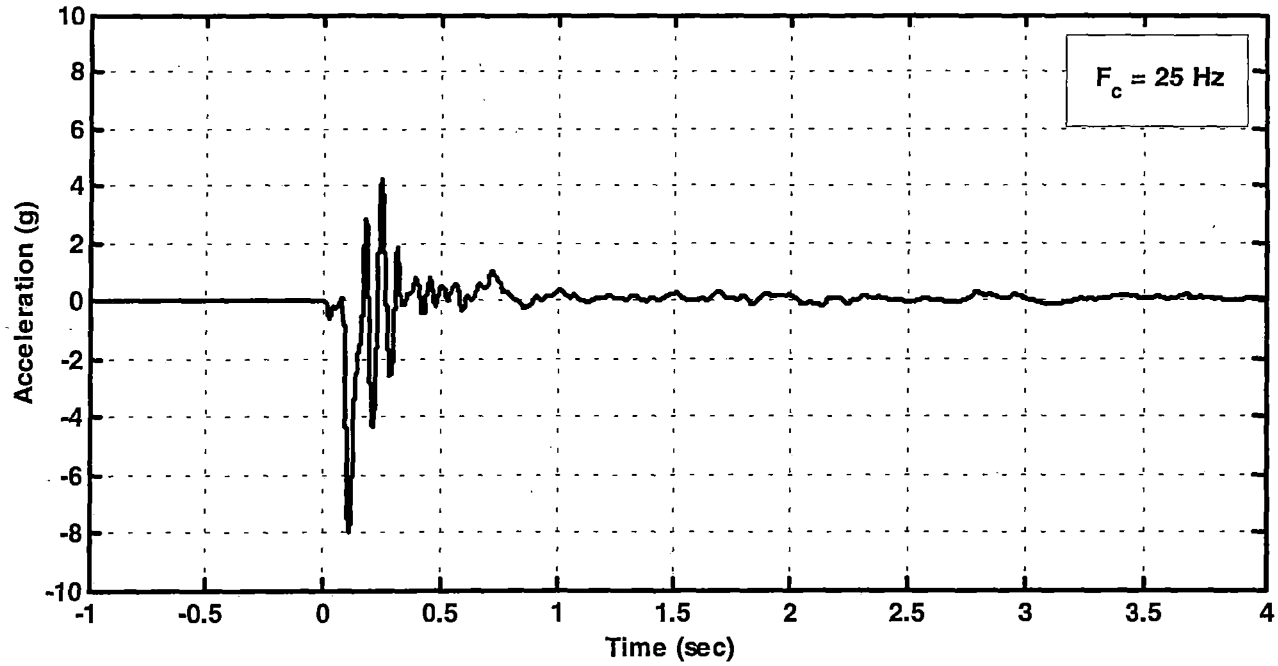

Figure D17. Target hopper 2, longitudinal acceleration
Channel Name: TH2_CGX

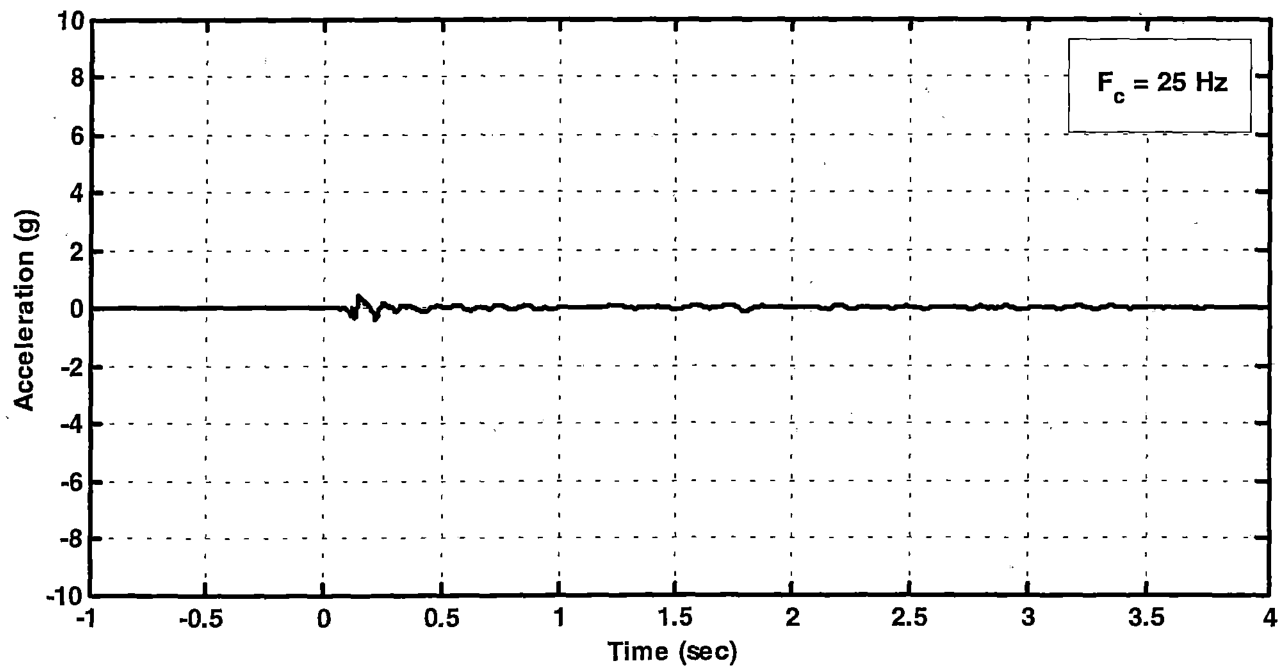

Figure D18. Target hopper 2, lateral acceleration
Channel Name: TH2_CGY

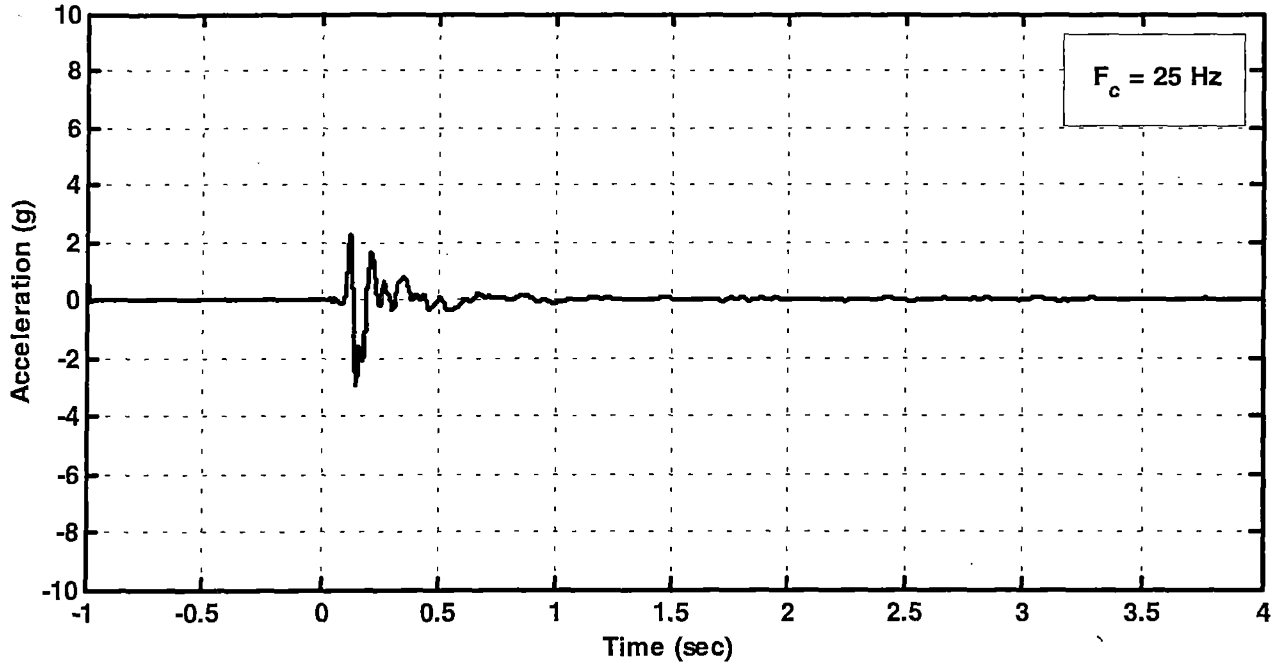

Figure D19. Target hopper 2, vertical acceleration
Channel Name: TH2_CGZ

APPENDIX E

Displacement and Coupler Force Data

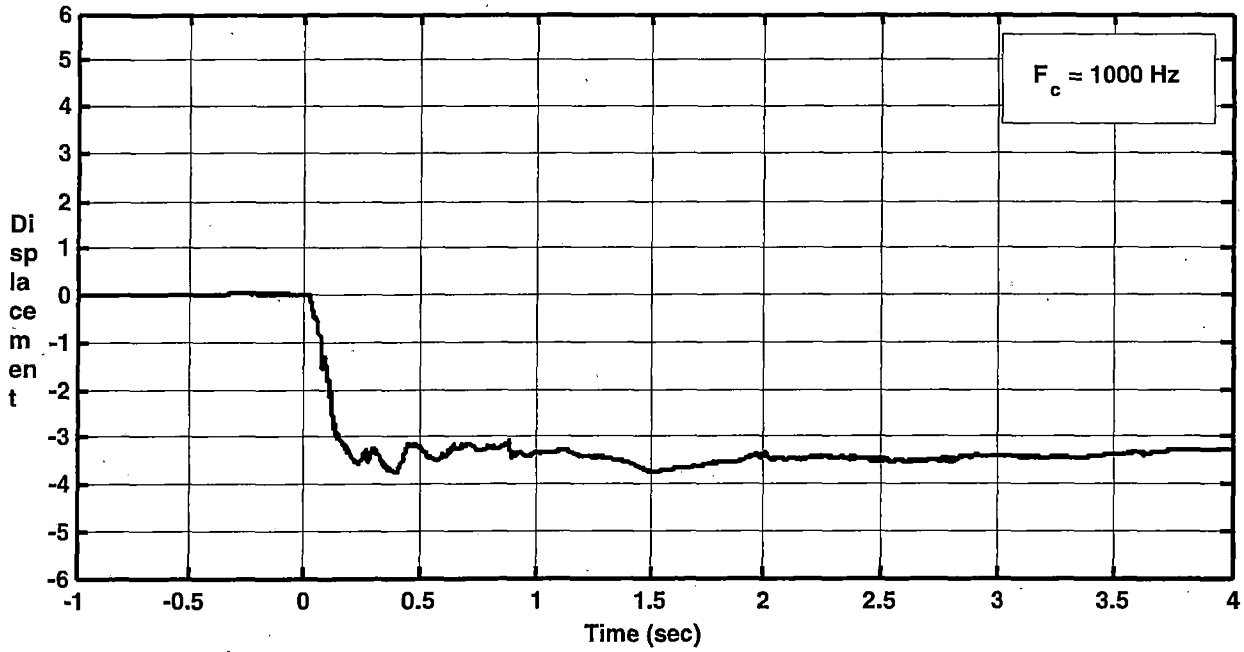

Figure E1. Bullet hopper 1, longitudinal coupler
Channel Name:

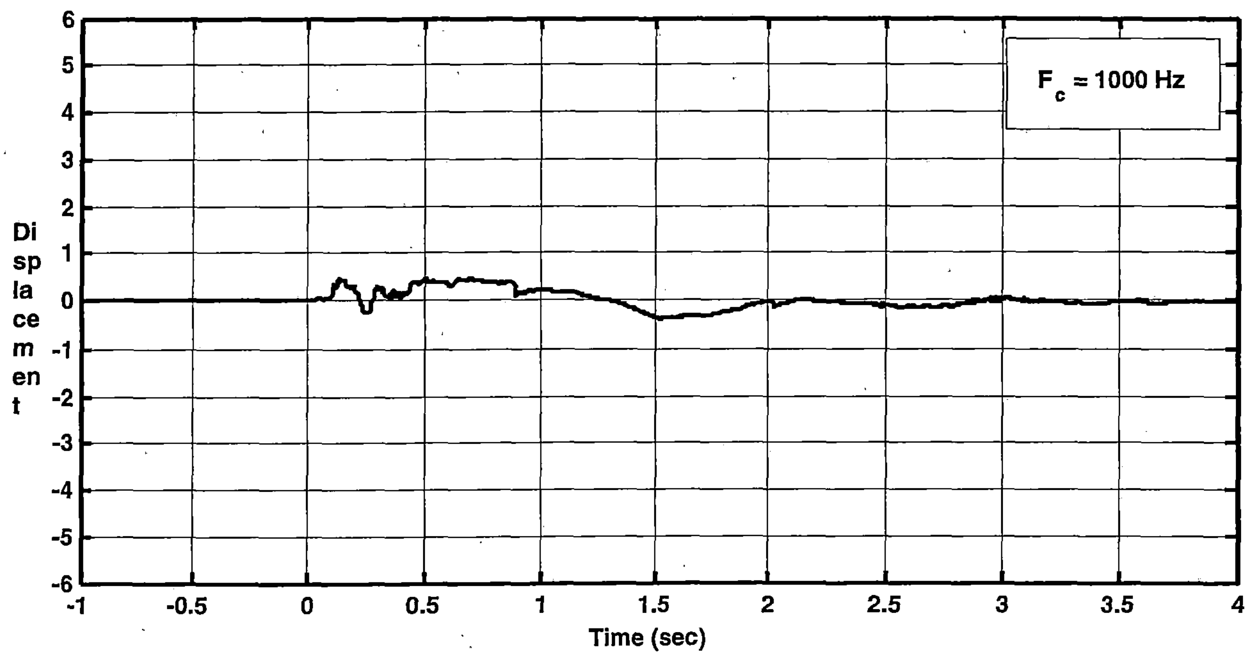

Figure E2. Bullet hopper 1, lateral coupler
Channel Name:

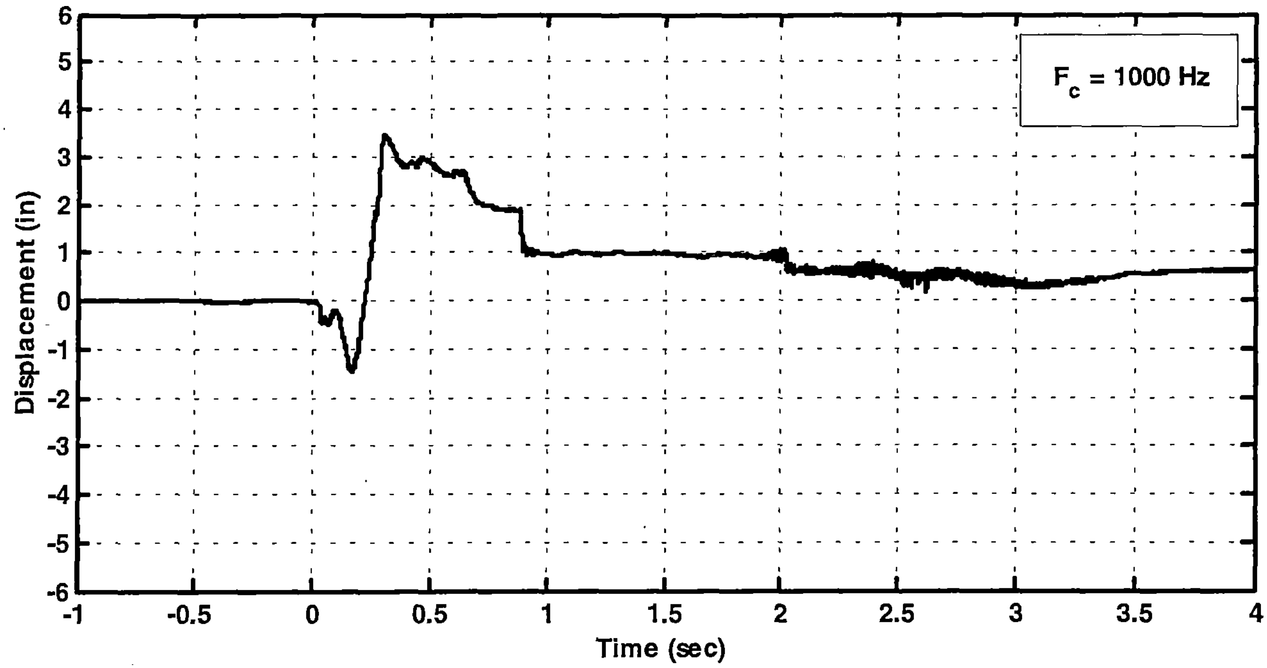

Figure E3. Bullet hopper 1, vertical coupler displacement
Channel Name: BH1_CAZ

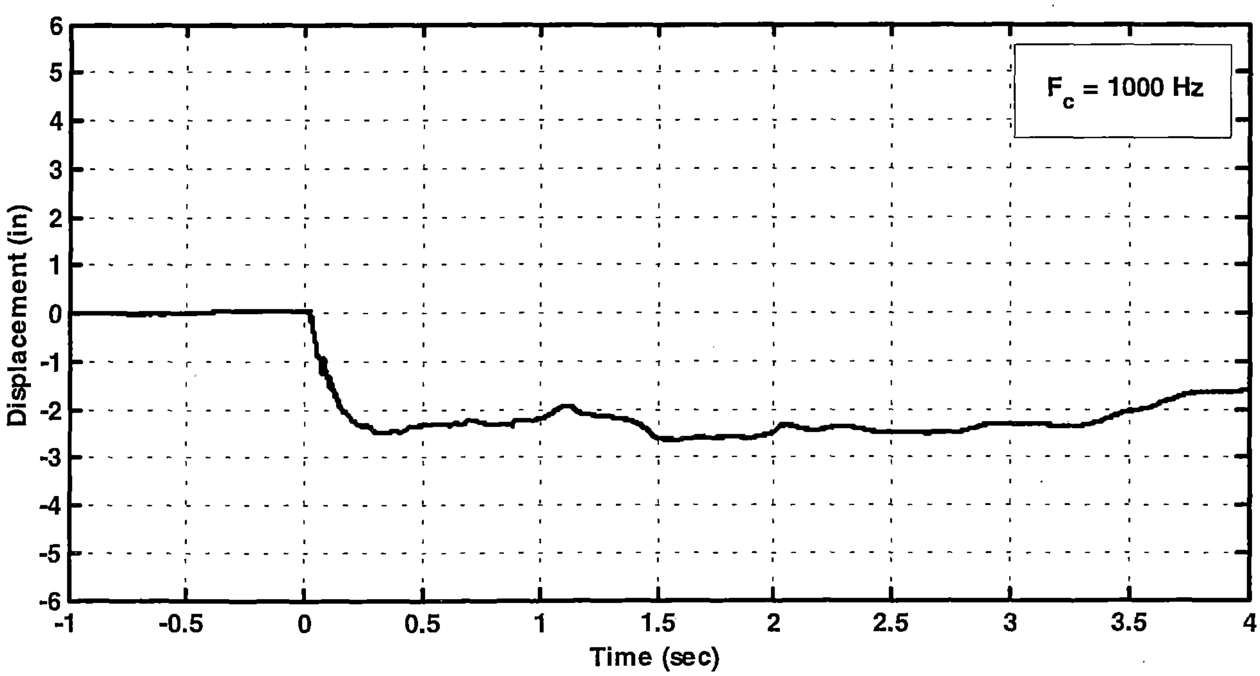

Figure E4. Locomotive, longitudinal coupler displacement
Channel Name: BL_CBX

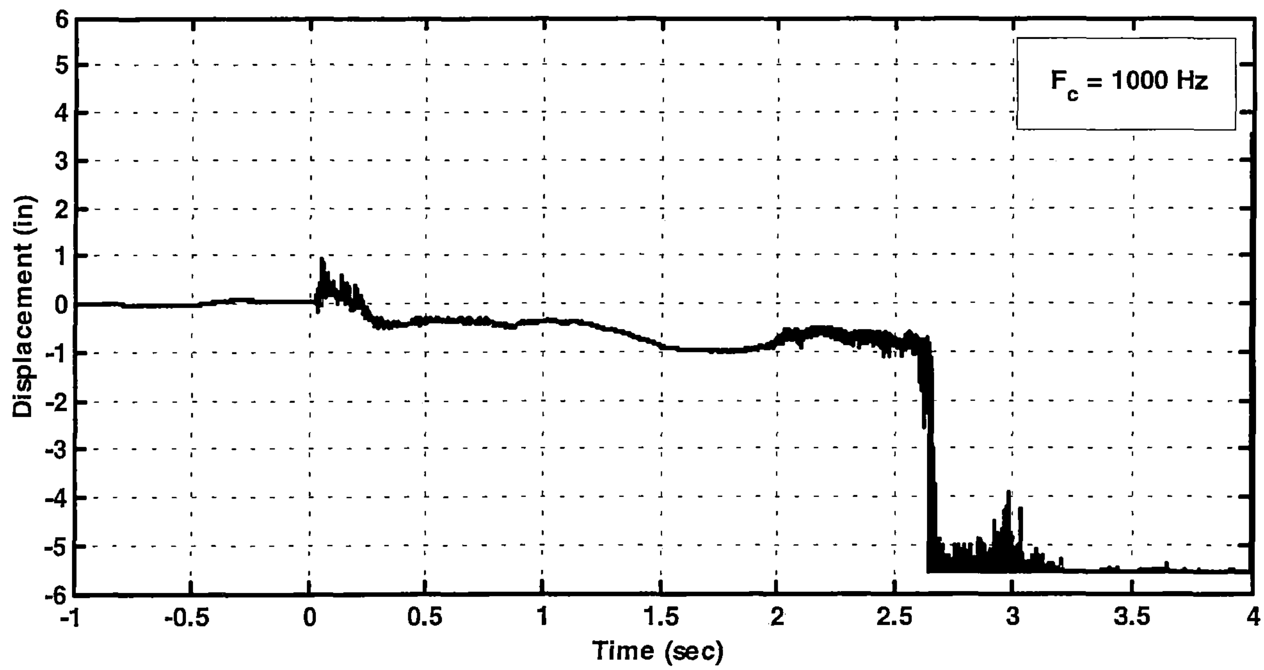

Figure E5. Locomotive, lateral coupler displacement
Channel Name: BL_CBY

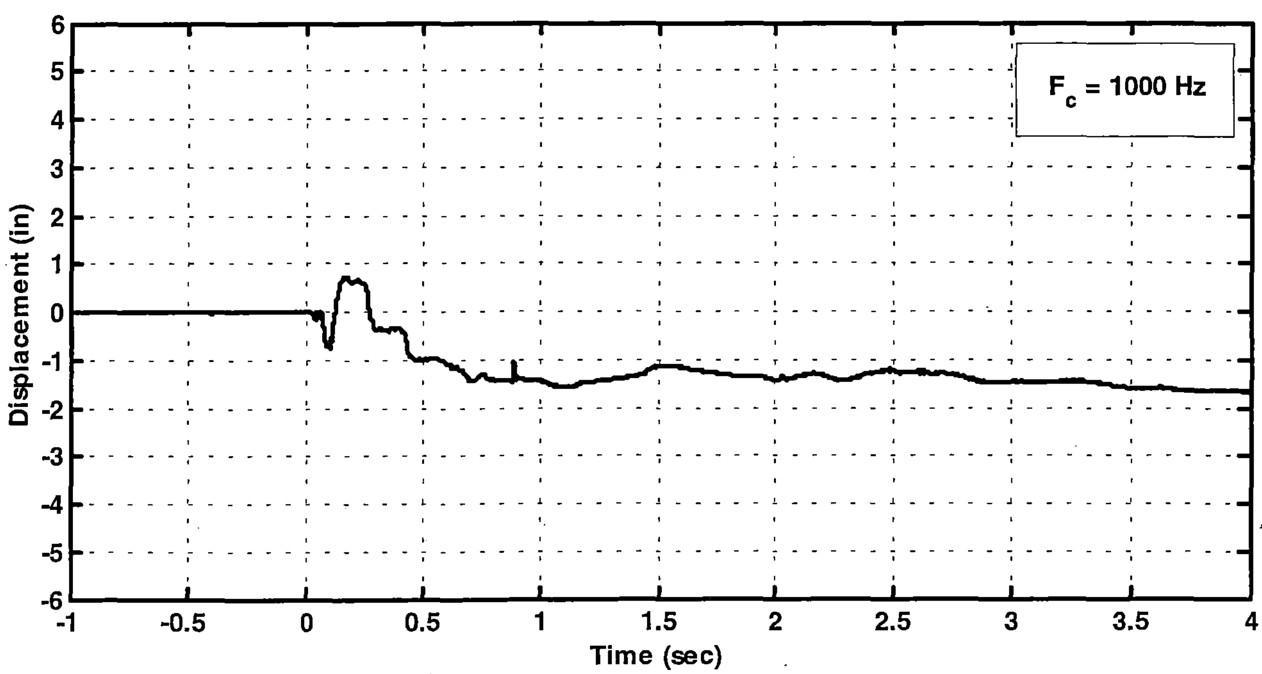

Figure E6. Locomotive, vertical coupler displacement
Channel Name: BL_CBZ

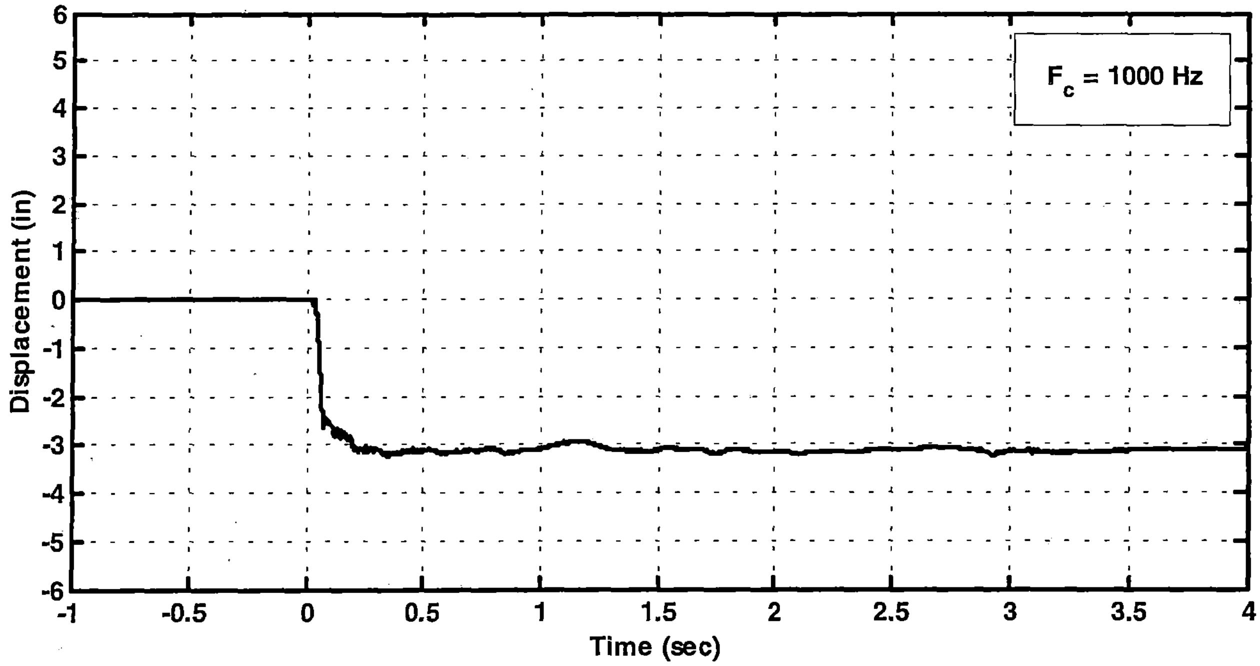

Figure E7. Target hopper 1, longitudinal coupler displacement, B end
Channel Name: TH1_CBX

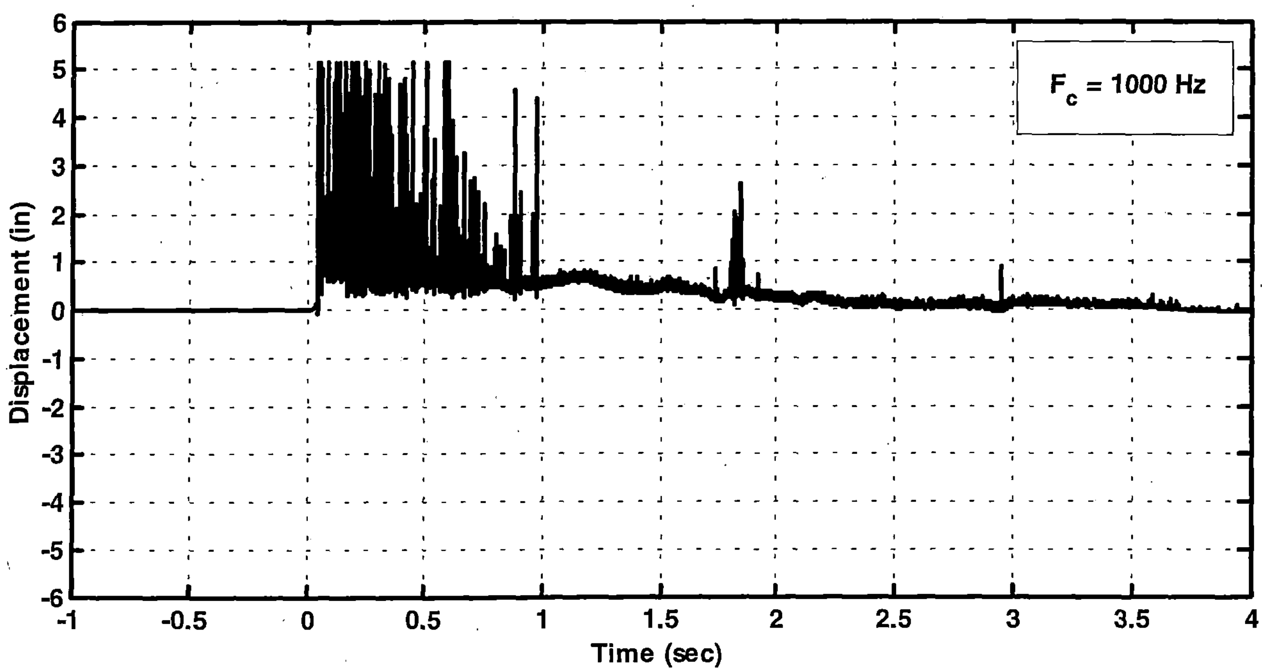

Figure E8. Target hopper 1, lateral coupler displacement, B end
Channel Name: TH1_CBY

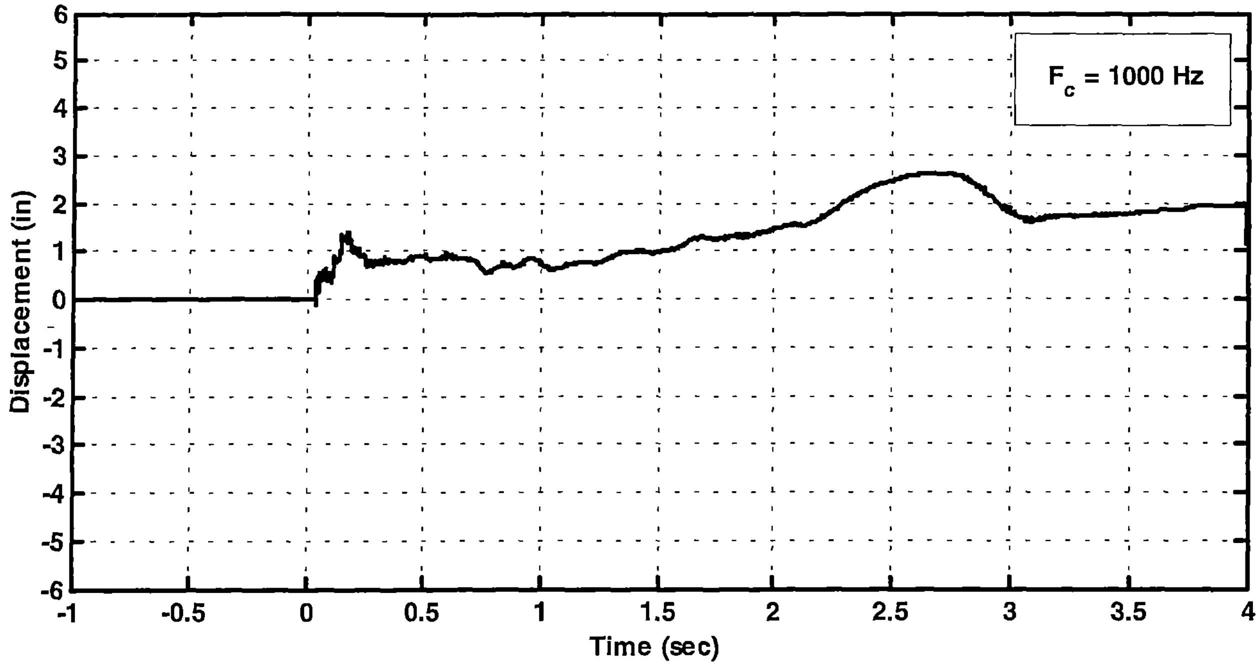

Figure E9. Target hopper 1, vertical coupler displacement, B end
Channel Name: TH1_CBZ

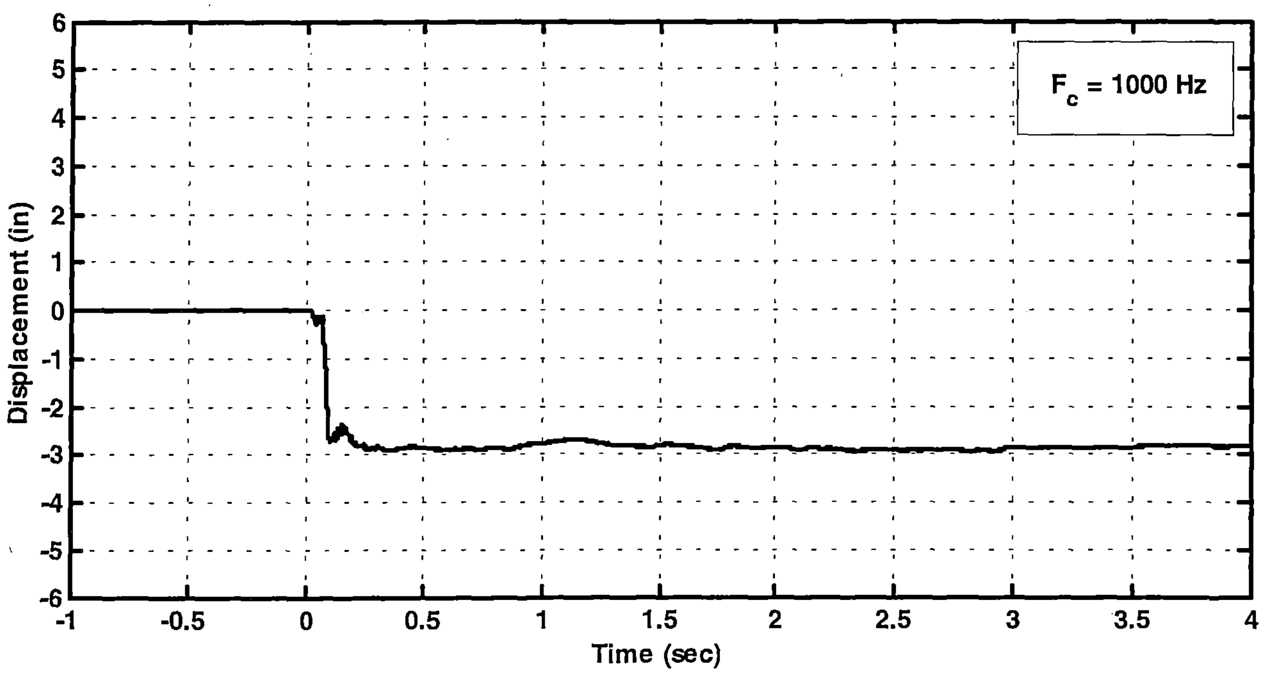

Figure E10. Target hopper 2, longitudinal coupler displacement, A end
Channel Name: TH2_CAX

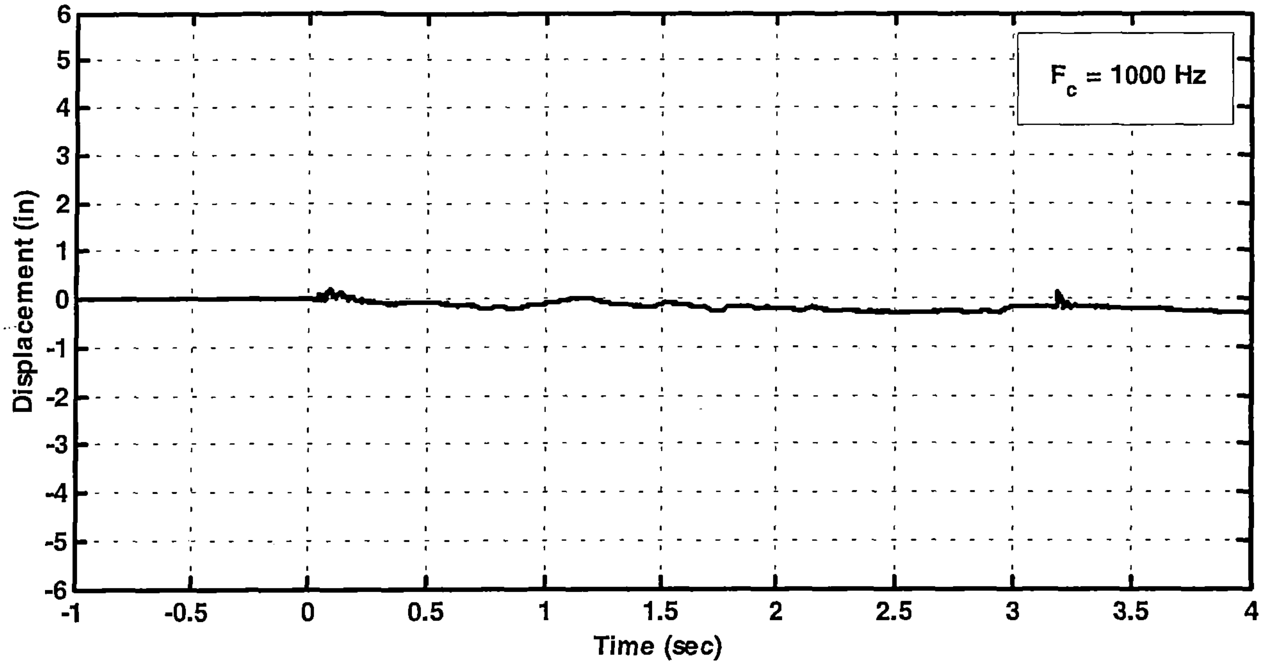

Figure E11. Target hopper 2, lateral coupler displacement, A end
Channel Name: TH2_CAY

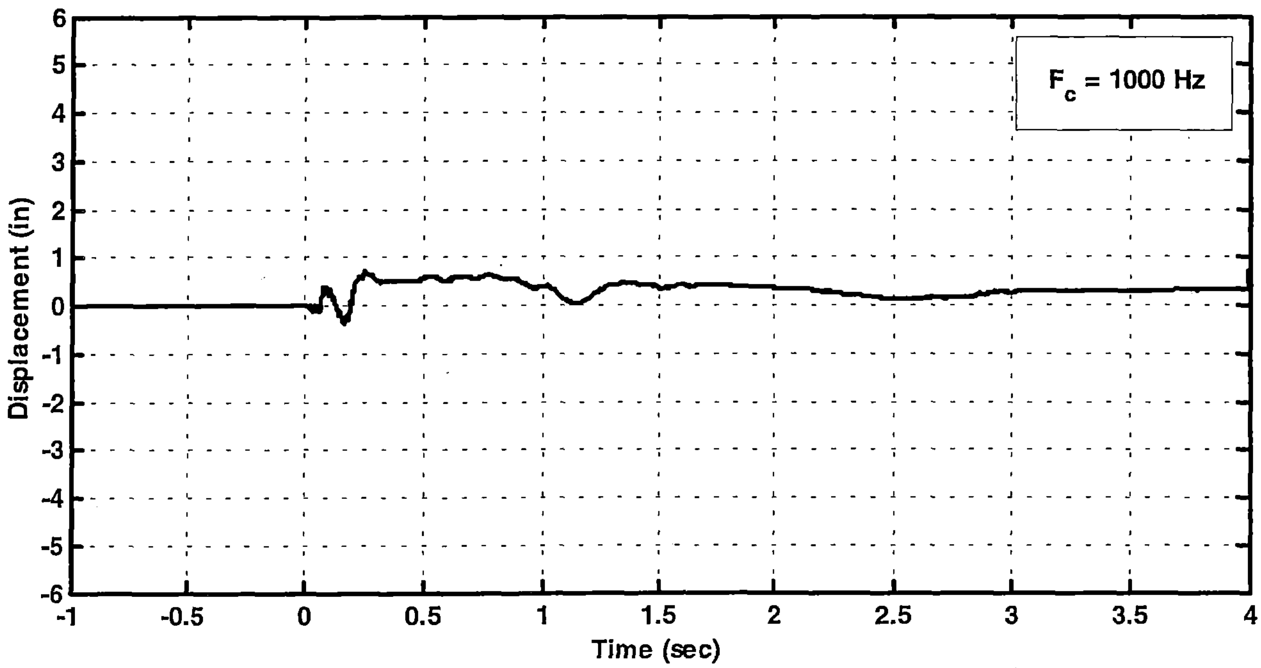

Figure E12. Target hopper 2, vertical coupler displacement, A end
Channel Name: TH2_CAZ

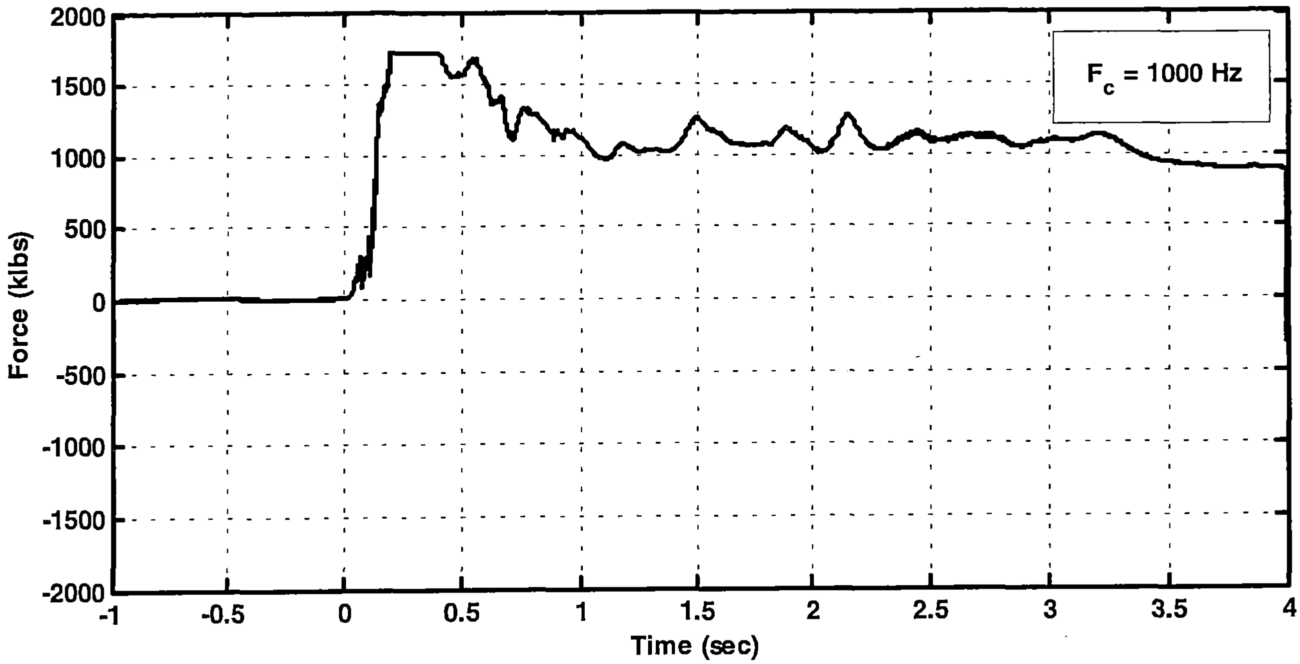

Figure E13. Bullet hopper 1, leading coupler force
Channel Name: BH1_Cload2

APPENDIX F

Strain Data

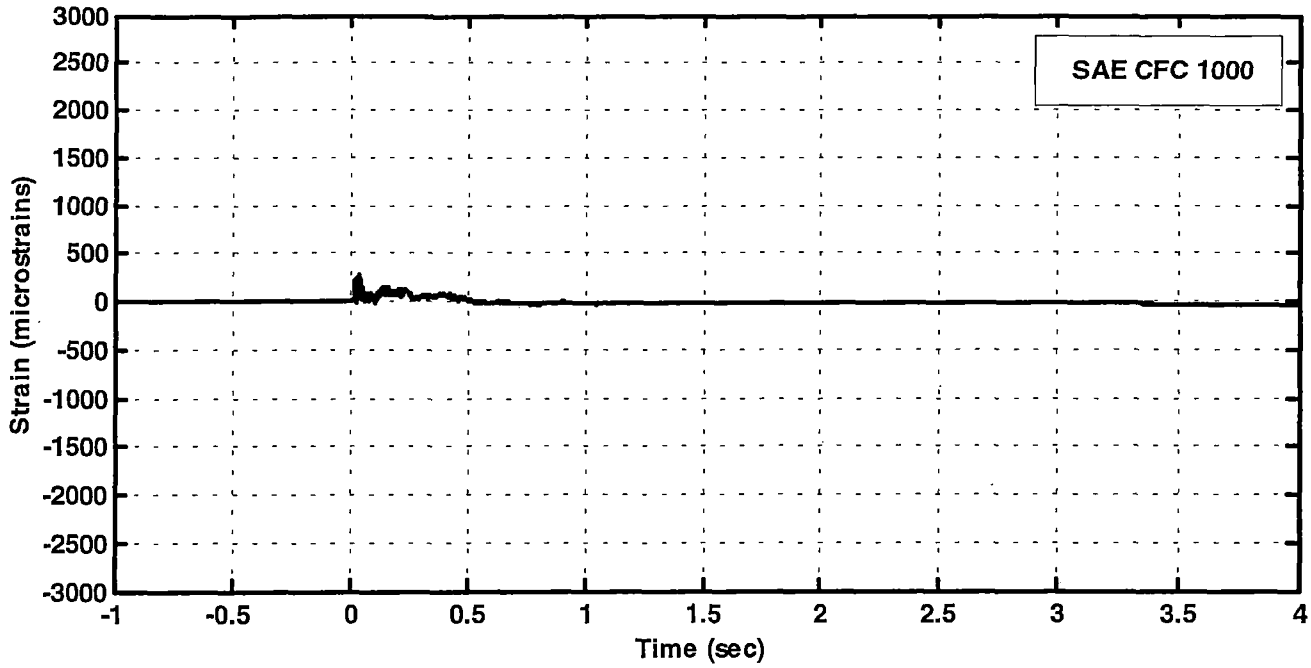

Figure F1. Strain on left collision post, bottom rear rosette, longitudinal element
Channel Name: CPLR1_1

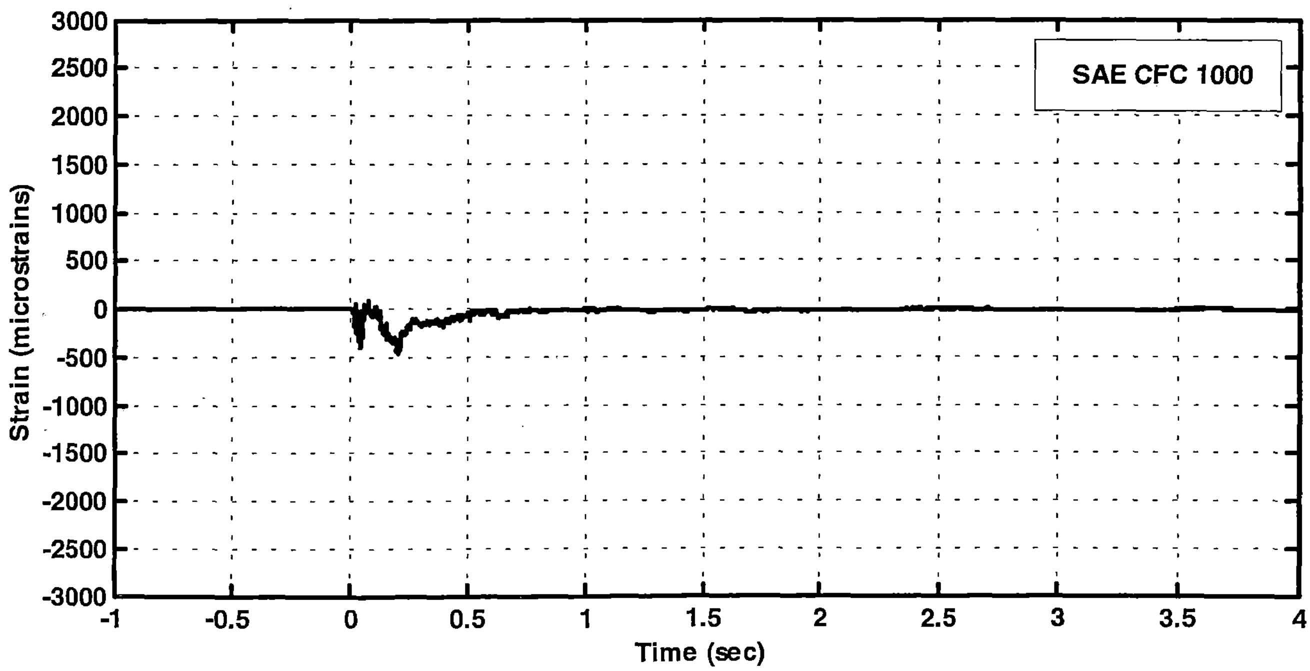

Figure F2. Strain on left collision post, bottom rear rosette, diagonal element
Channel Name: CPLR1_2

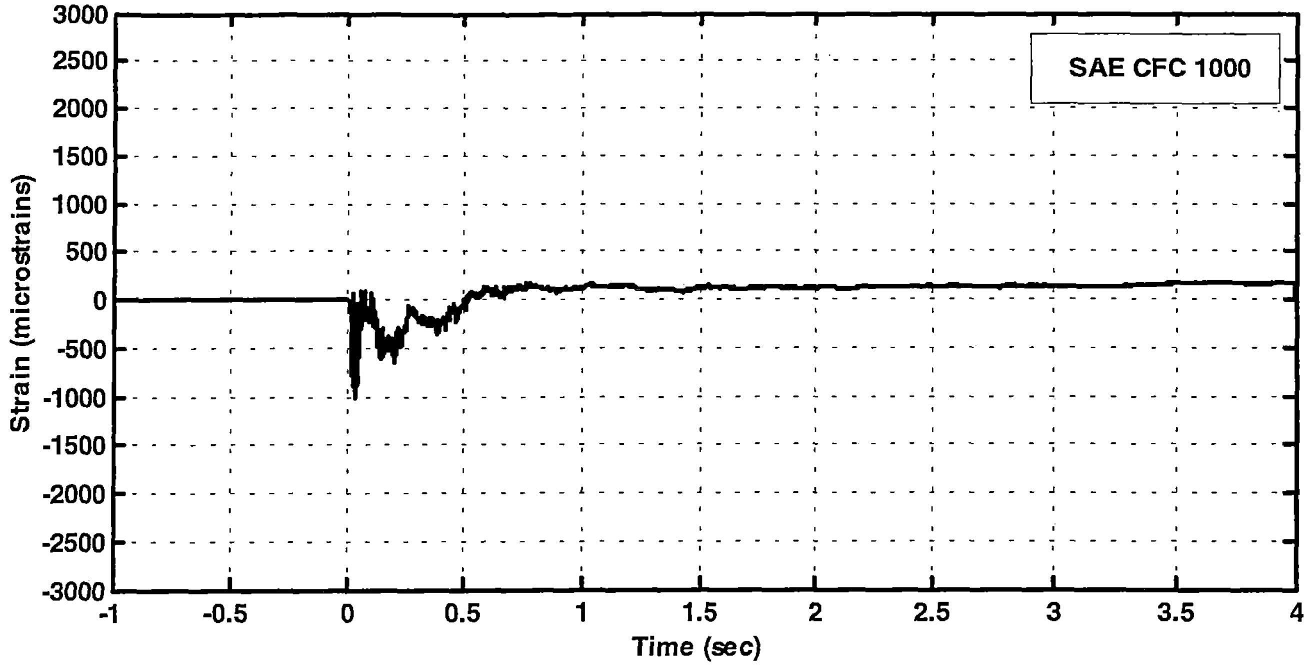

Figure F3. Strain on left collision post, bottom rear rosette, vertical element
Channel Name: CPLR1_3

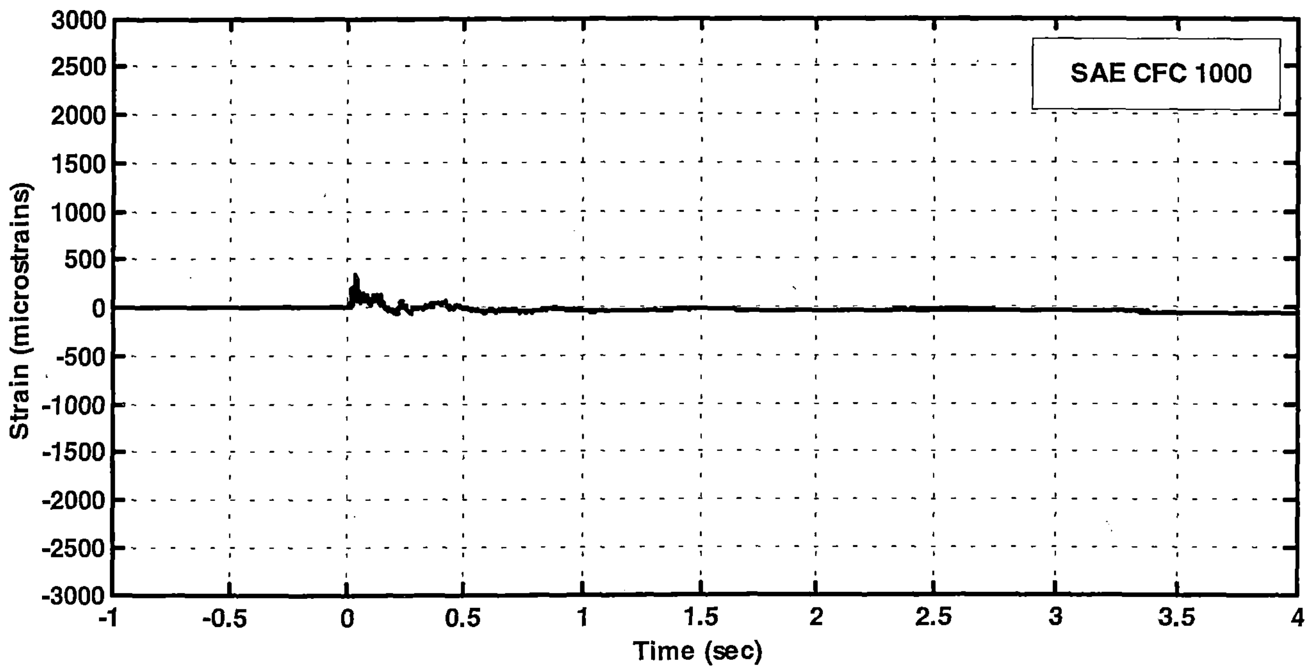

Figure F4. Strain on left collision post, bottom center rosette, longitudinal element
Channel Name: CPLR2_1

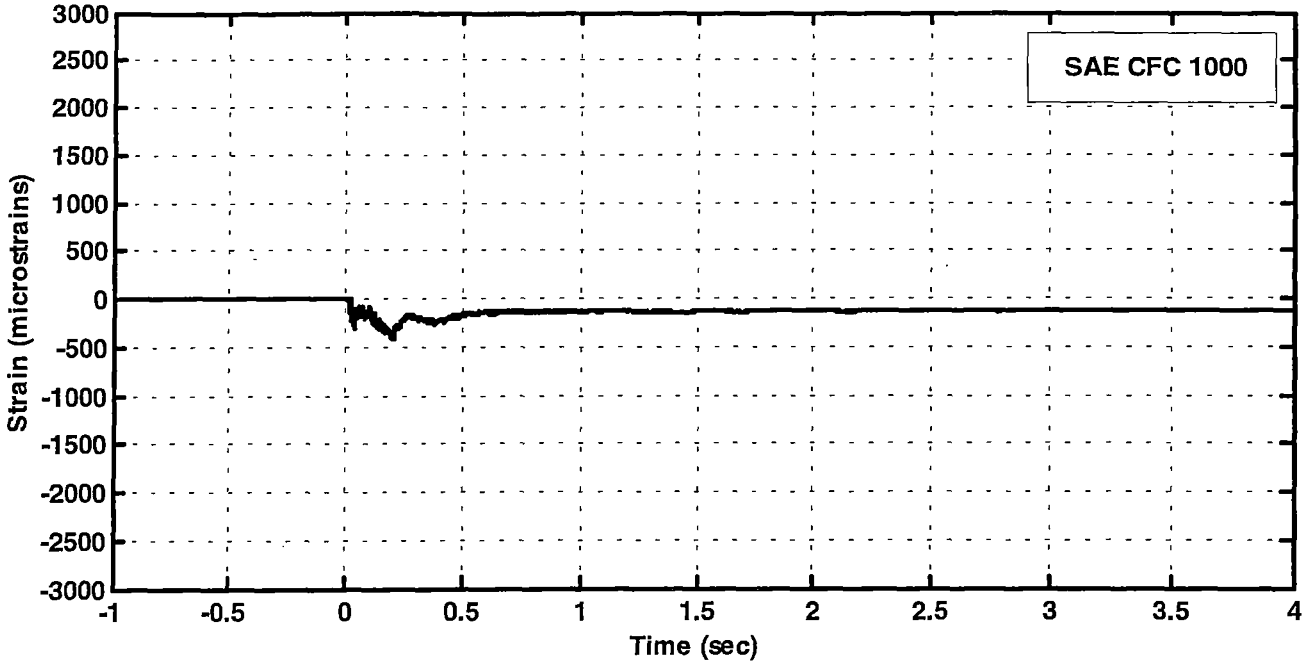

Figure F5. Strain on left collision post, bottom center rosette, diagonal element
Channel Name: CPLR2_2

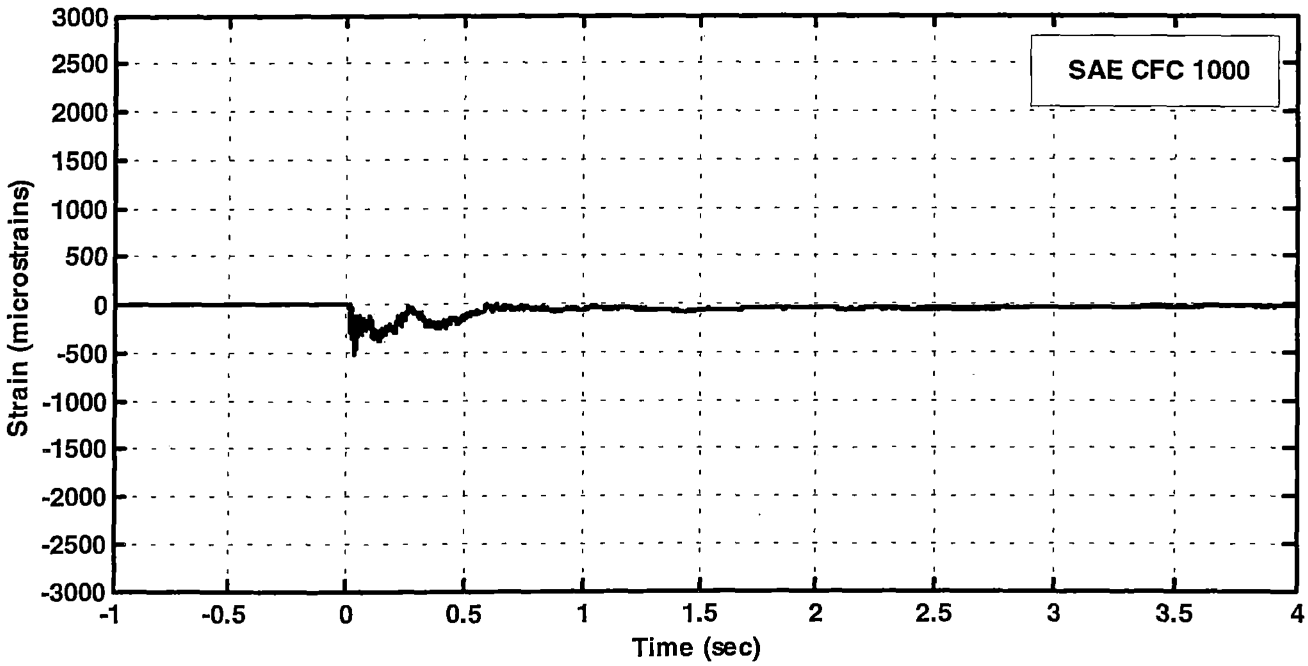

Figure F6. Strain on left collision post, bottom center rosette, vertical element
Channel Name: CPLR2_3

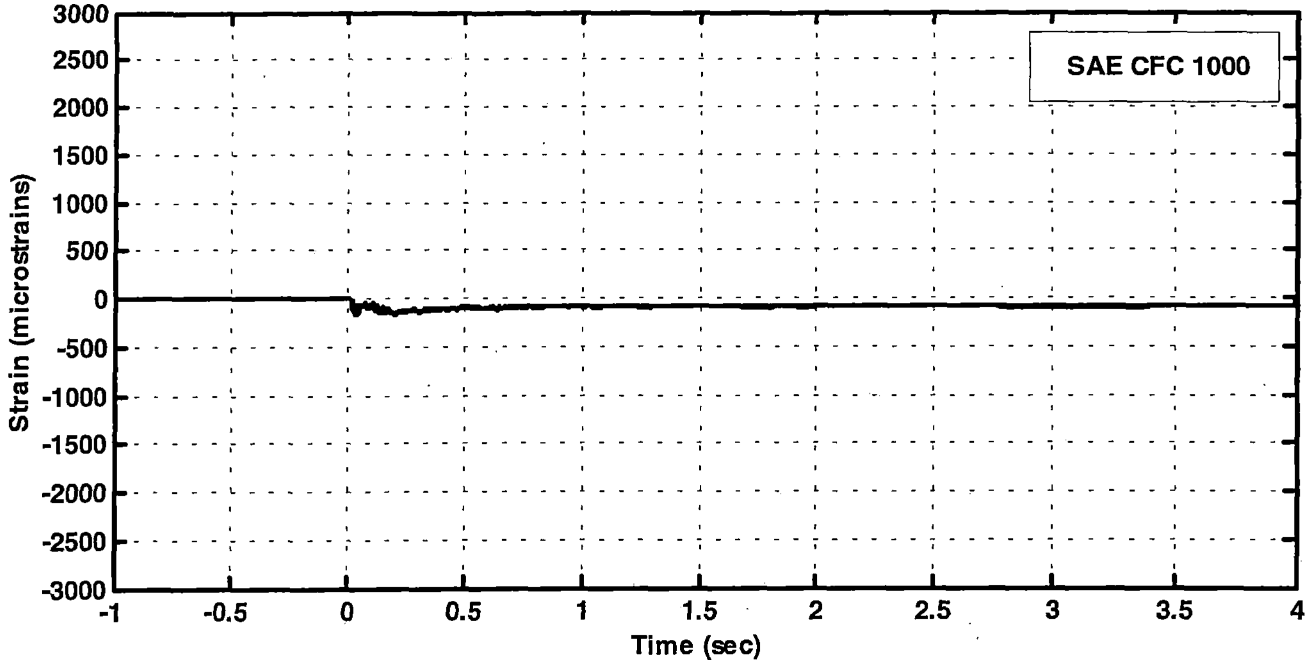

Figure F7. Strain on left collision post, bottom front rosette, longitudinal element
Channel Name: CPLR3_1

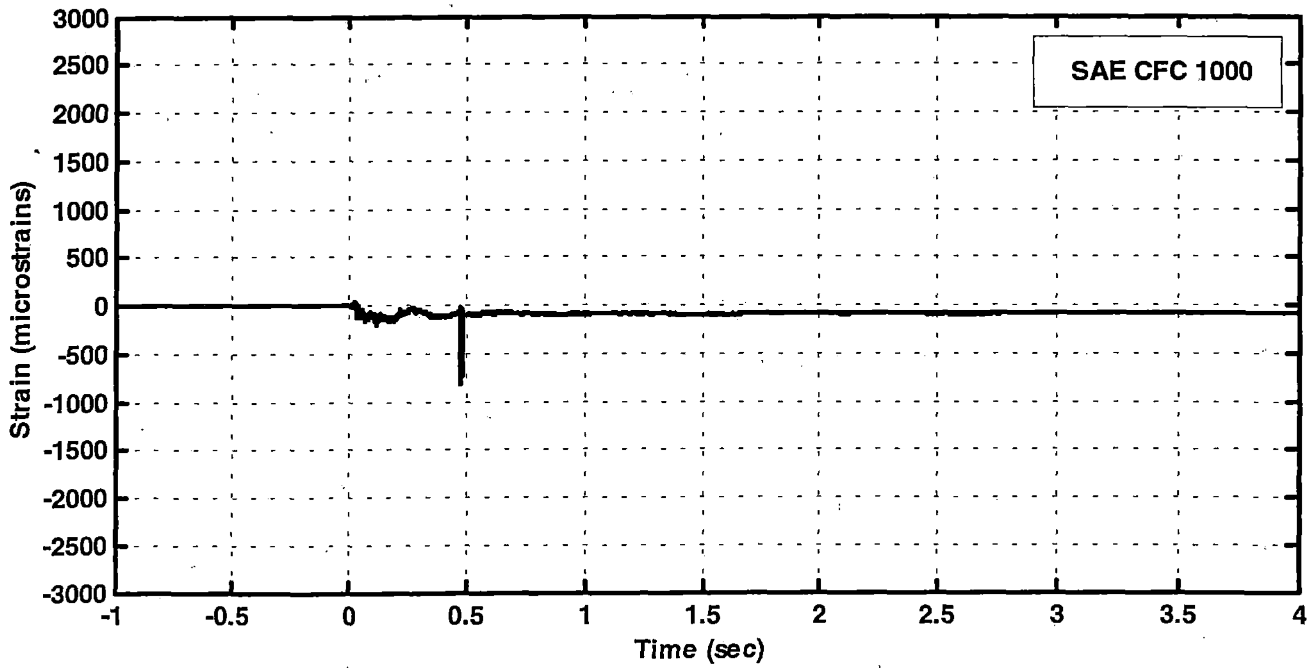

Figure F8. Strain on left collision post, bottom front rosette, diagonal element
Channel Name: CPLR3_2

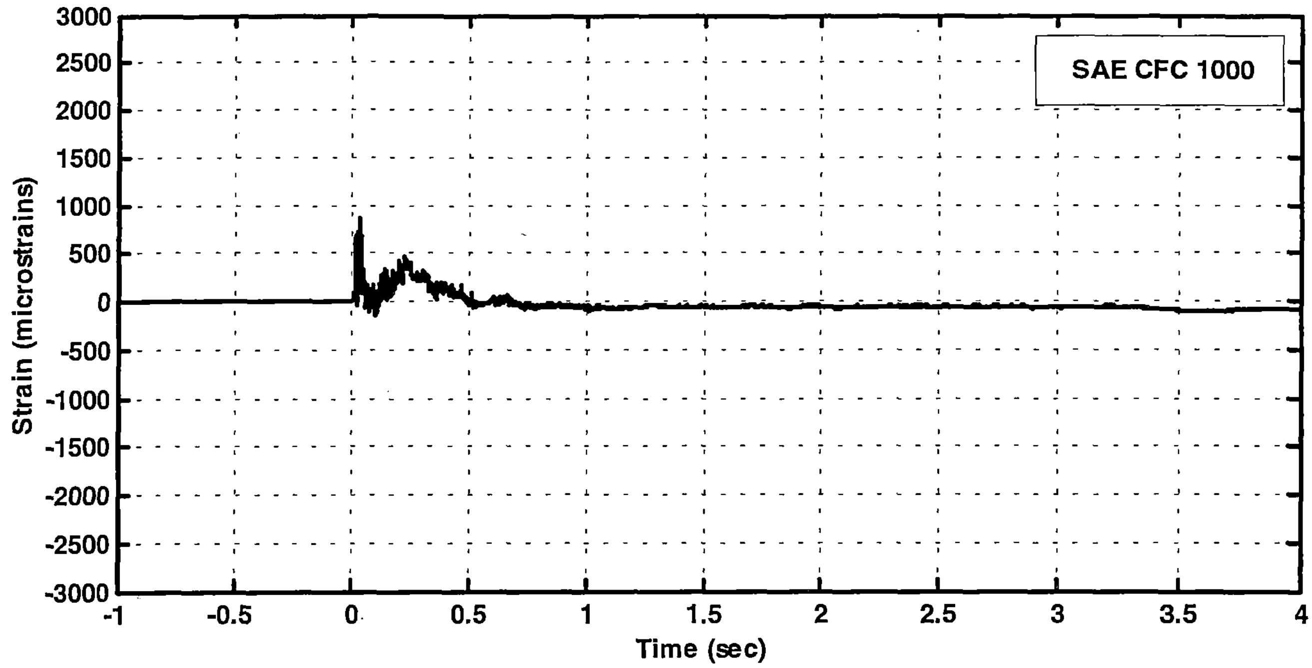

Figure F9. Strain on left collision post, bottom front rosette, vertical element
Channel Name: CPLR3_3

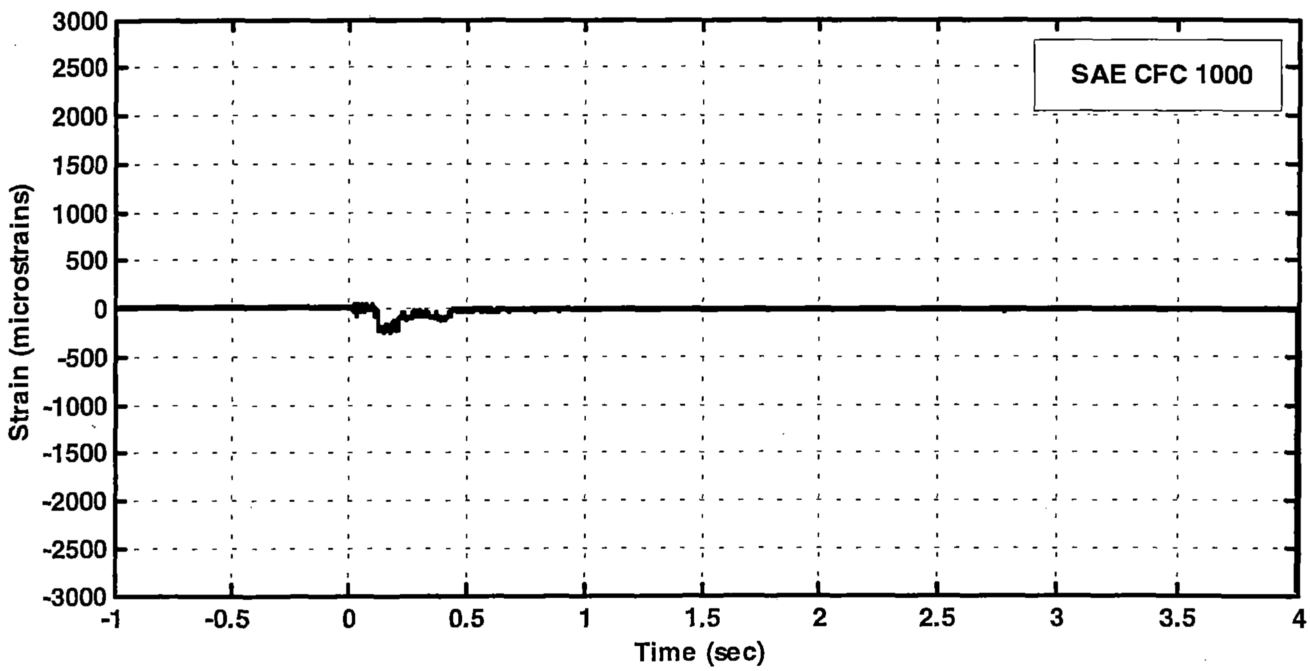

Figure F10. Strain on left collision post, top front rosette, longitudinal element
Channel Name: CPLR4_1

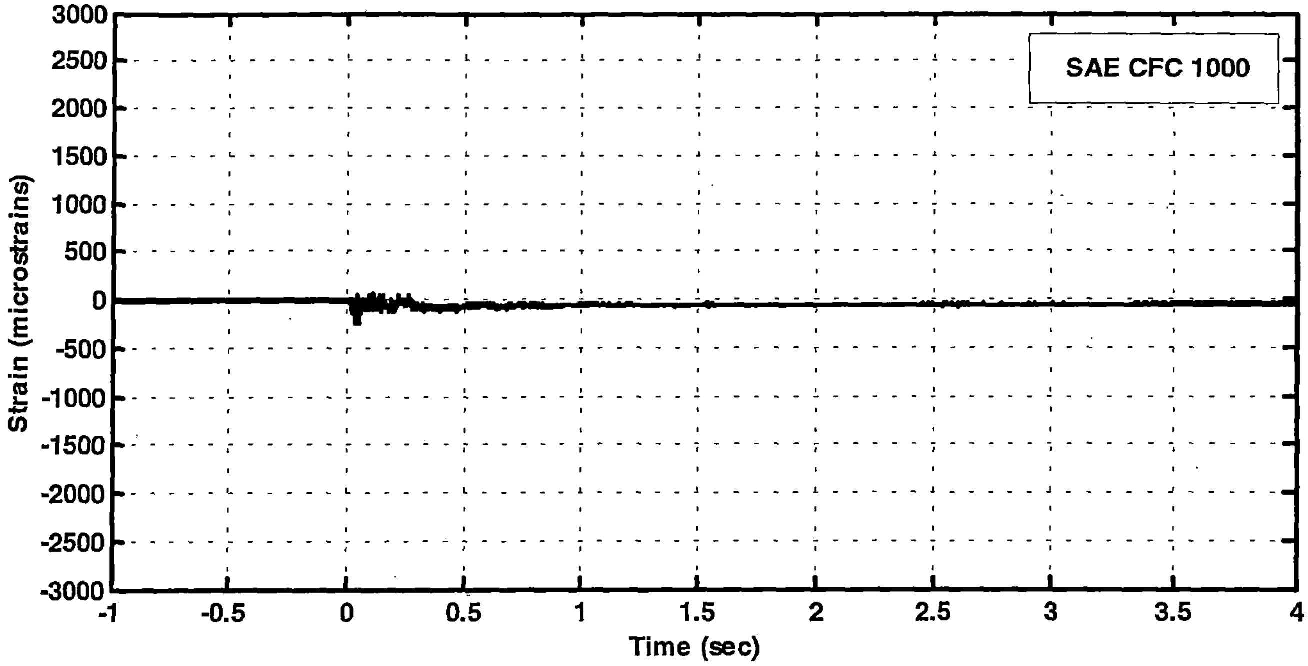

Figure F11. Strain on left collision post, top front rosette, diagonal element
Channel Name: CPLR4_2

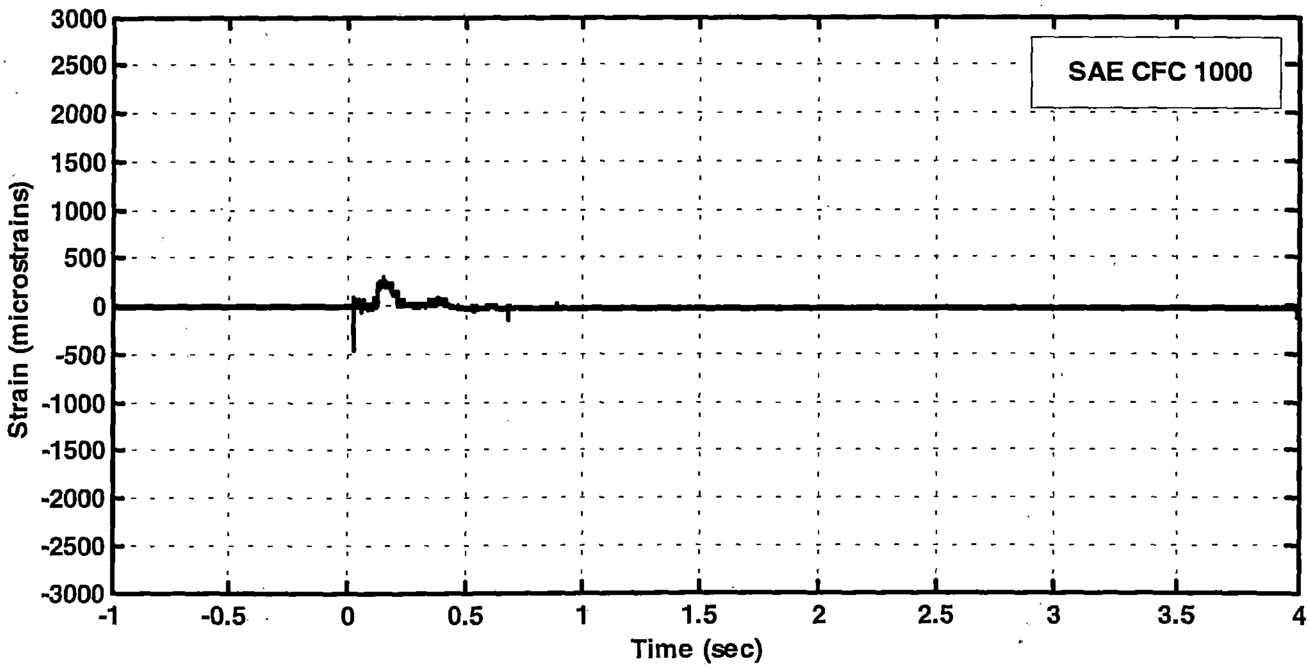

Figure F12. Strain on left collision post, top front rosette, vertical element
Channel Name: CPLR4_3

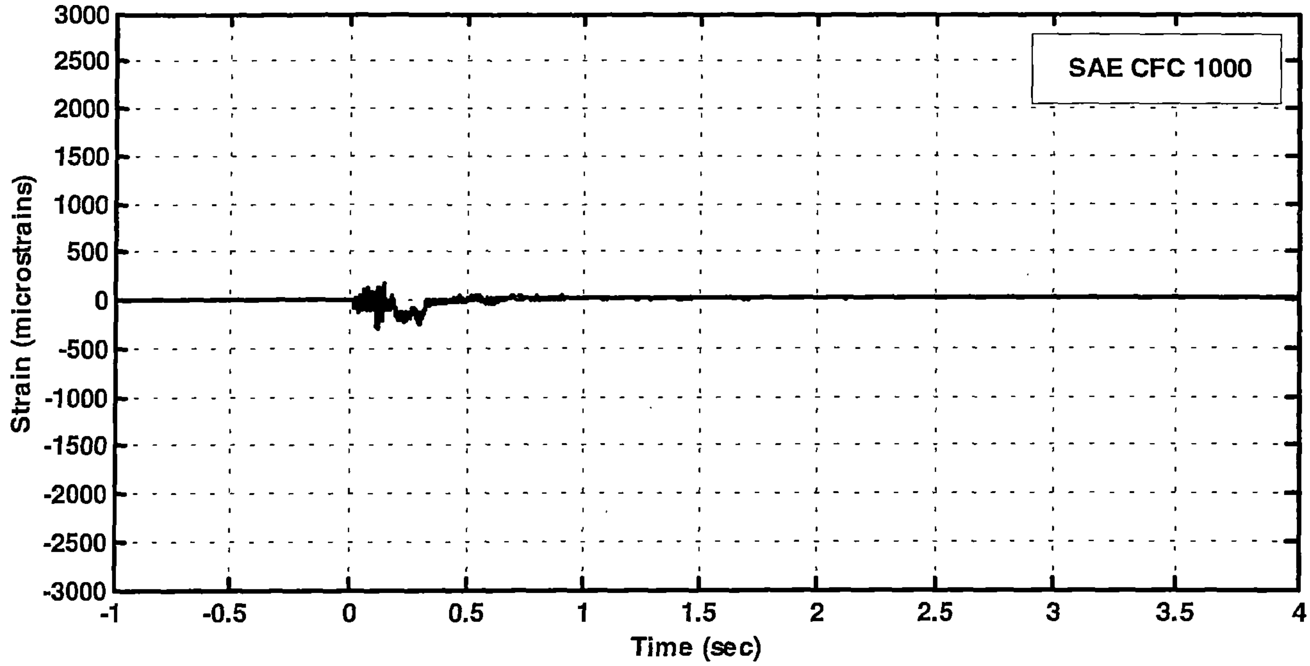

Figure F13. Strain on left collision post, middle front rosette, longitudinal element
Channel Name: CPLR5_1

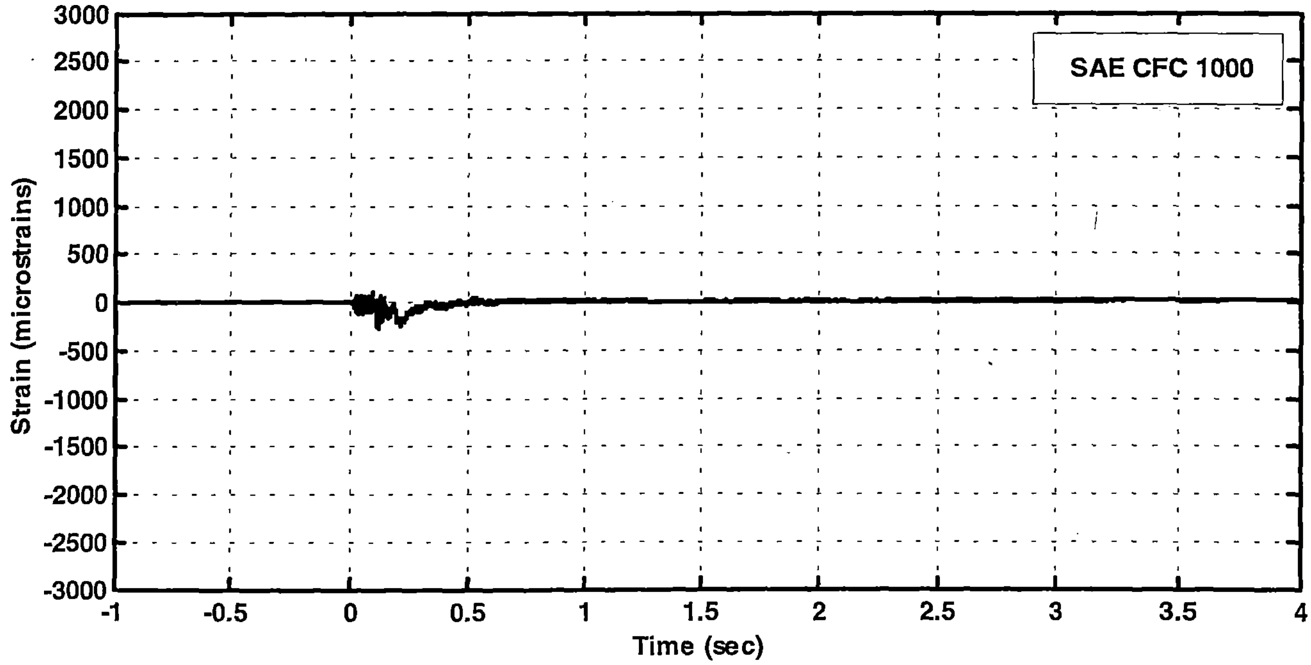

Figure F14. Strain on left collision post, middle front rosette, diagonal element
Channel Name: CPLR5_2

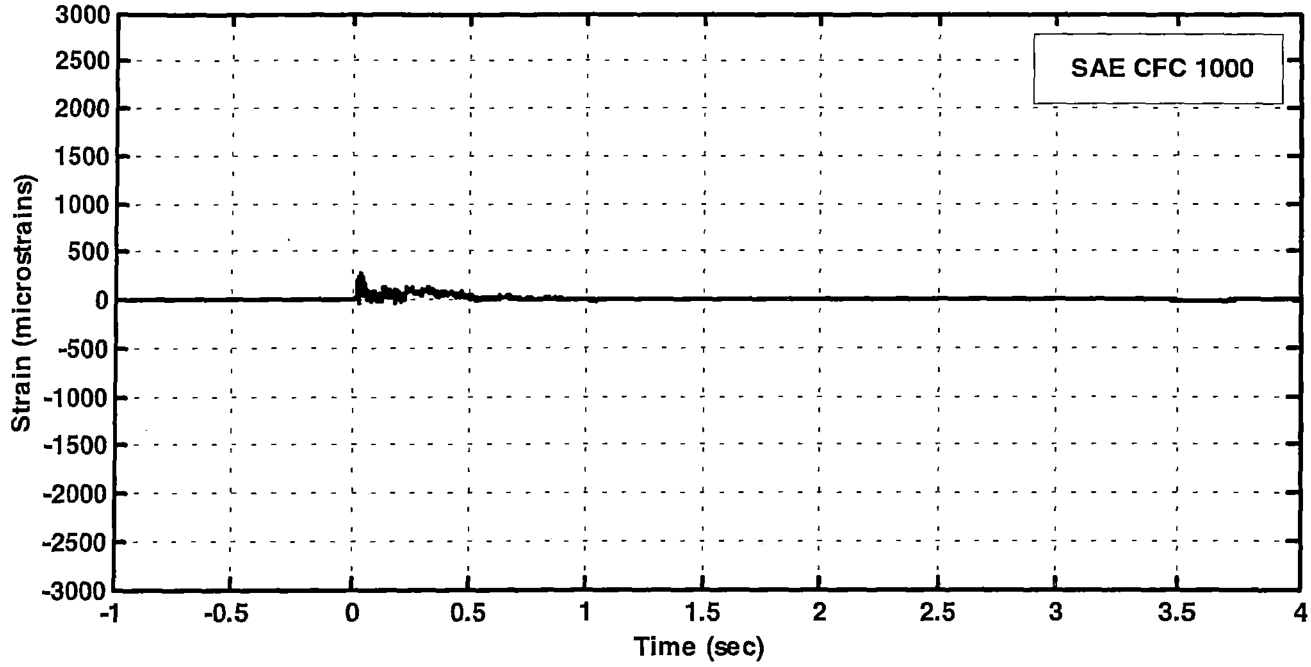

Figure F15. Strain on left collision post, middle front rosette, vertical element
Channel Name: CPLR5_3

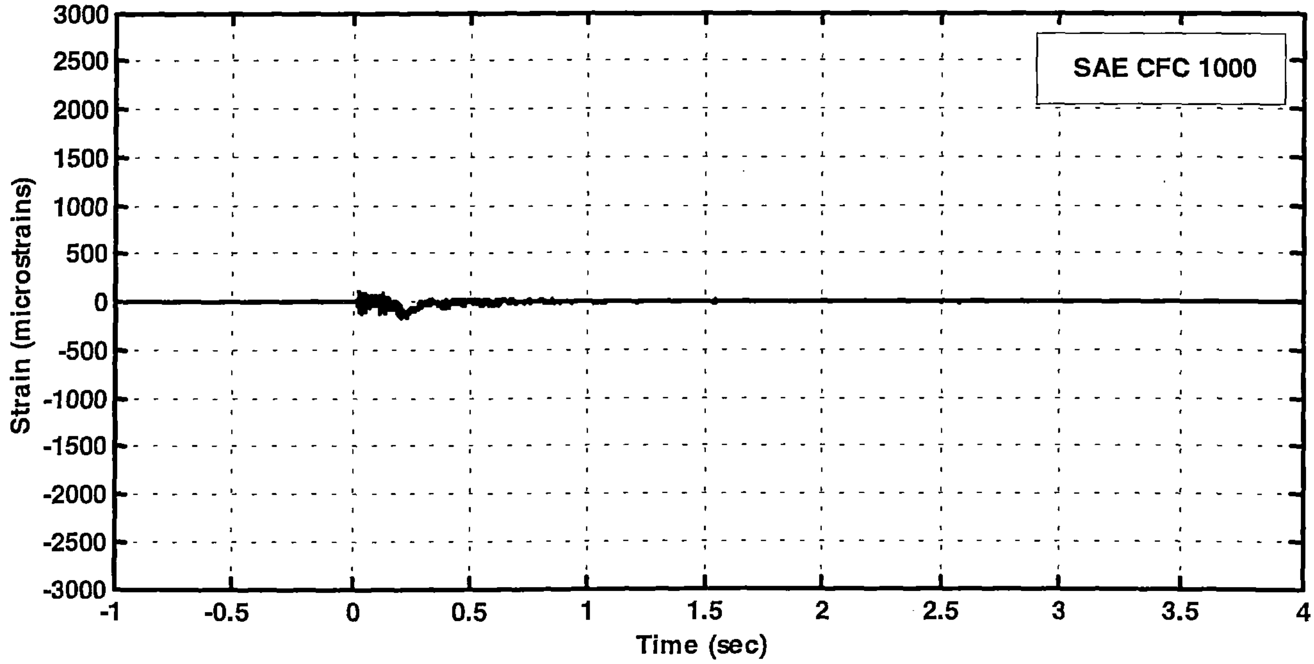

Figure F16. Longitudinal strain on left collision post, center, 3/4 up from bottom edge
Channel Name: CPLS1

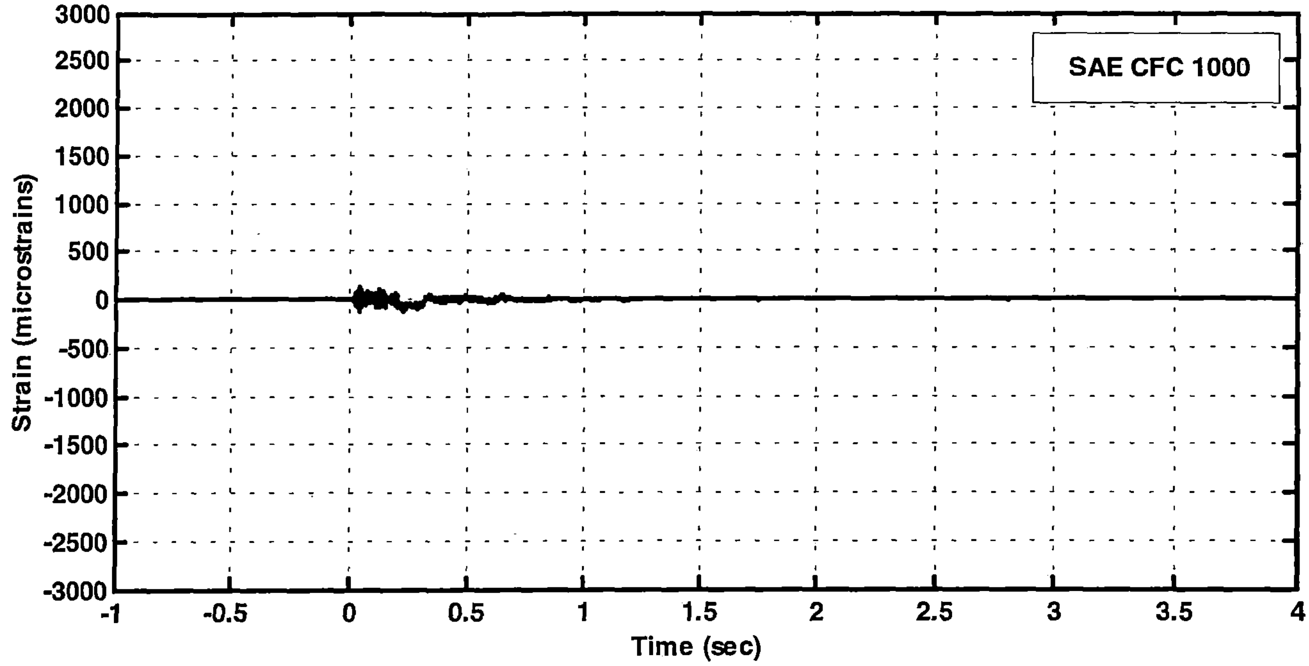

Figure F17. Longitudinal strain on left collision post, center, 1/2 up from bottom edge
Channel Name: CPLS2

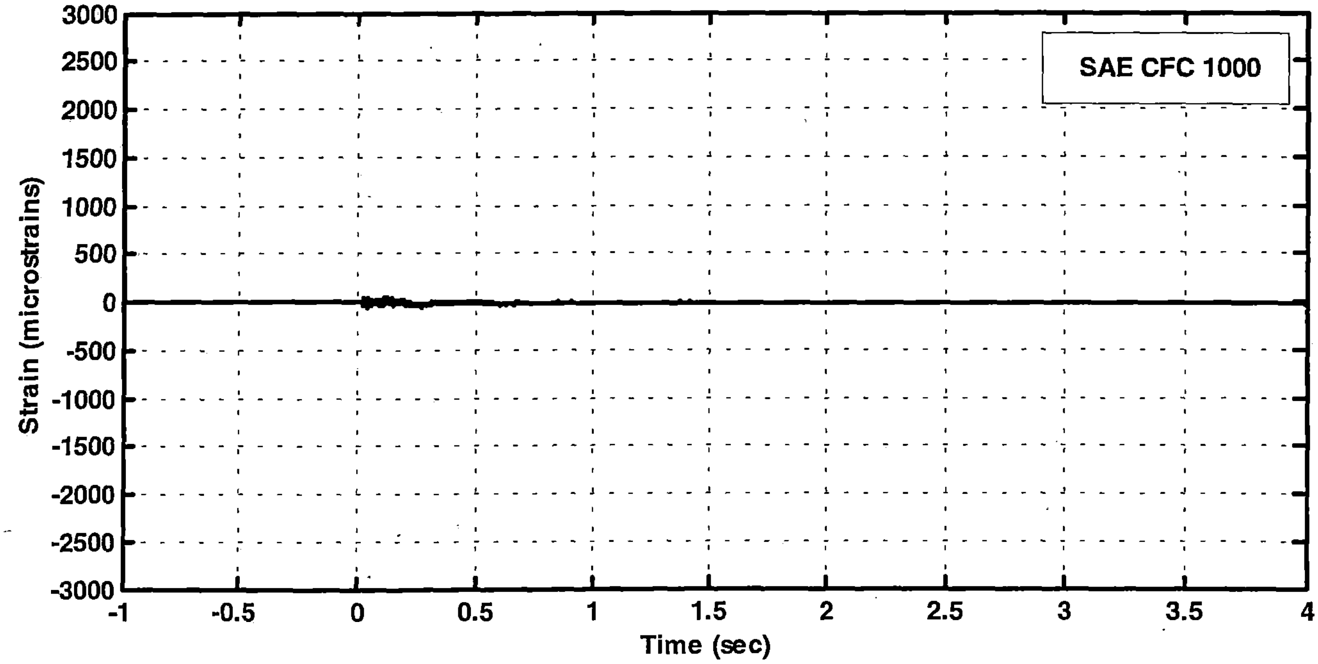

Figure F18. Longitudinal strain on left collision post, center, 1/4 up from bottom edge
Channel Name: CPLS3

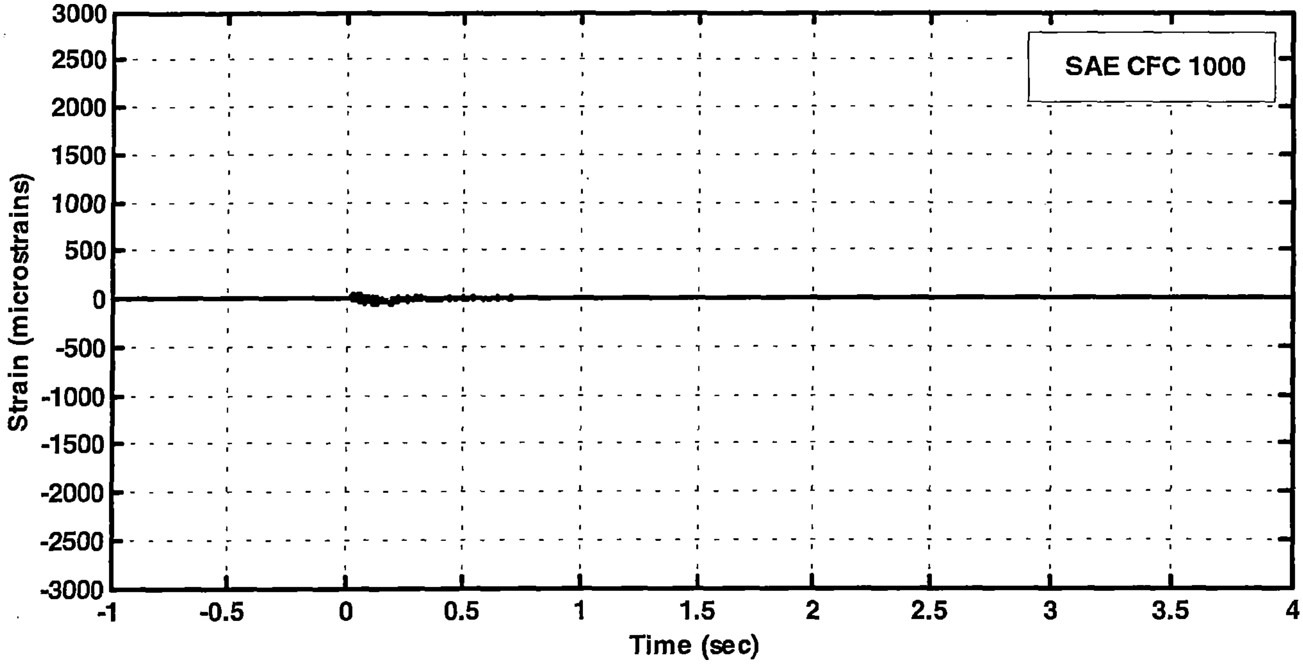

Figure F19. Longitudinal strain on left collision post, top rear corner
Channel Name: CPLS4

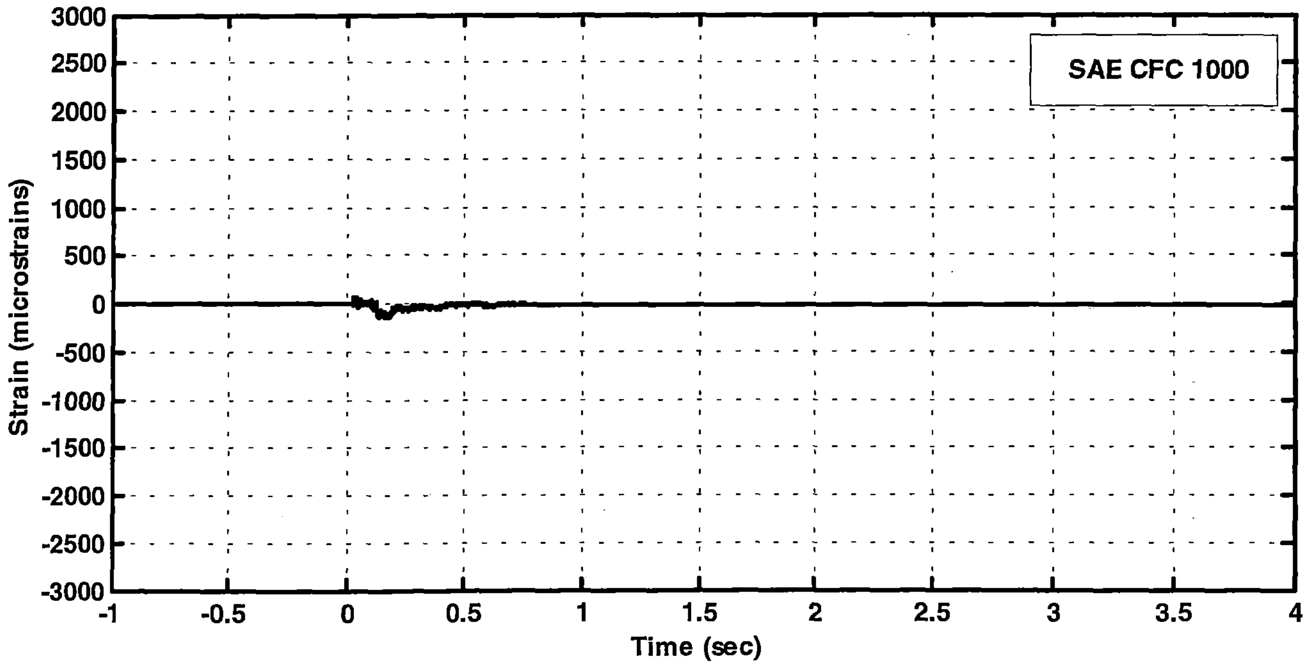

Figure F20. Longitudinal strain on left collision post, centered longitudinally, top edge
Channel Name: CPLS5

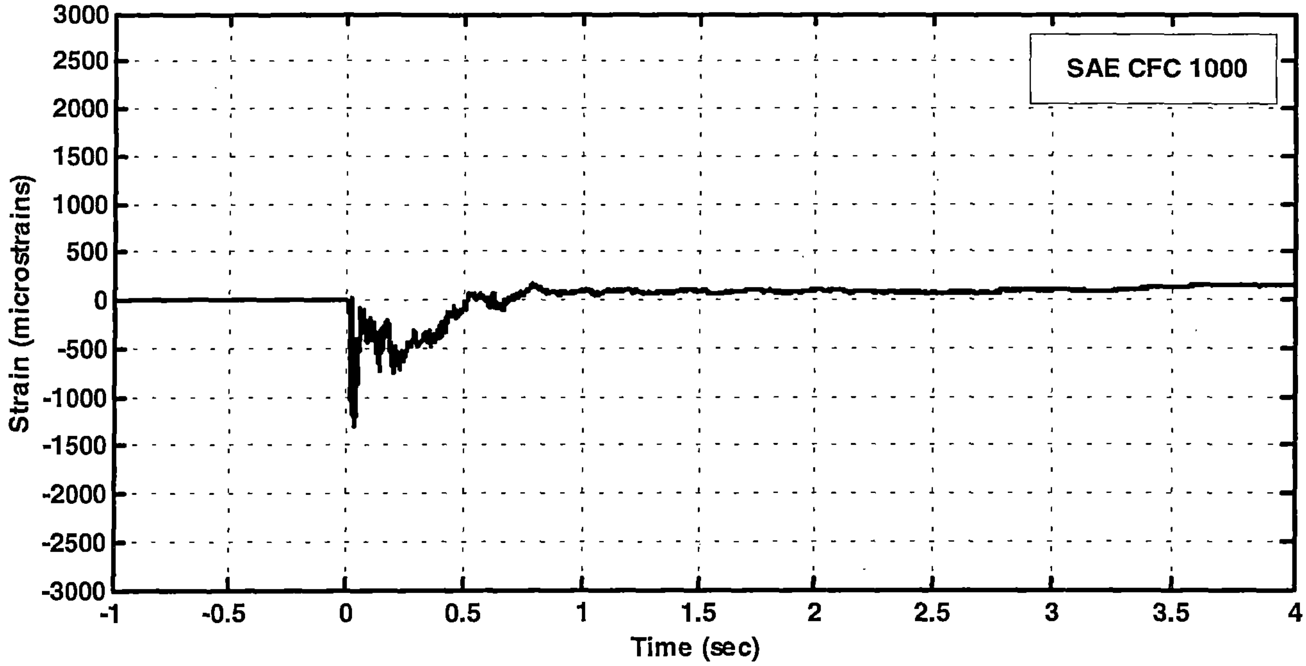

Figure F21. Strain on right collision post, bottom rear rosette, vertical element
Channel Name: CPRR1_1

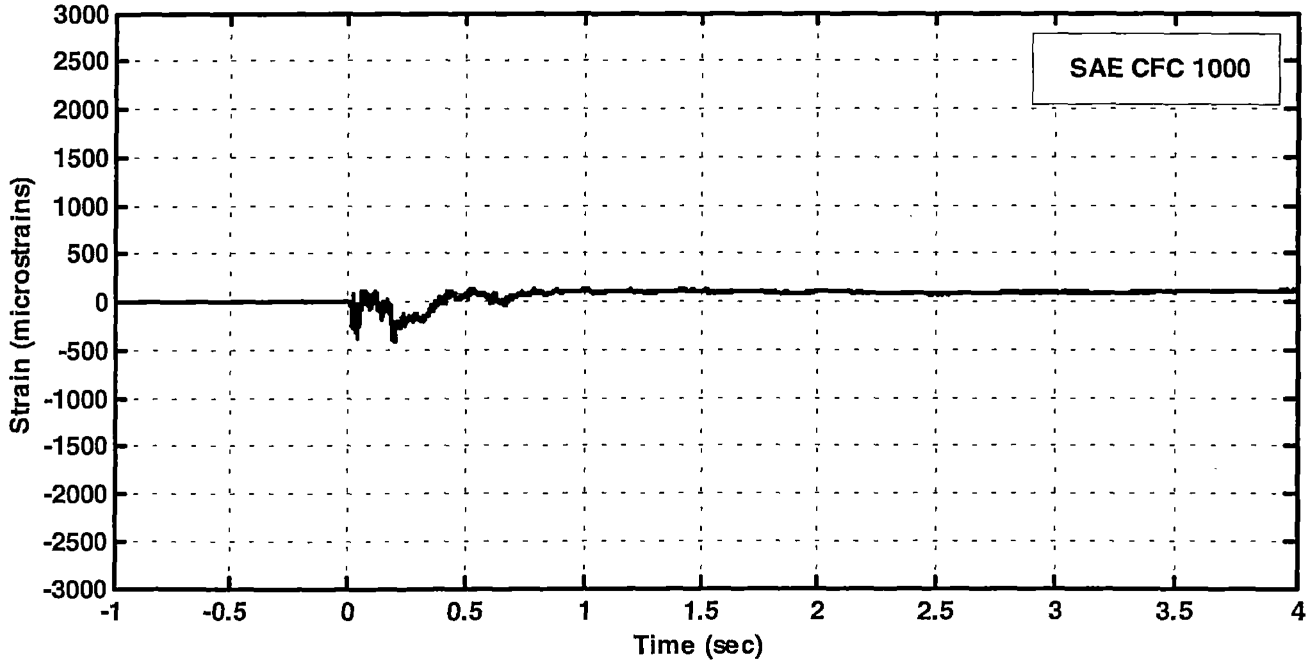

Figure F22. Strain on right collision post, bottom rear rosette, diagonal element
Channel Name: CPRR1_2

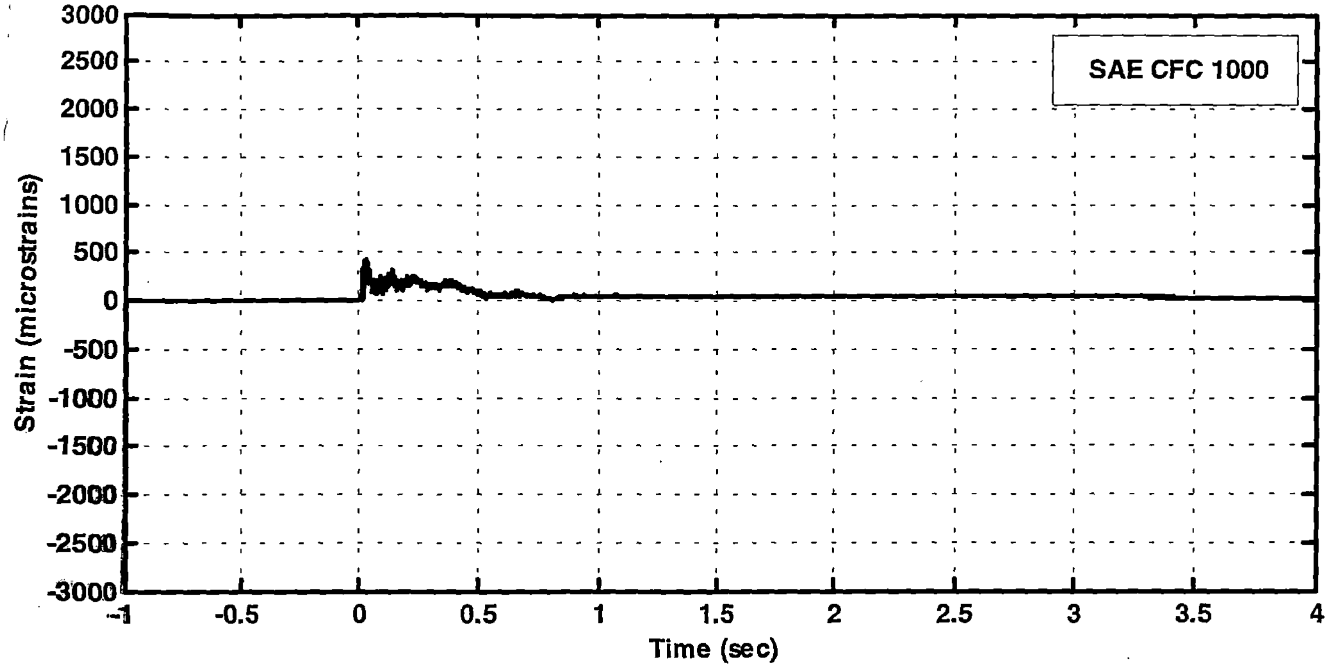

Figure F23. Strain on right collision post, bottom rear rosette, longitudinal element
Channel Name: CPRR1_3

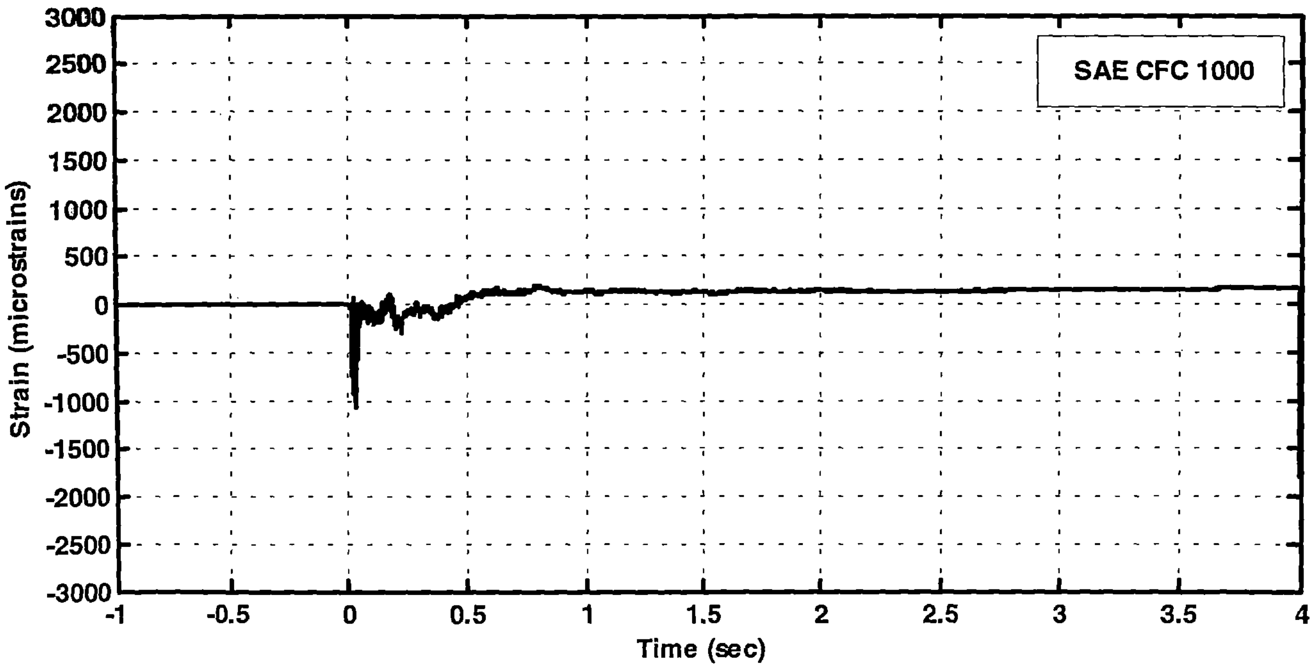

Figure F24. Strain on right collision post, bottom center rosette, vertical element
Channel Name: CPRR2_1

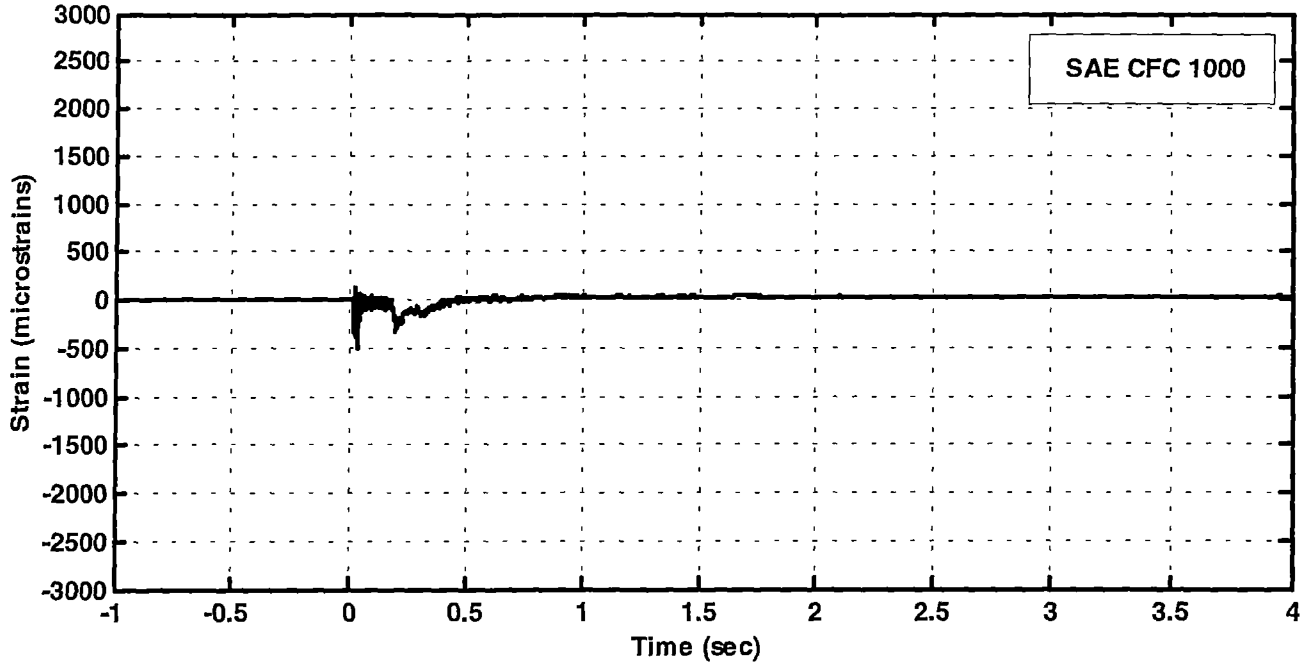

Figure F25. Strain on right collision post, bottom center rosette, diagonal element
Channel Name: CPRR2_2

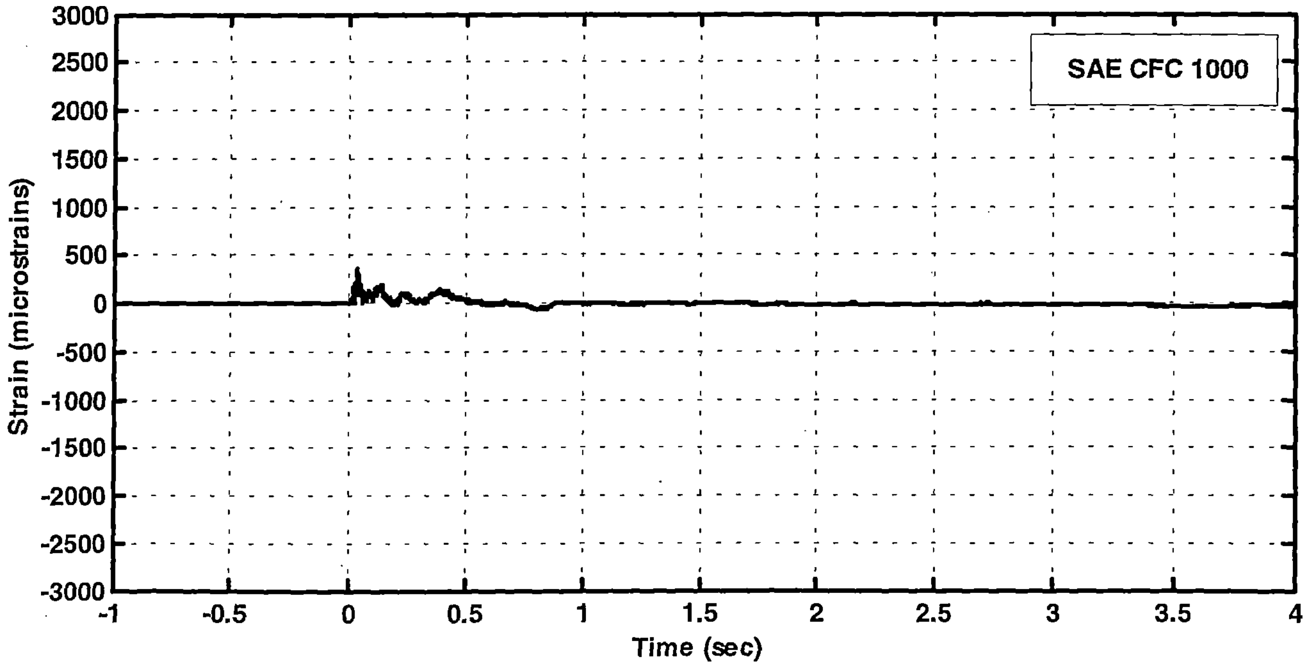

Figure F26. Strain on right collision post, bottom center rosette, longitudinal element
Channel Name: CPRR2_3

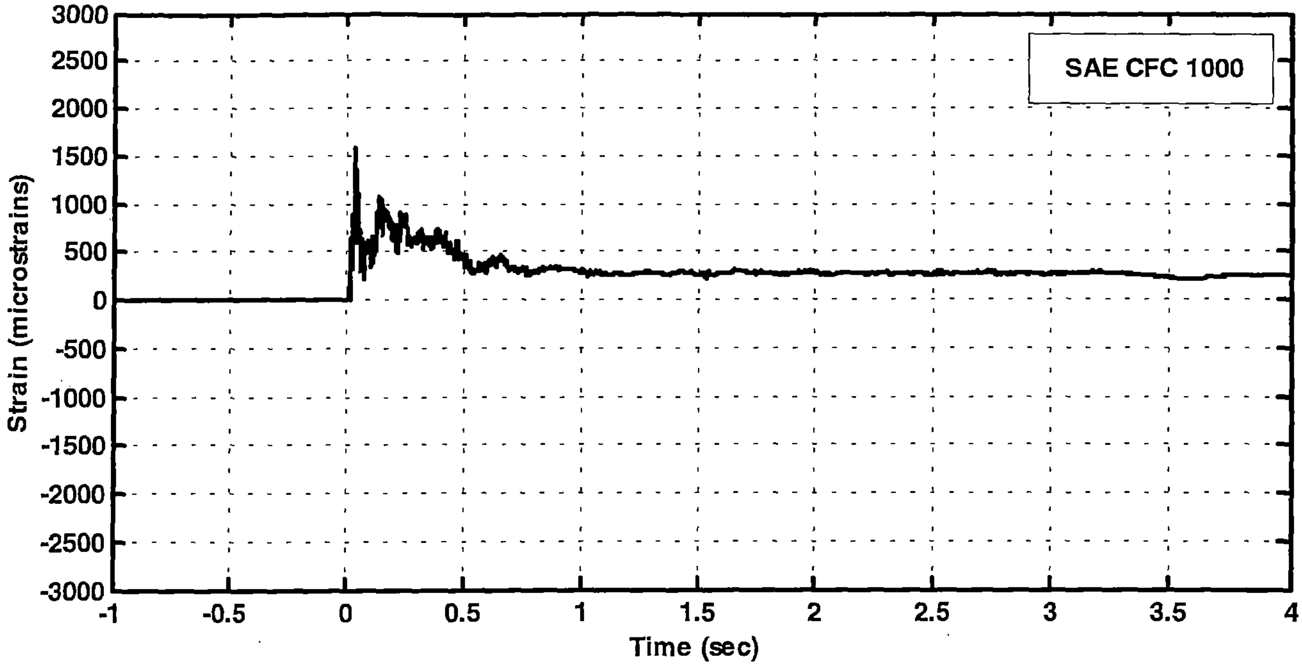

Figure F27. Strain on right collision post, bottom front rosette, vertical element
Channel Name: CPRR3_1

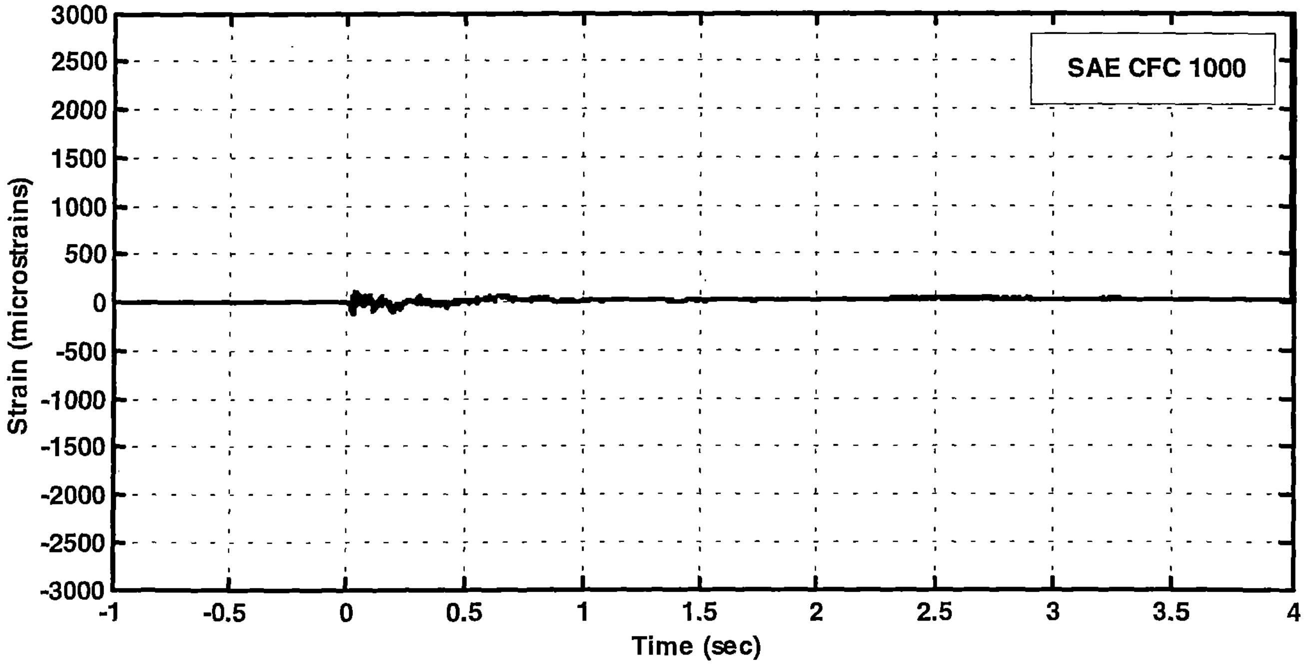

Figure F28. Strain on right collision post, bottom front rosette, diagonal element
Channel Name: CPRR3_2

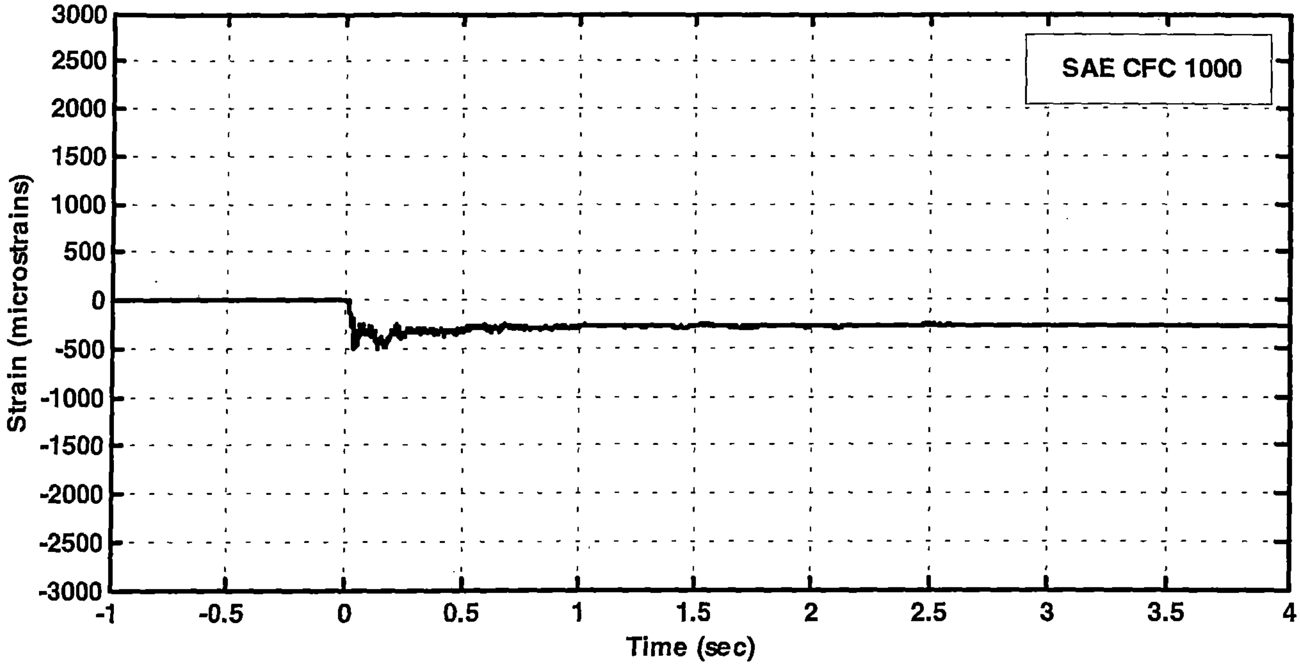

Figure F29. Strain on right collision post, bottom front rosette, longitudinal element
Channel Name: CPRR3_3

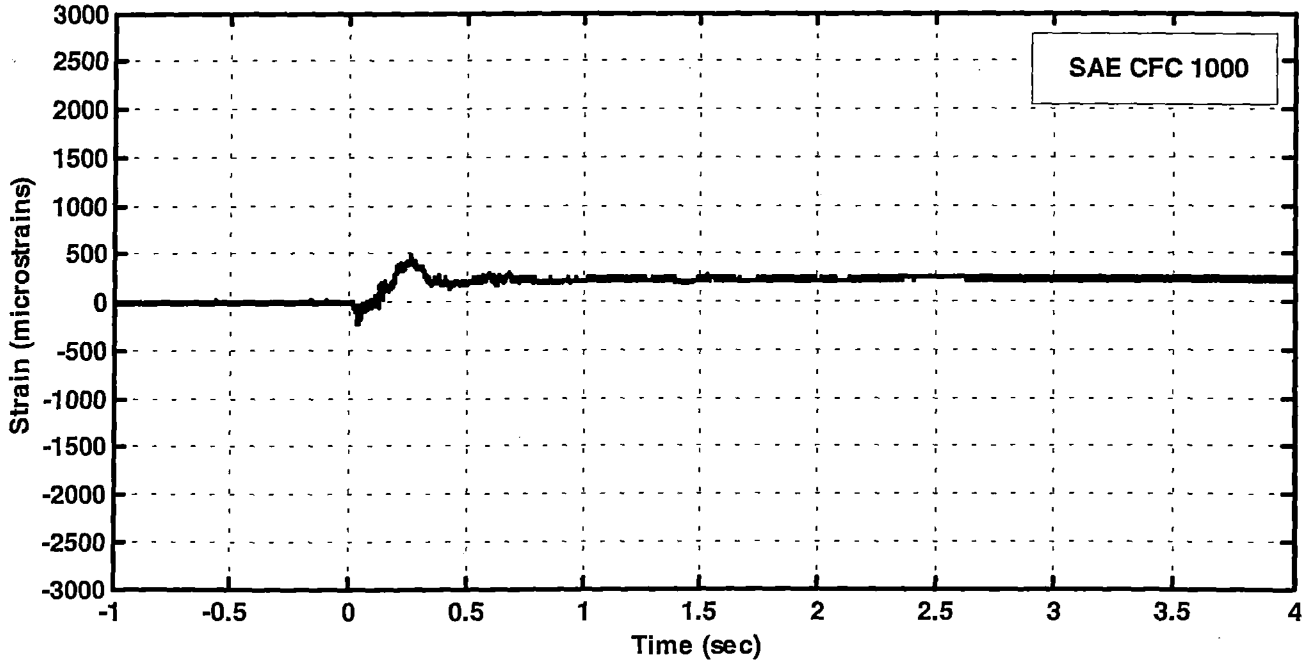

Figure F30. Strain on right collision post, top front rosette, vertical element
Channel Name: CPRR4_1

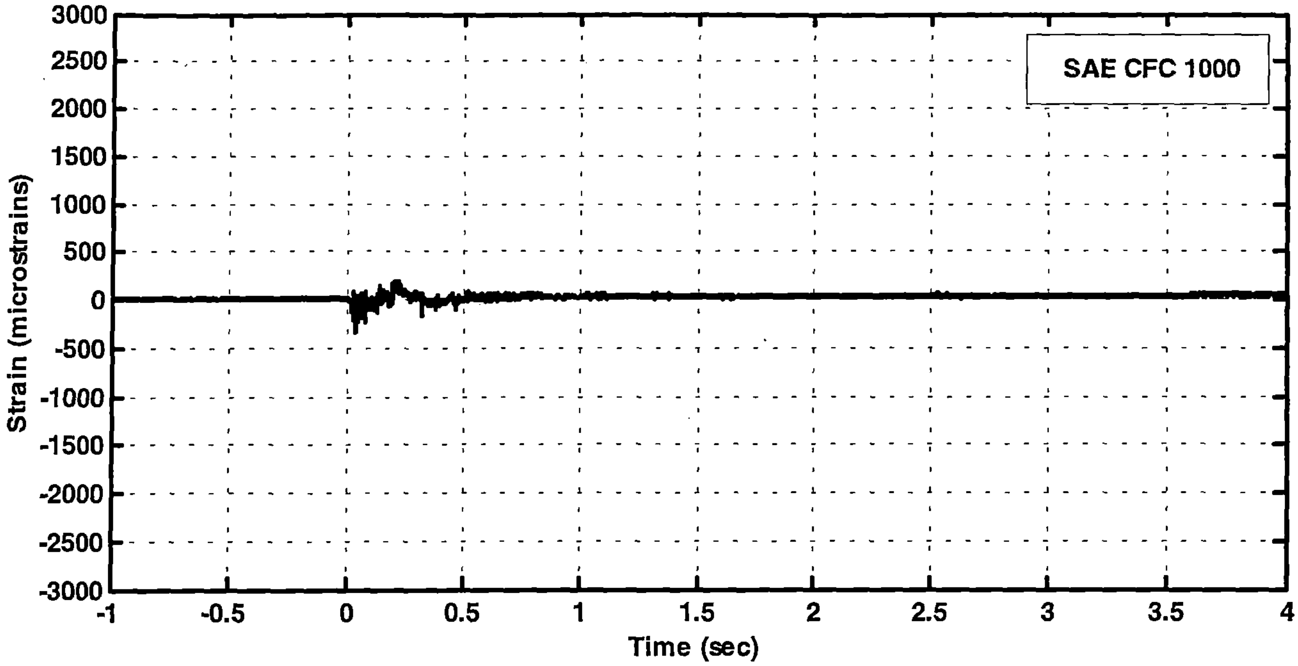

Figure F31. *Strain on right collision post, top front rosette, diagonal element*
Channel Name: CPRR4_2

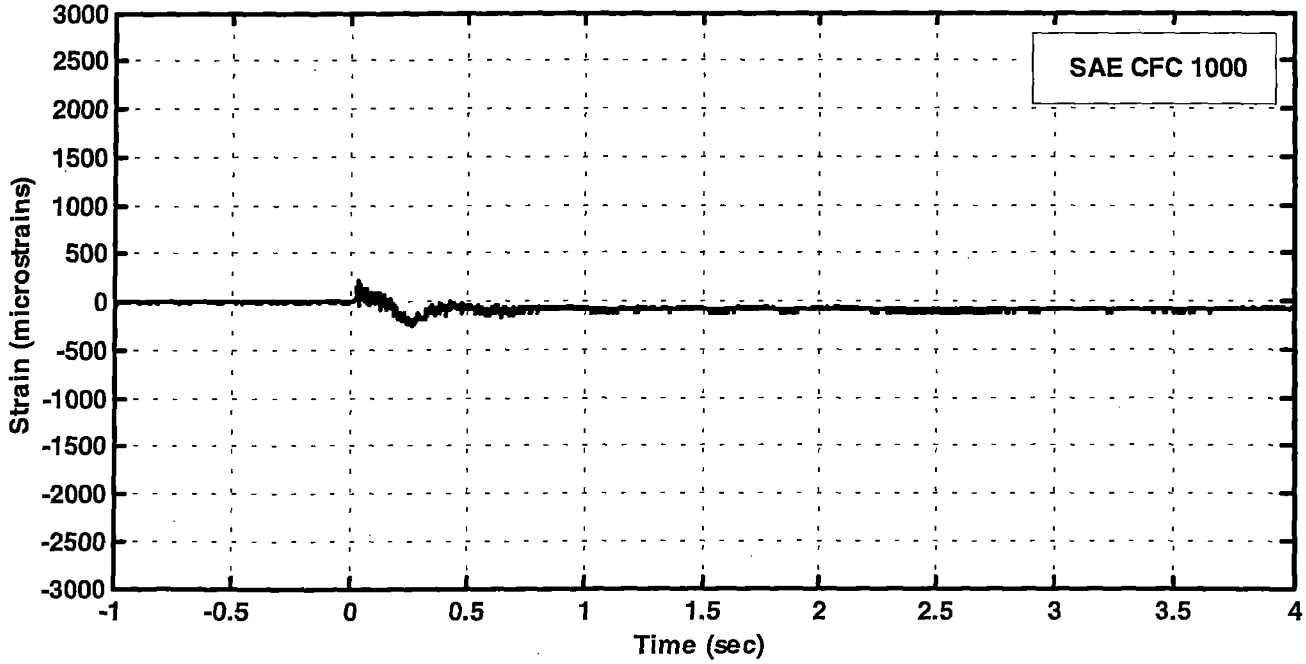

Figure F32. Strain on right collision post, top front rosette, longitudinal element
Channel Name: CPRR4_3

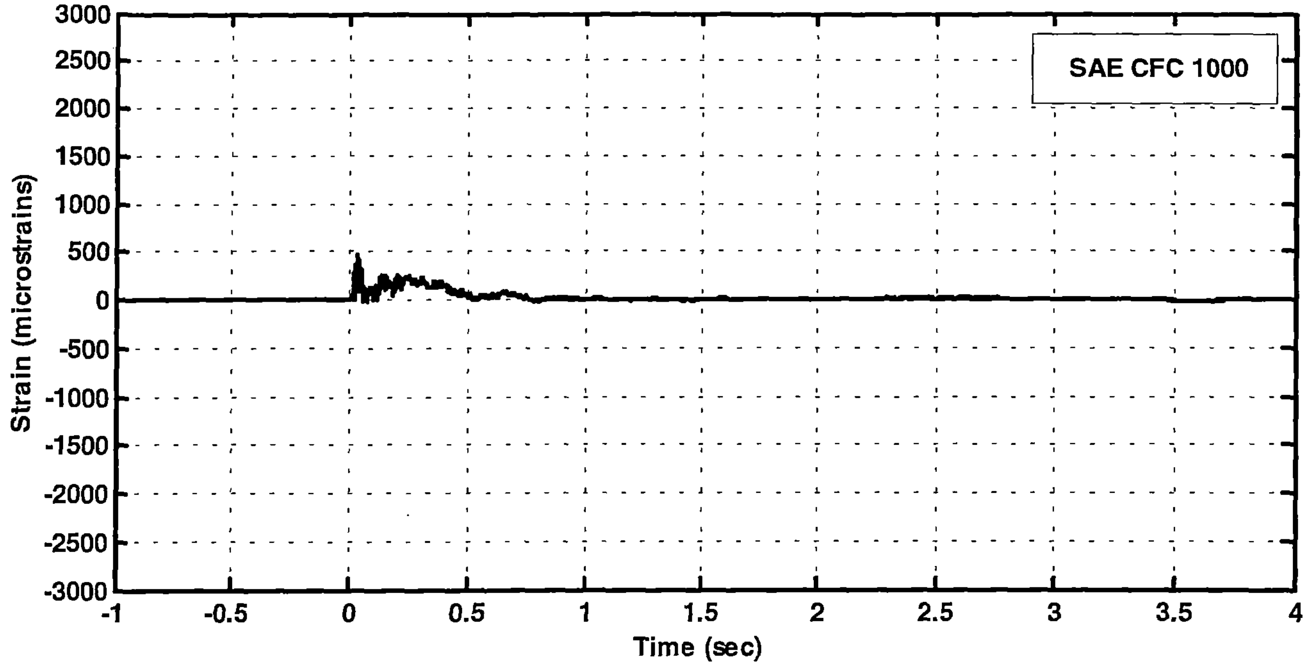

Figure F33. Strain on right collision post, middle front rosette, vertical element
Channel Name: CPRR5_1

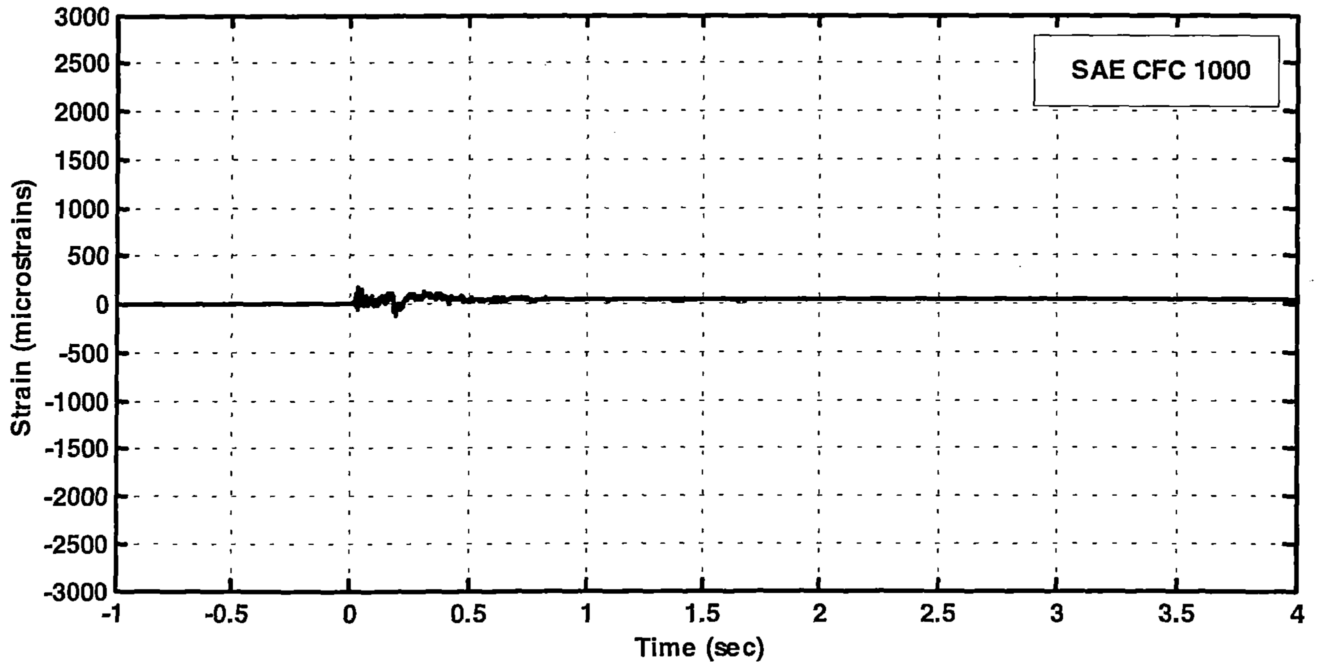

Figure F34. Strain on right collision post, middle front rosette, diagonal element
Channel Name: CPRR5_2

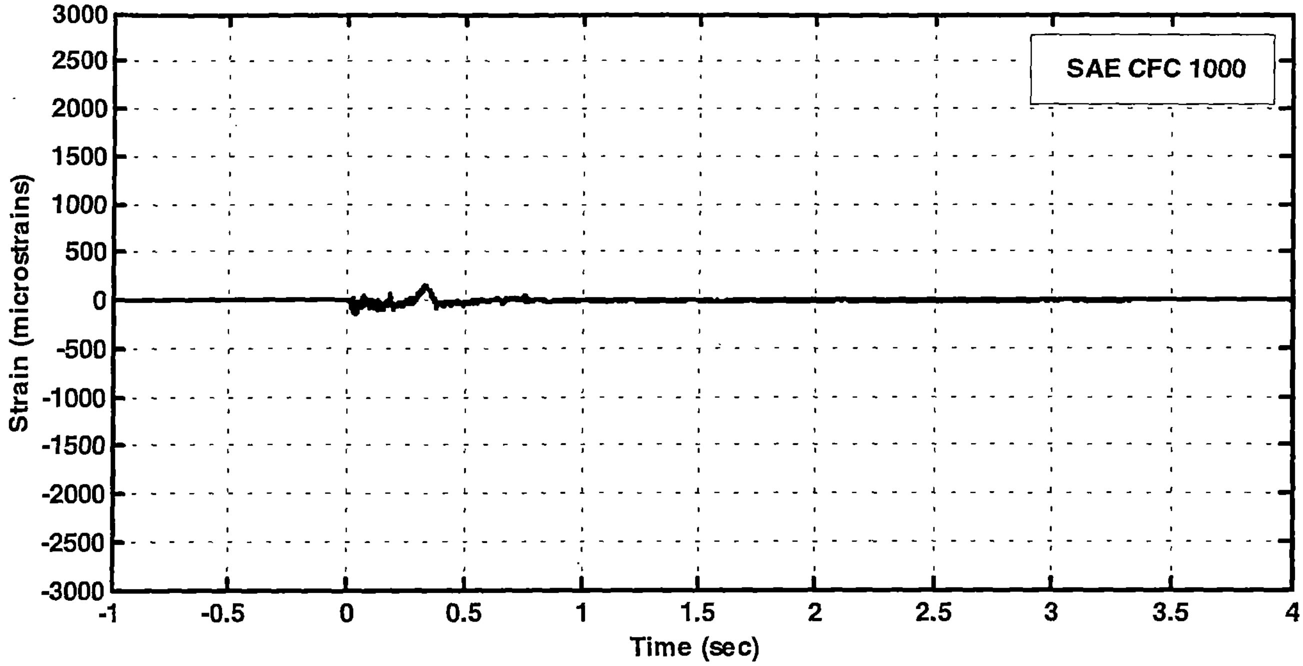

Figure F35. Strain on right collision post, middle front rosette, longitudinal element
Channel Name: CPRR5_3

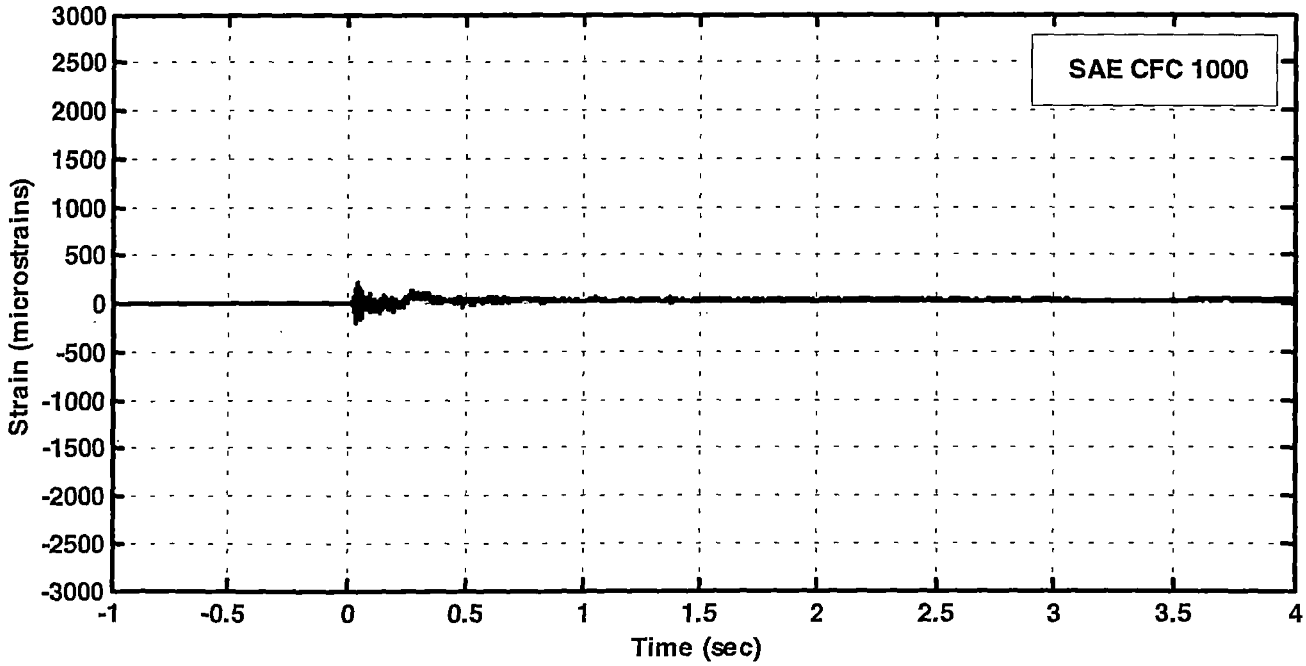

Figure F36. Longitudinal strain on right collision post, center, 3/4 up from bottom edge
Channel Name: CPRS1

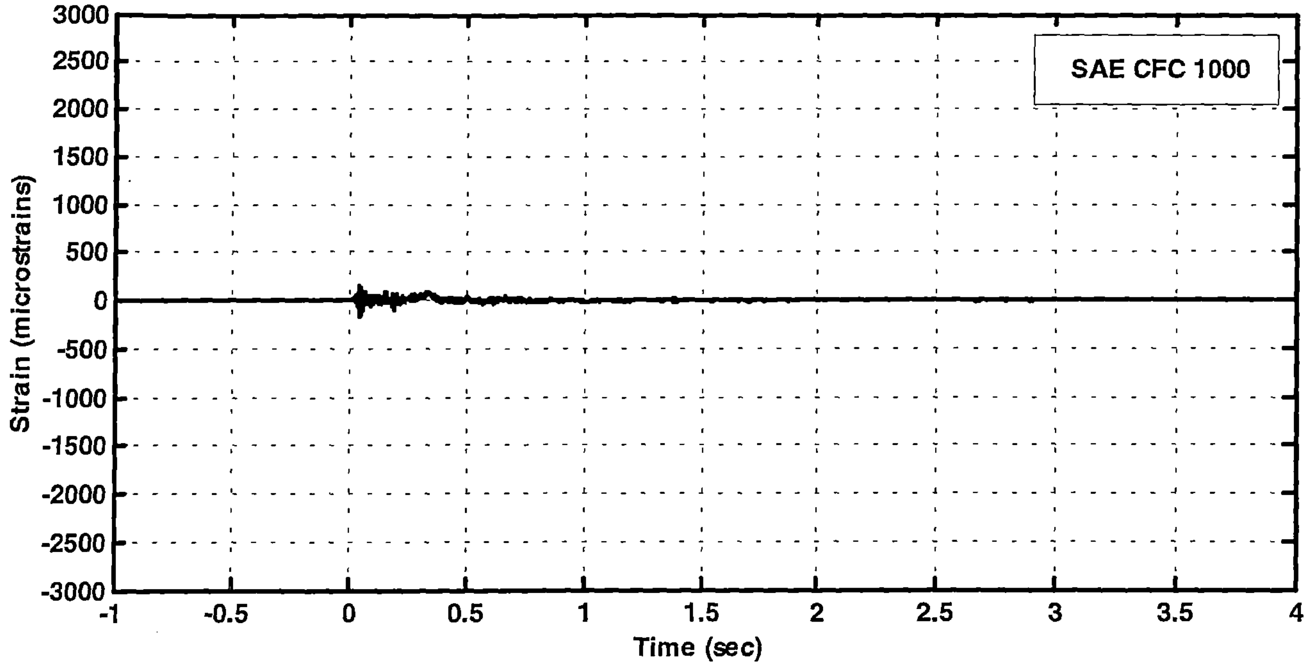

Figure F37. Longitudinal strain on right collision post, center, 1/2 up from bottom edge
Channel Name: CPRS2

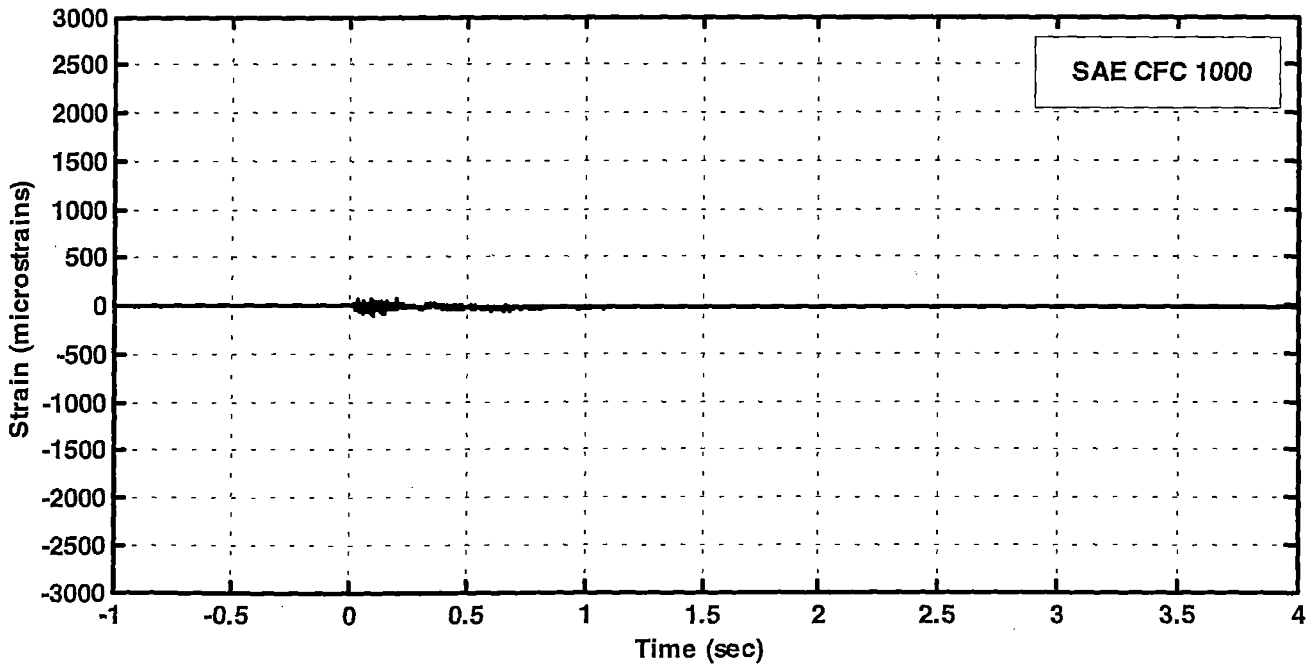

Figure F38. Longitudinal strain on right collision post, center, 1/4 up from bottom edge
Channel Name: CPRS3

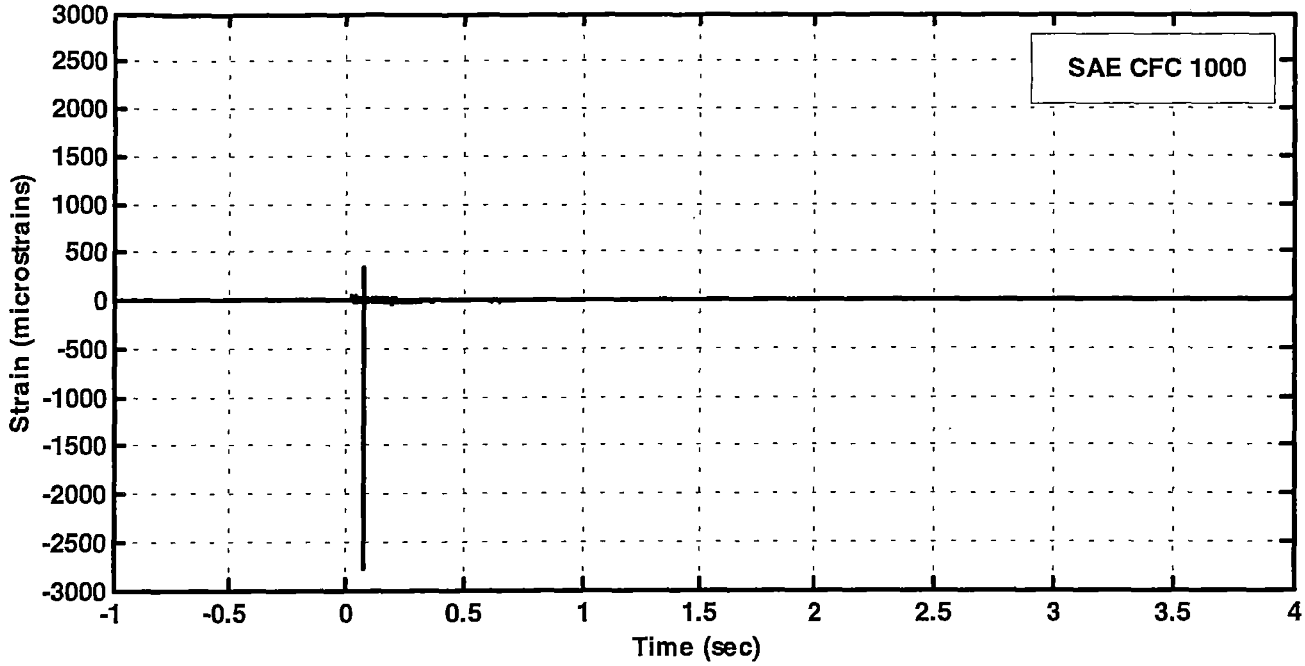

Figure F39. Longitudinal strain on right collision post, top rear corner
Channel Name: CPRS4

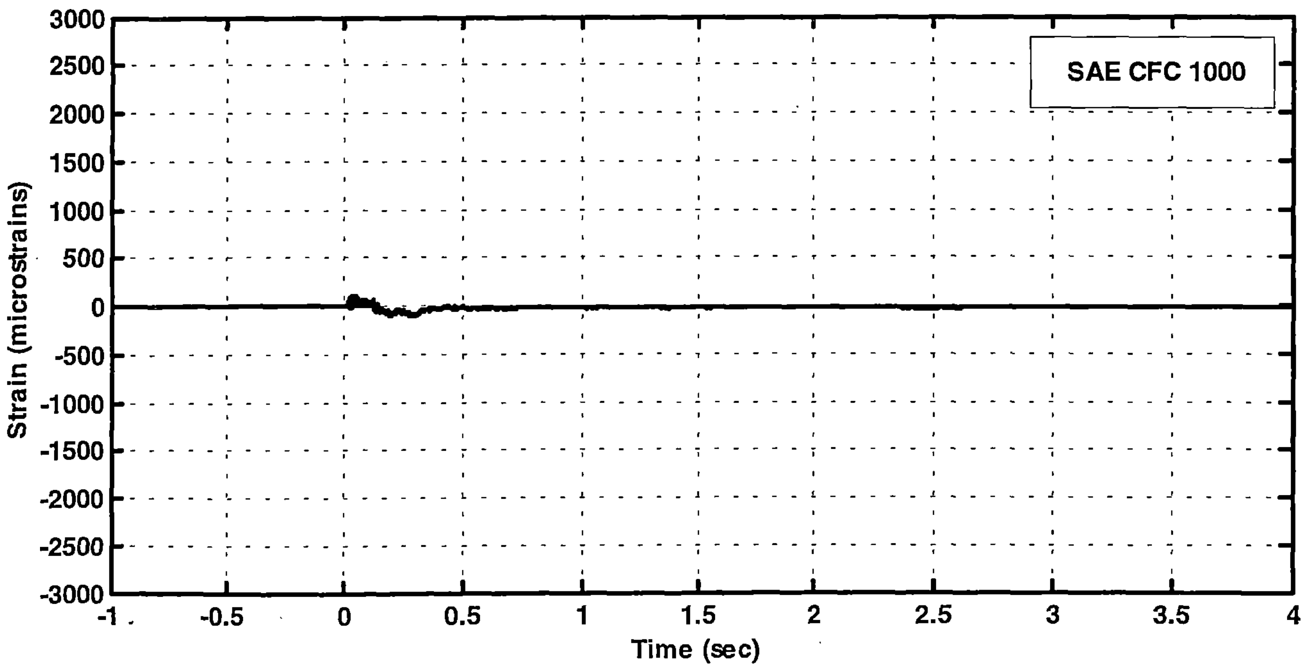

Figure F40. Longitudinal strain on right collision post, centered longitudinally, top edge
Channel Name: CPRS5

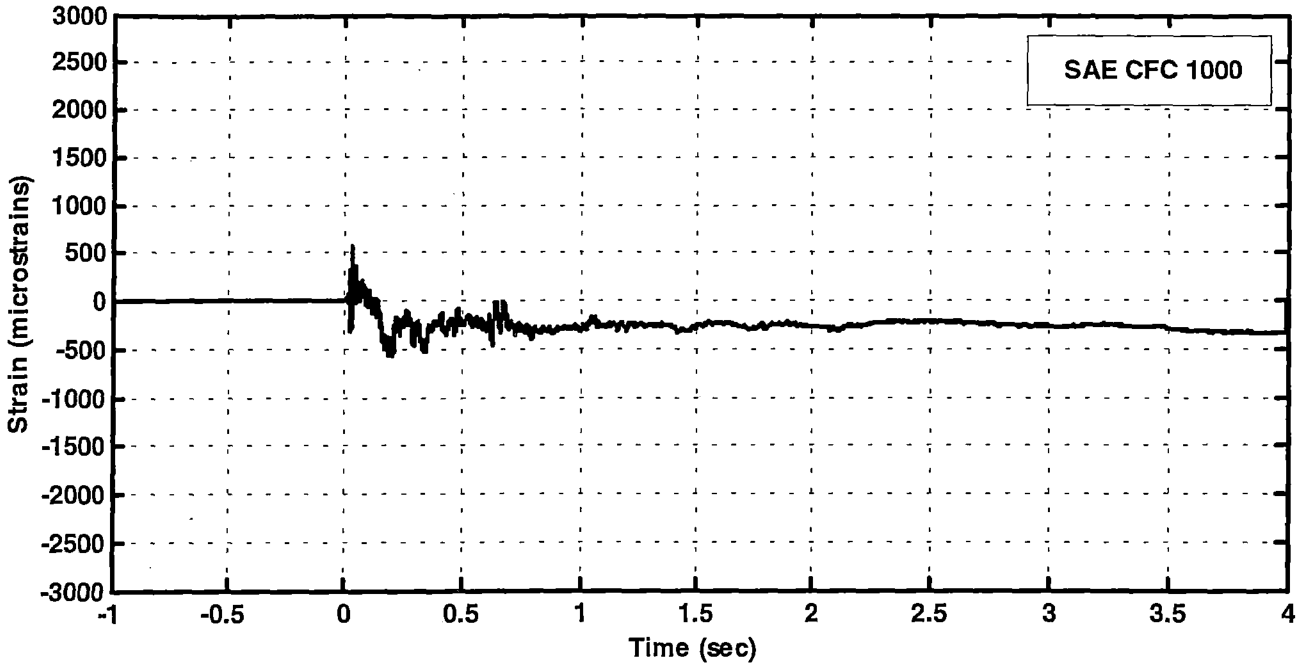

Figure F41. Vertical strain on windshield post, bottom edge of windshield, left side
Channel Name: CPWBL

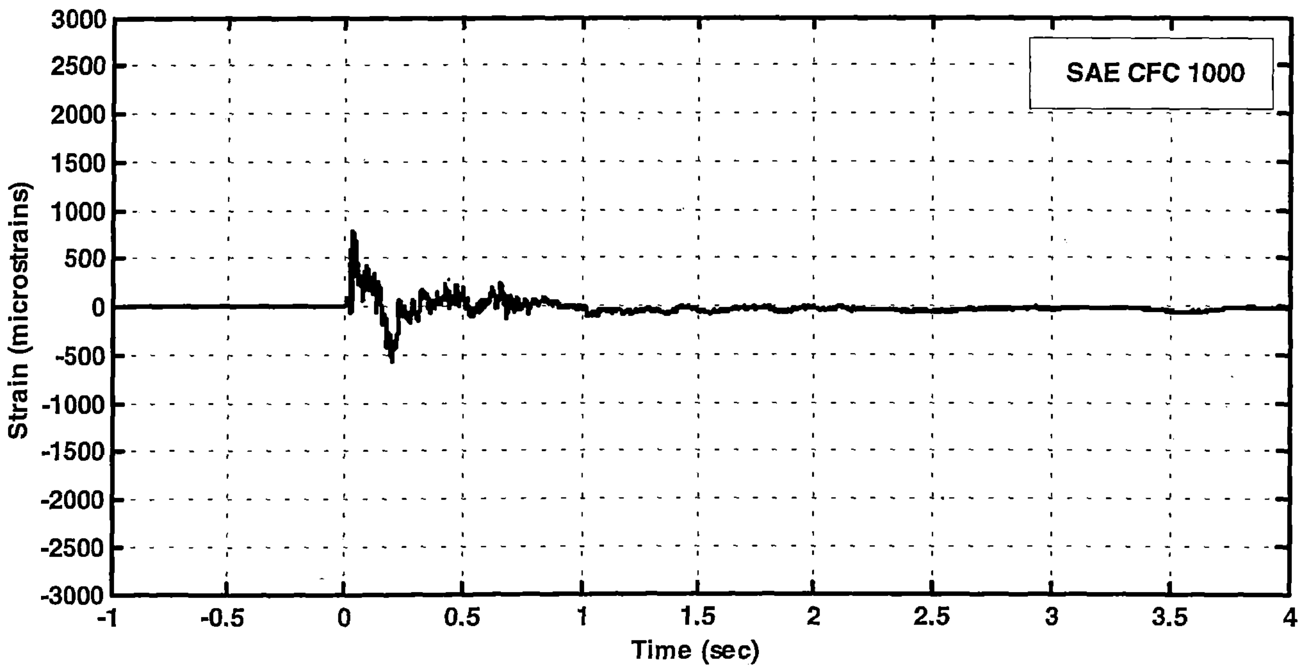

Figure F42. Vertical strain on windshield post, bottom edge of windshield, right side
Channel Name: CPWBR

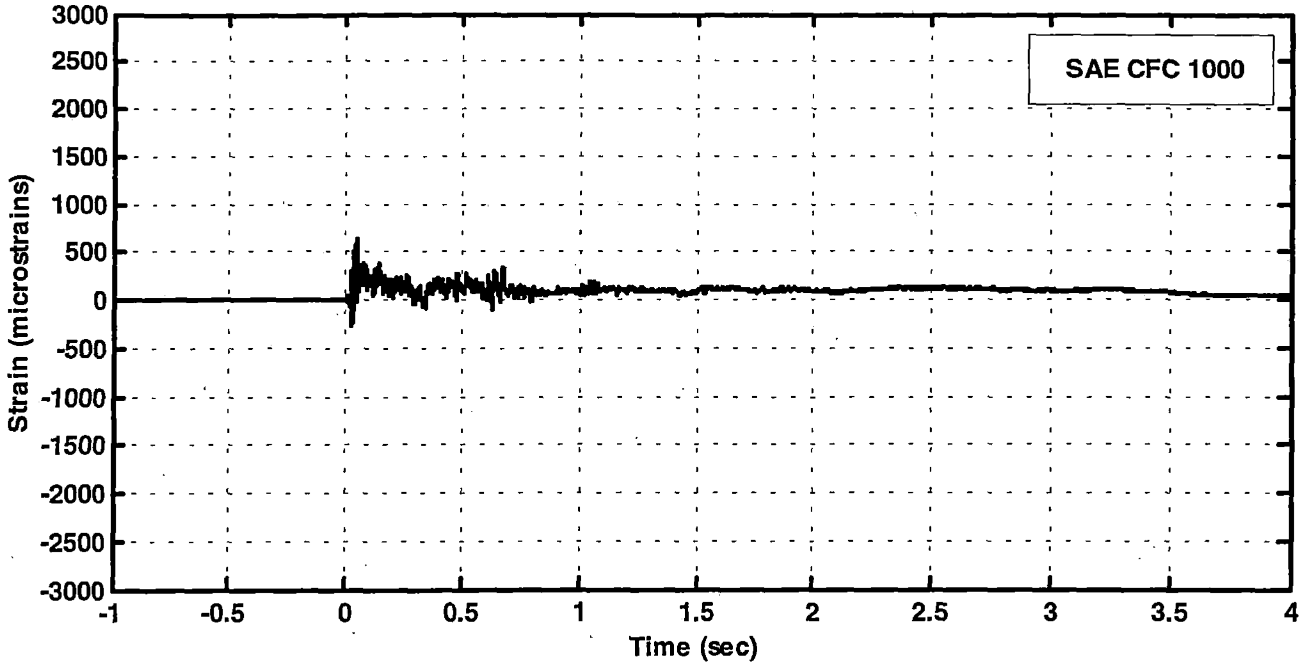

Figure F43. Vertical strain on windshield post, middle of windshield, left side
Channel Name: CPWML

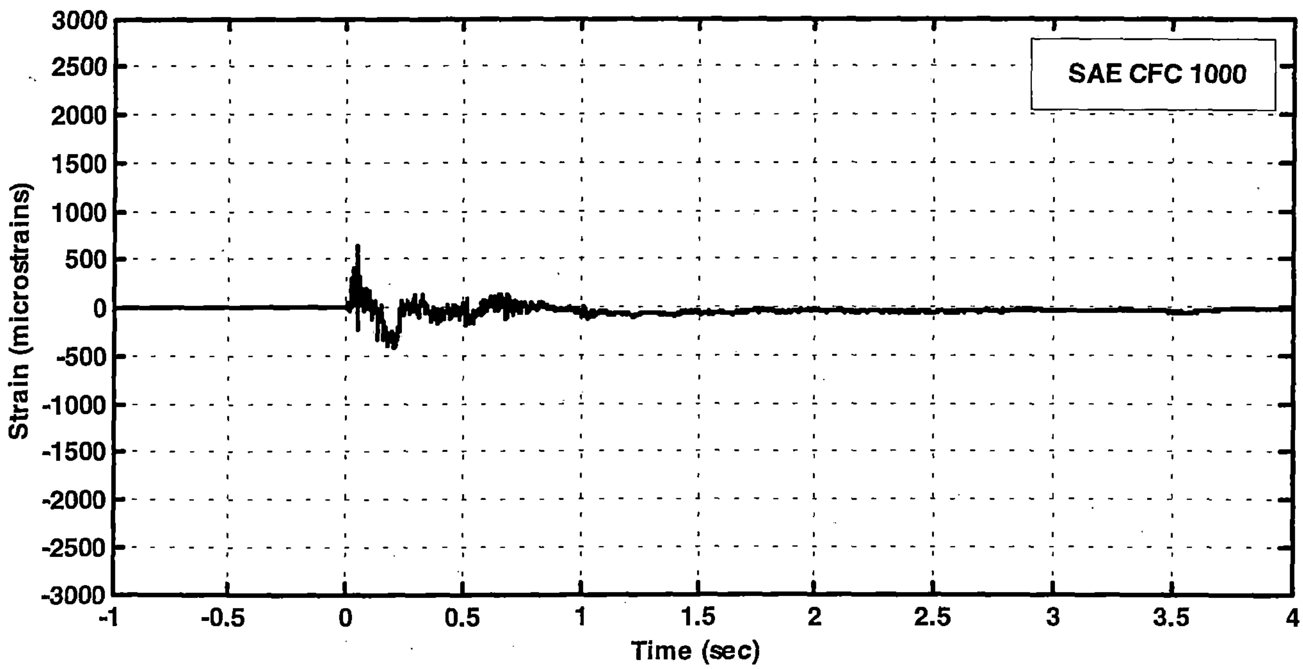

Figure F44. Vertical strain on windshield post, middle of windshield, right side
Channel Name: CPWMR

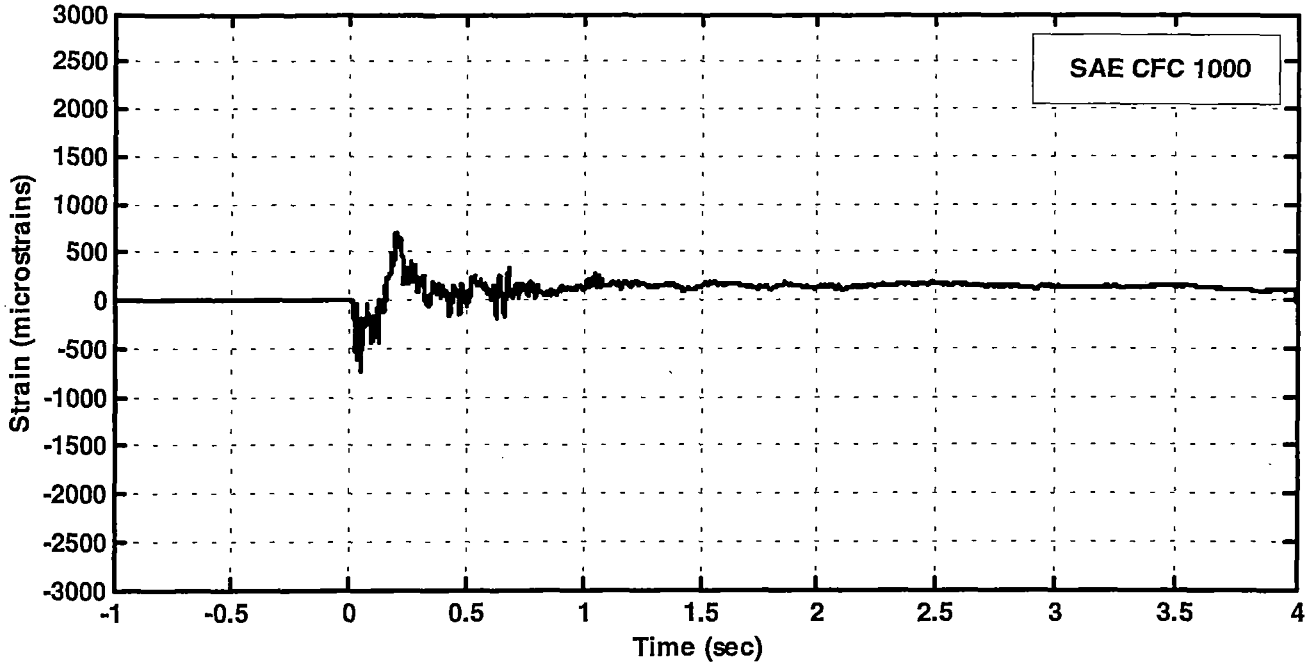

Figure F45. Vertical strain on windshield post, top edge of windshield, left side
Channel Name: CPWTL

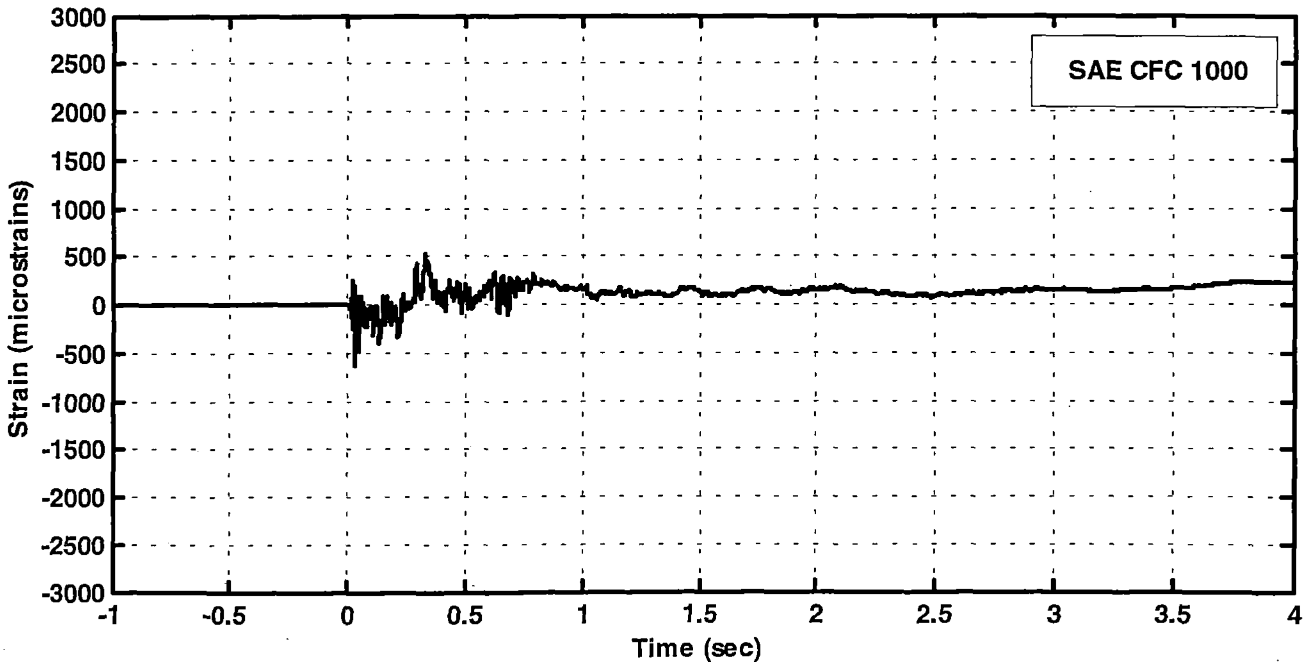

Figure F46. Vertical strain on windshield post, top edge of windshield, right side
Channel Name: CPWTR

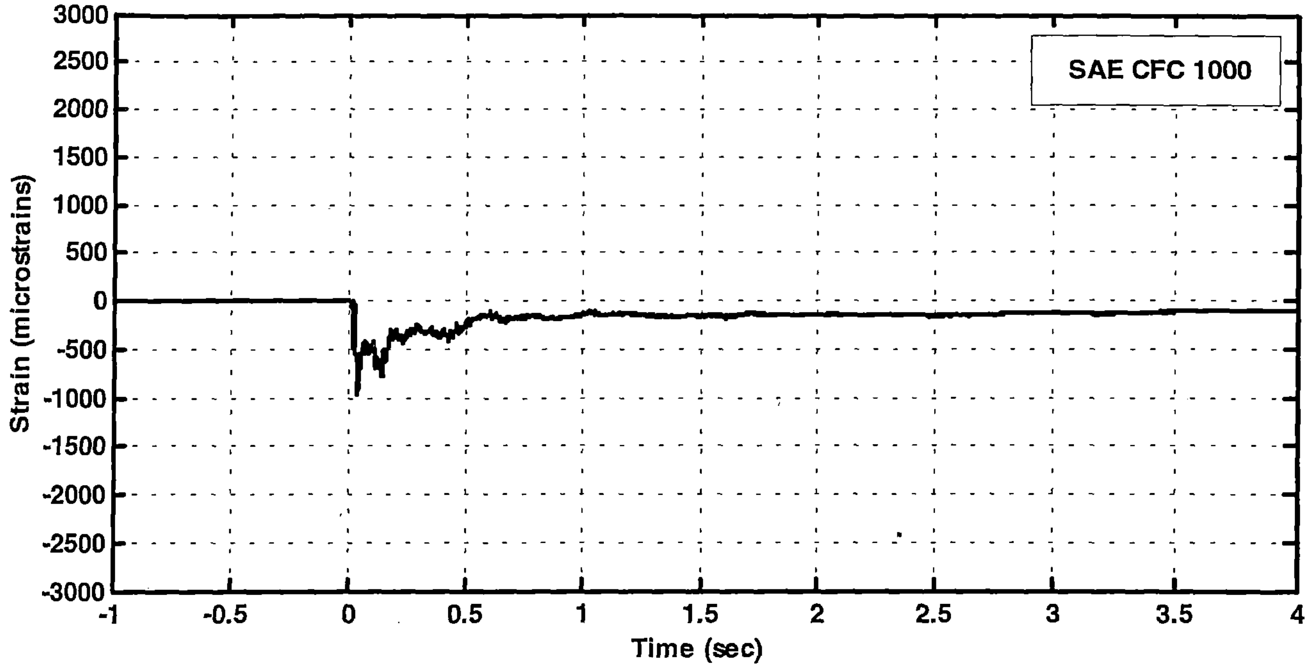

Figure F47. Longitudinal strain on underframe, about even with the leading axle, left side
Channel Name: ULF

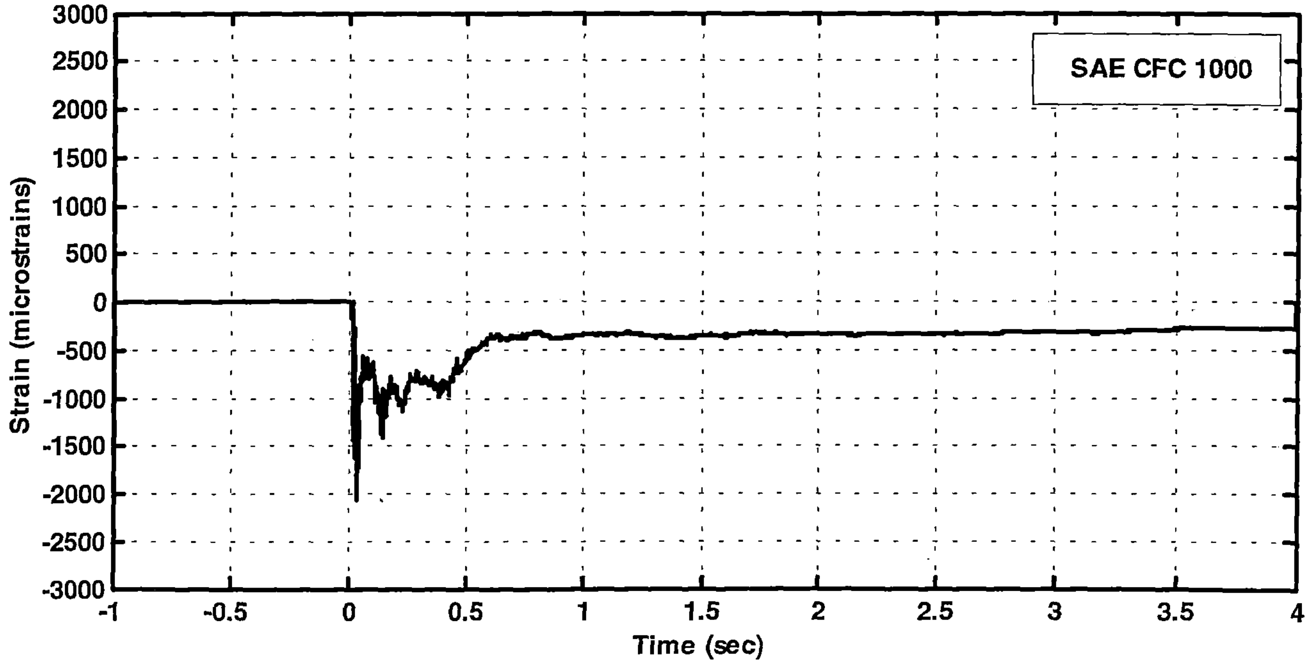

Figure F48. Longitudinal strain on underframe, about even with the leading axle, center
Channel Name: UMF

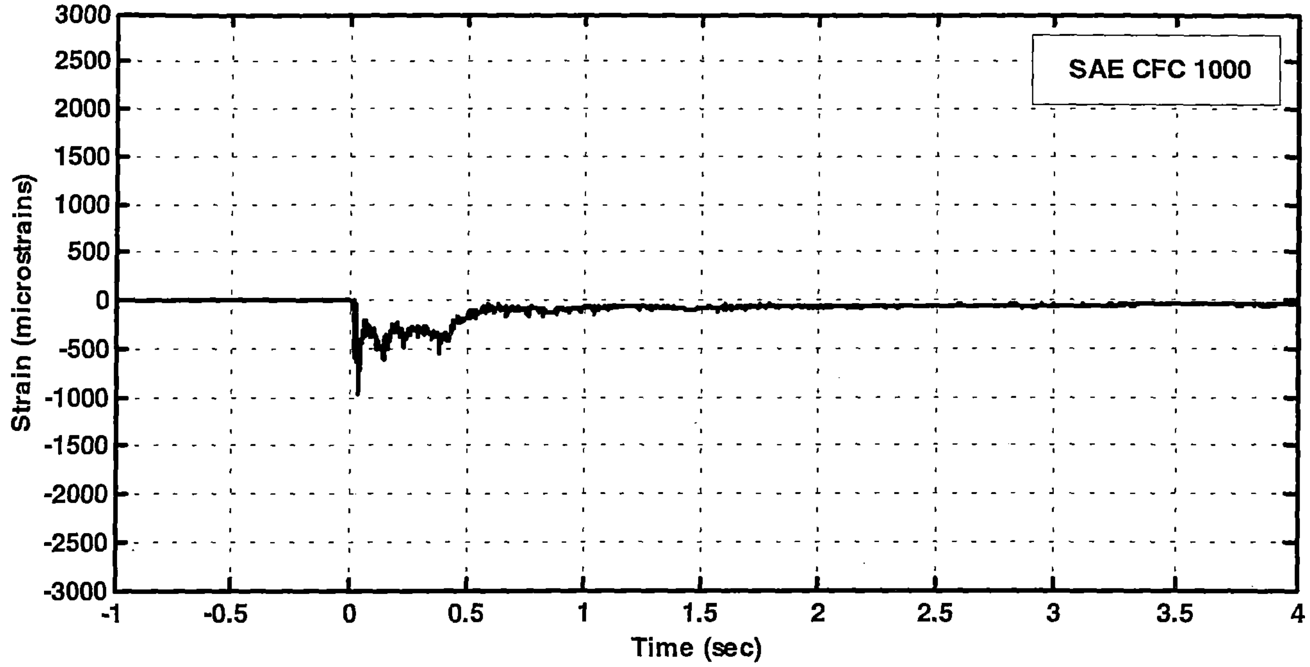

Figure F49. Longitudinal strain on underframe, about even with the leading axle, right side
Channel Name: URF

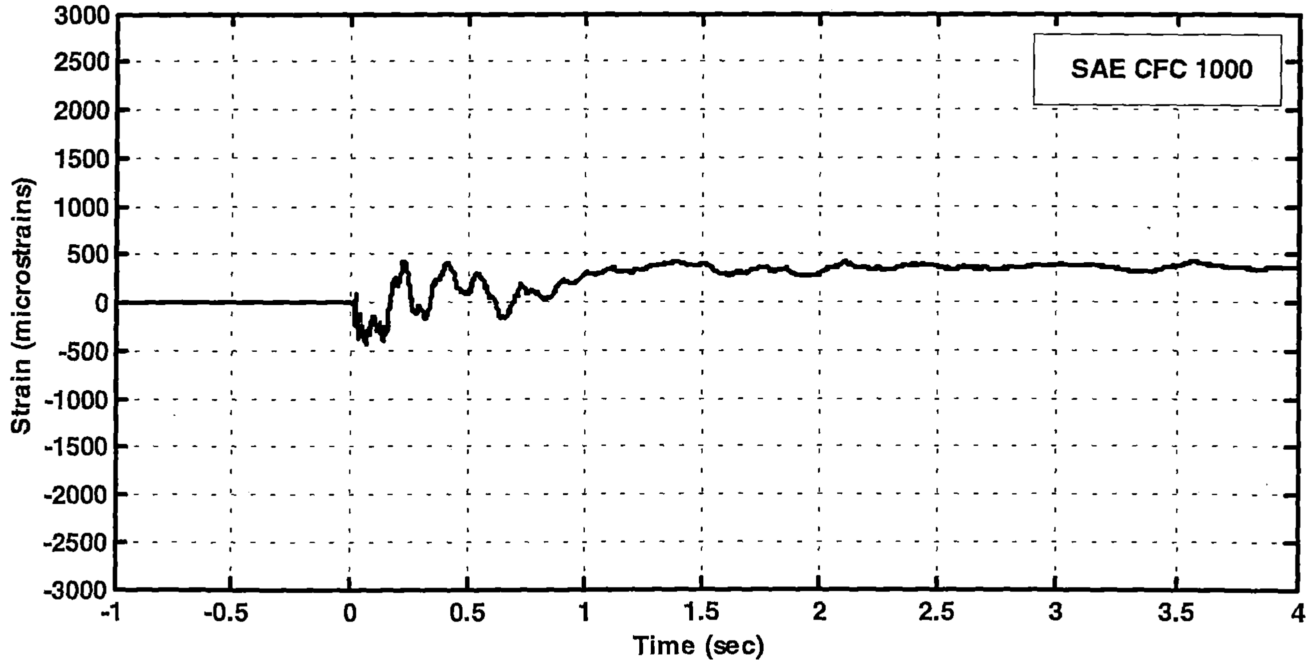

Figure F50. Longitudinal strain on underframe, just in front of the fuel tank, left side
Channel Name: ULMF

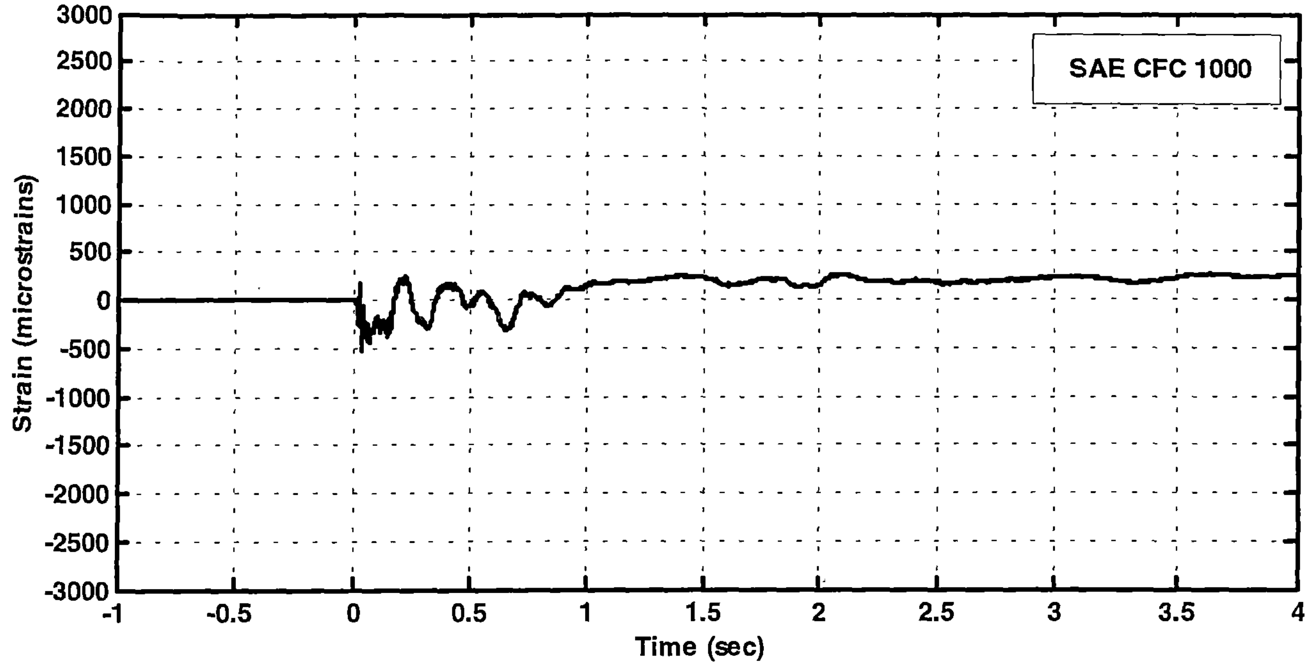

Figure F51. Longitudinal strain on underframe, just in front of the fuel tank, center
Channel Name: UMMF

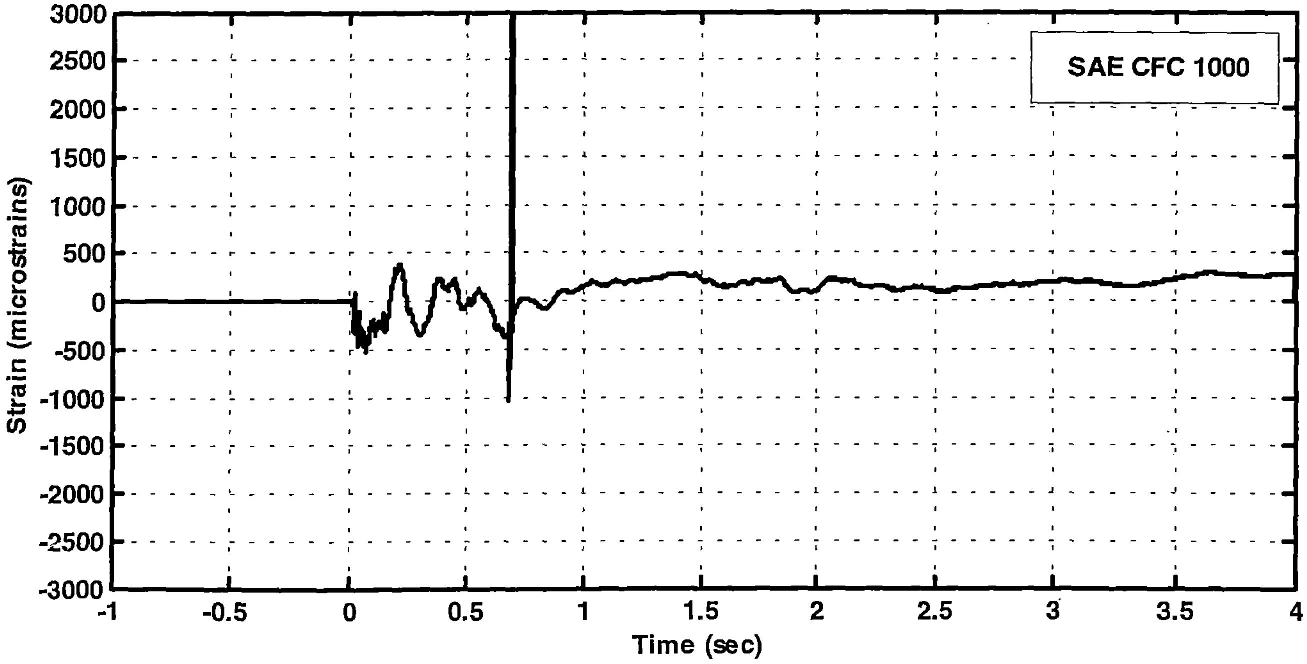

Figure F52. Longitudinal strain on underframe, just in front of the fuel tank, right side
Channel Name: URMF

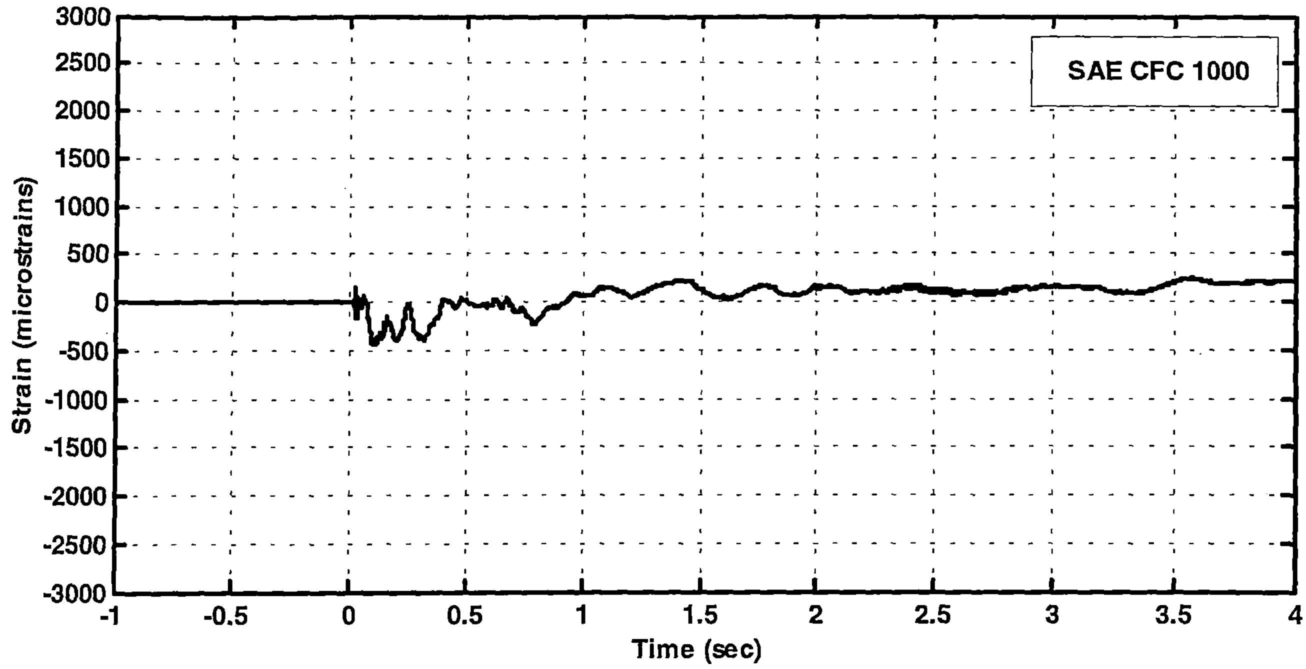

Figure F53. Longitudinal strain on underframe, just behind the fuel tank, left side
Channel Name: ULMR

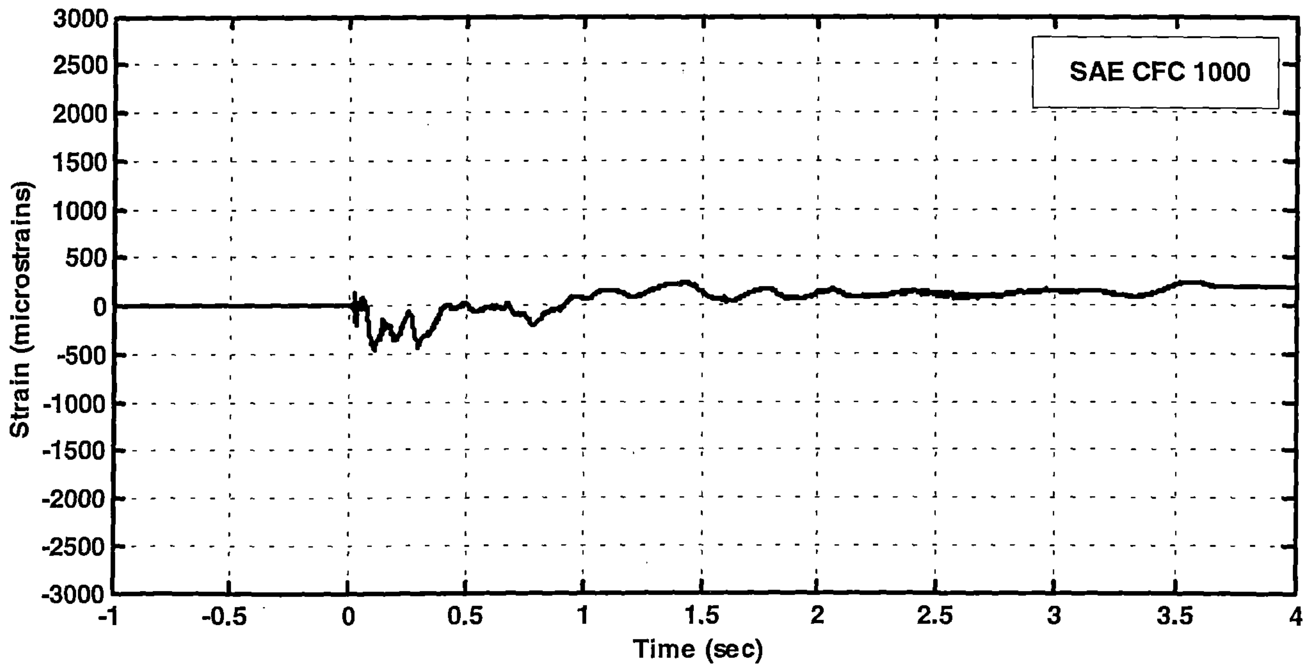

Figure F54. Longitudinal strain on underframe, just behind the fuel tank, center
Channel Name: UMMR

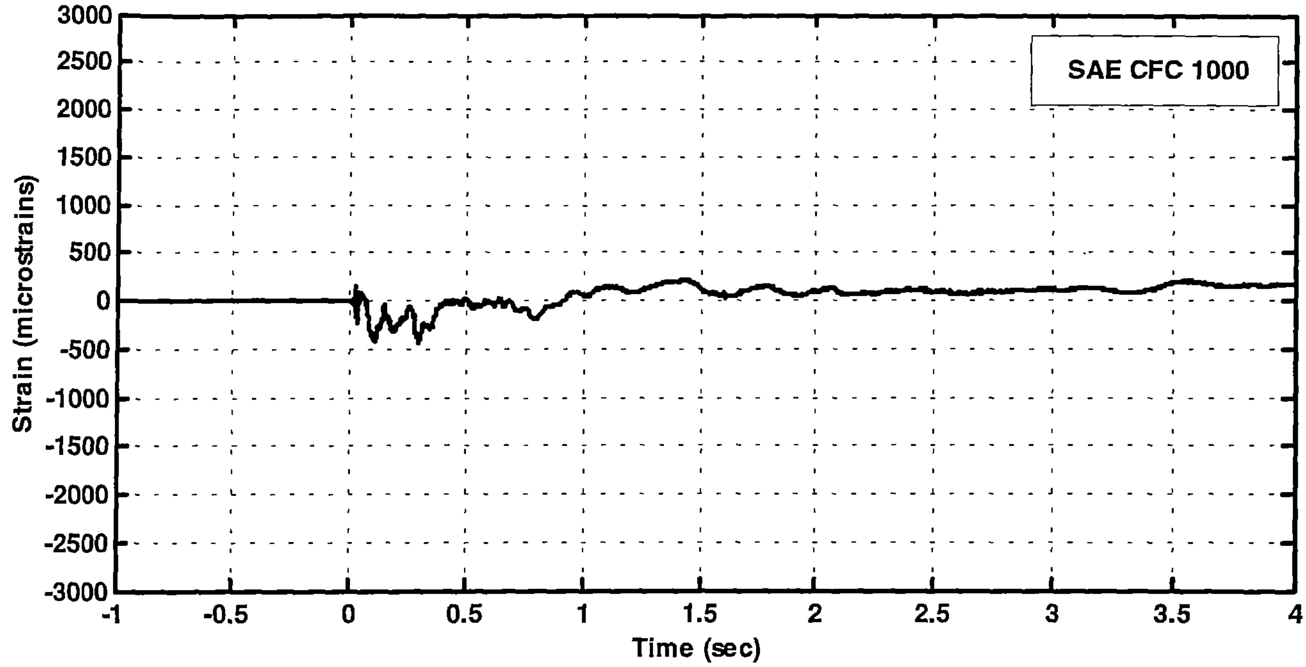

Figure F55. Longitudinal strain on underframe, just behind the fuel tank, right side
Channel Name: URMR

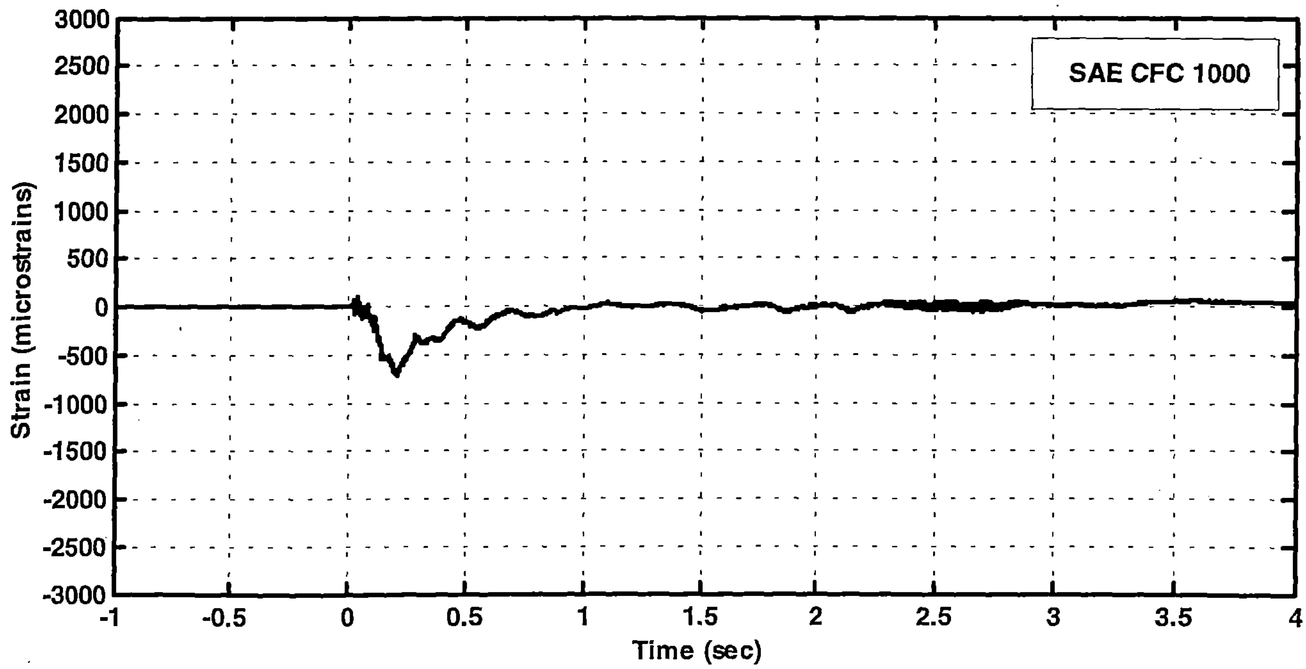

Figure F56. Longitudinal strain on underframe, about even with the trailing axle, left side
Channel Name: ULR

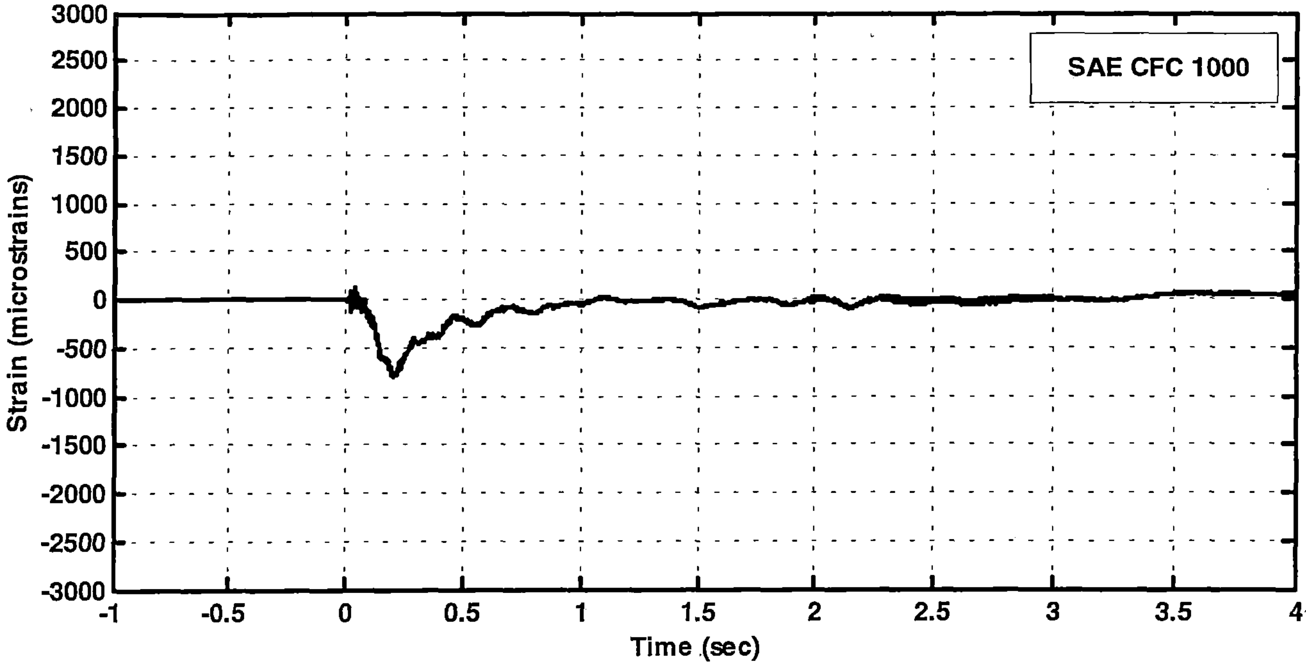

Figure F57. Longitudinal strain on underframe, about even with the trailing axle, center
Channel Name: UMR

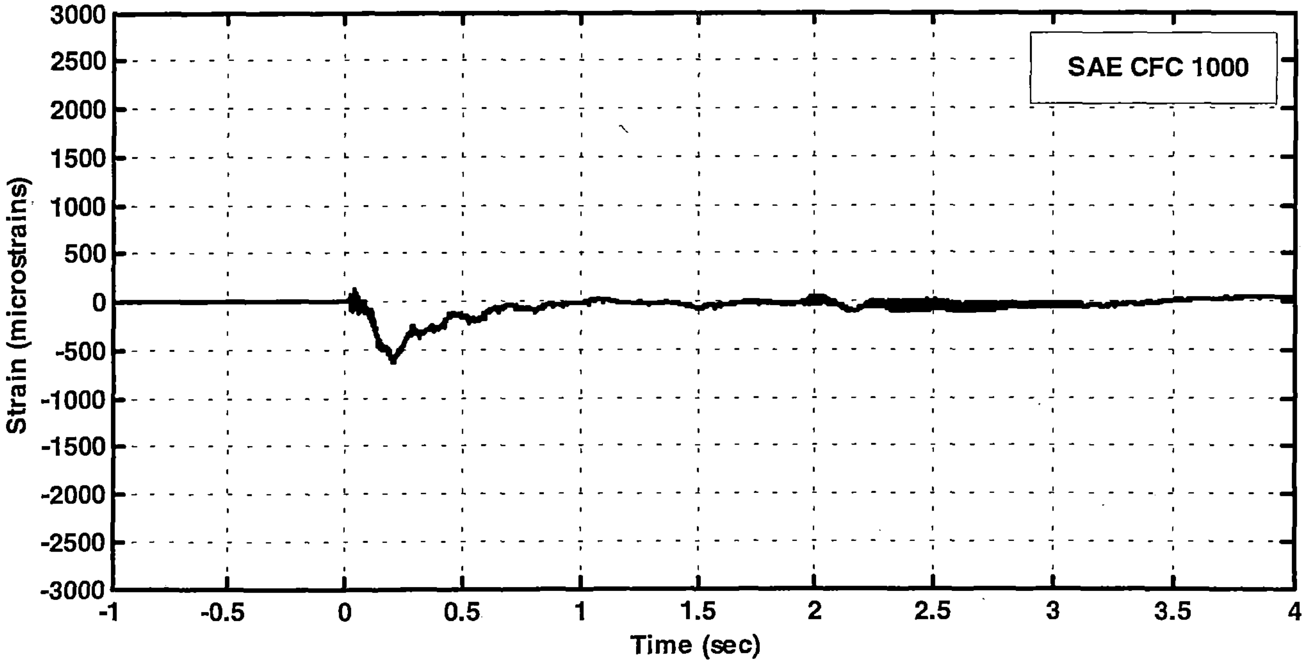

Figure F58. Longitudinal strain on underframe, about even with the trailing axle, right side
Channel Name: URR

APPENDIX G

Anthropomorphic Test Device (ATD) Data

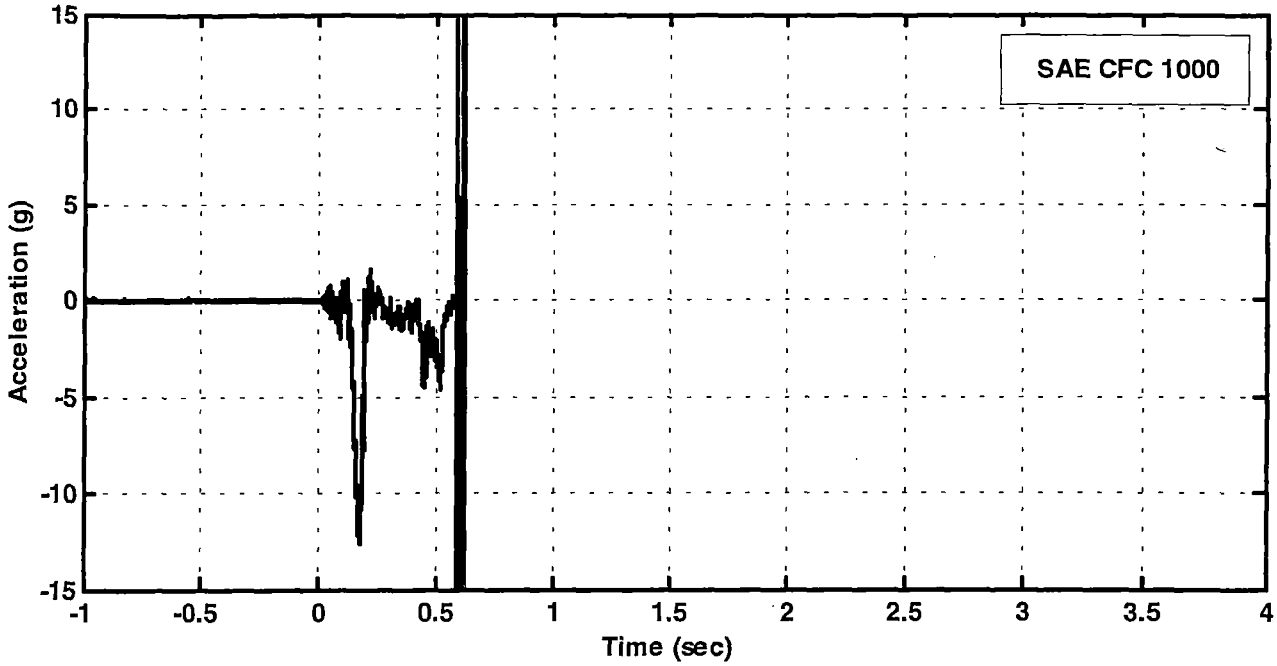

Figure G1. Anthropomorphic test device, chest acceleration, x direction
Channel Name: ATD_CX

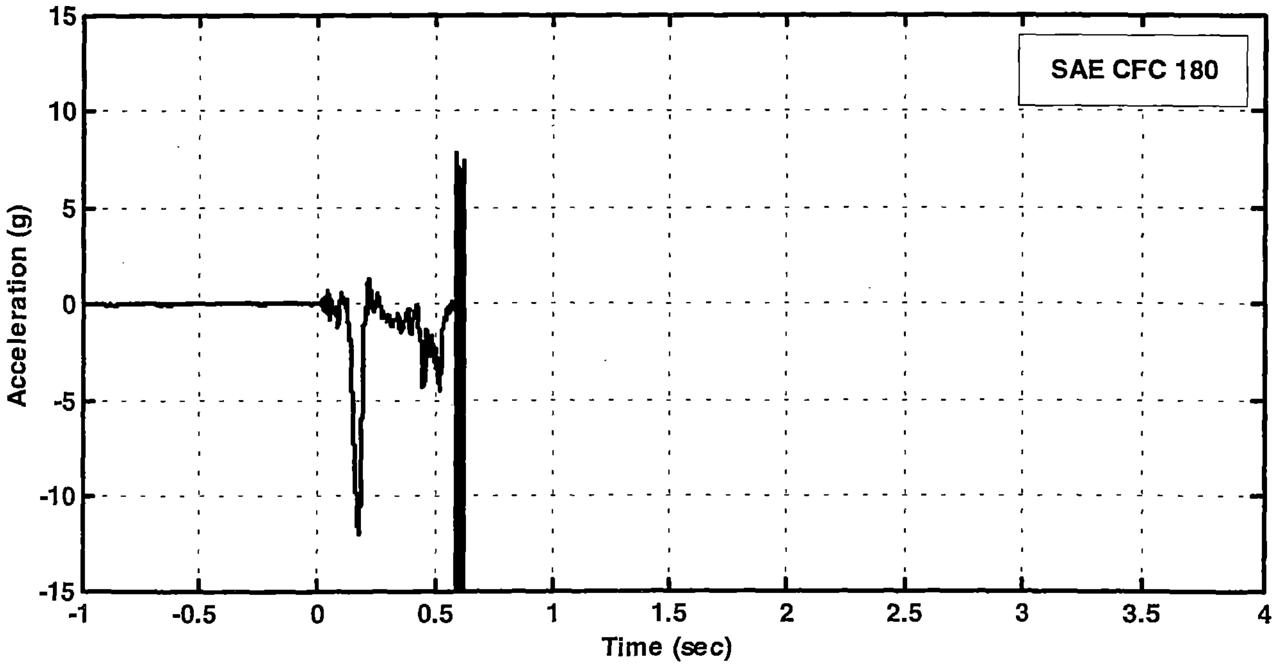

Figure G2. Anthropomorphic test device, chest acceleration, x direction
Channel Name: ATD_CX

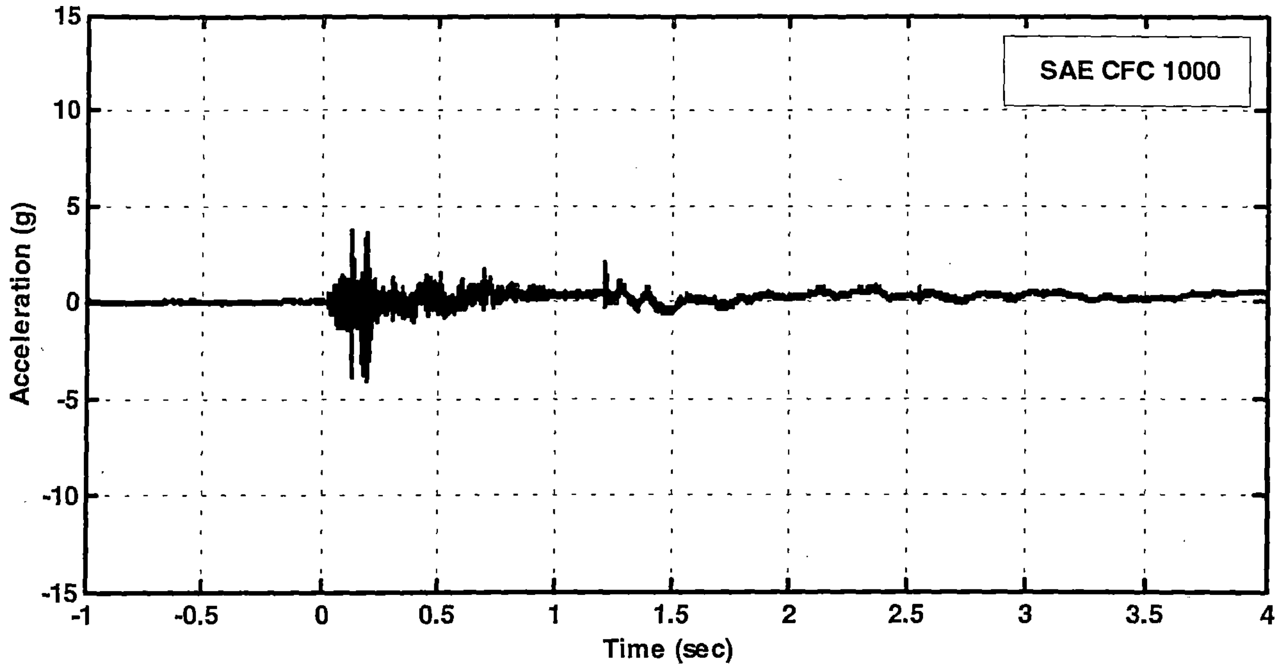

Figure G3. Anthropomorphic test device, chest acceleration, y direction
Channel Name: ATD_CY

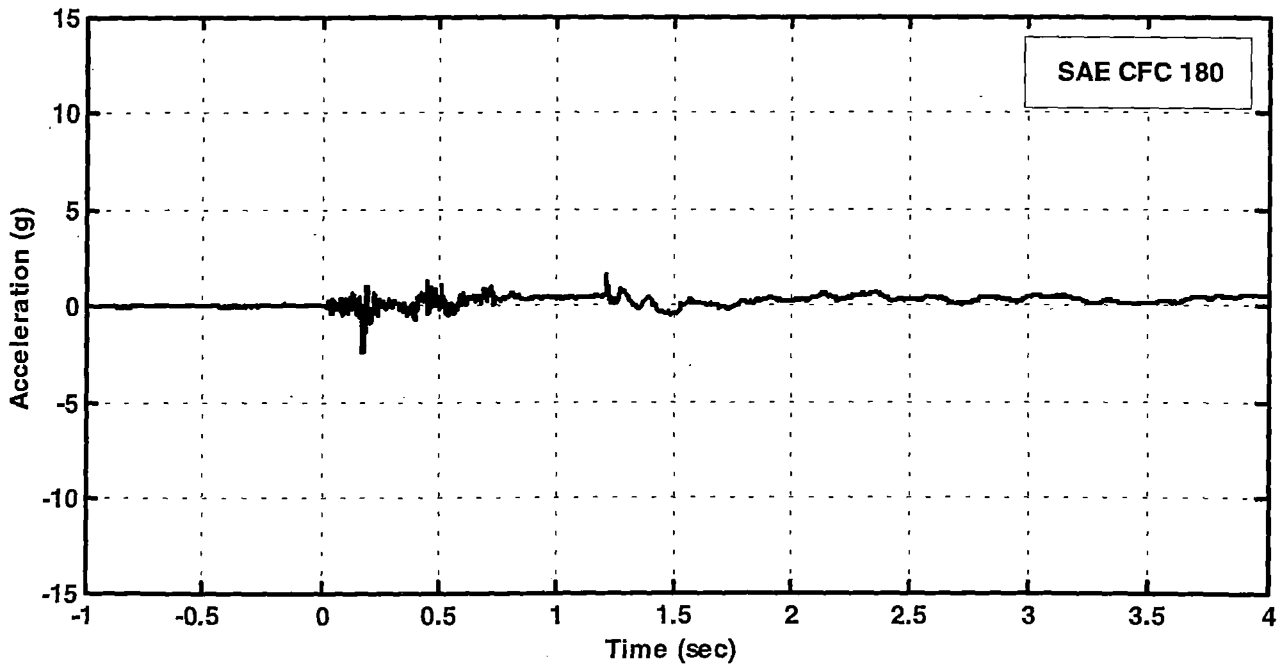

Figure G4. Anthropomorphic test device, chest acceleration, y direction
Channel Name: ATD_CY

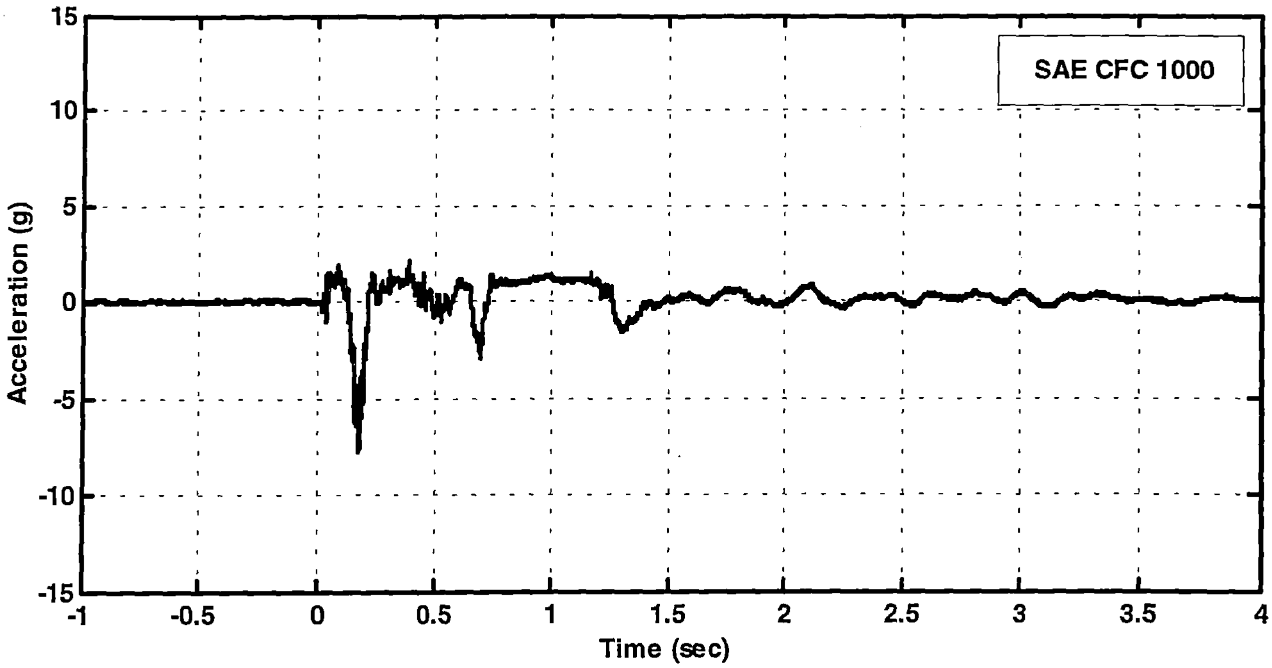

Figure G5. Anthropomorphic test device, chest acceleration, z direction
Channel Name: ATD_CZ

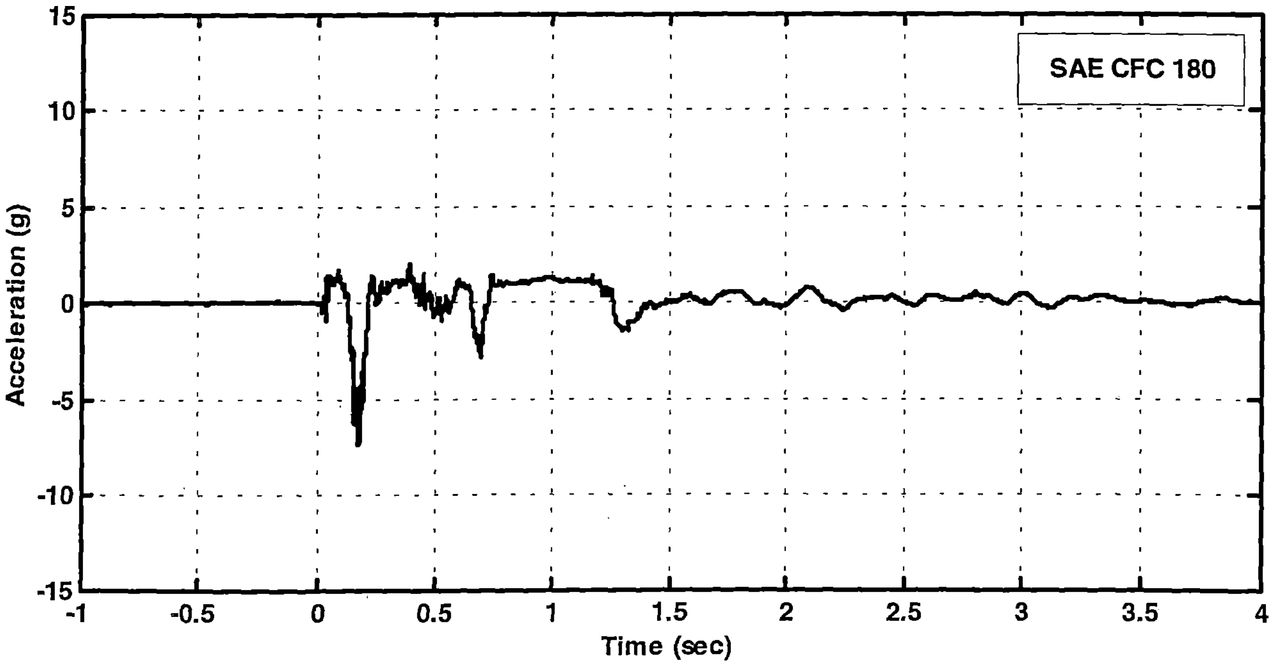

Figure G6. Anthropomorphic test device, chest acceleration, z direction
Channel Name: ATD_CZ

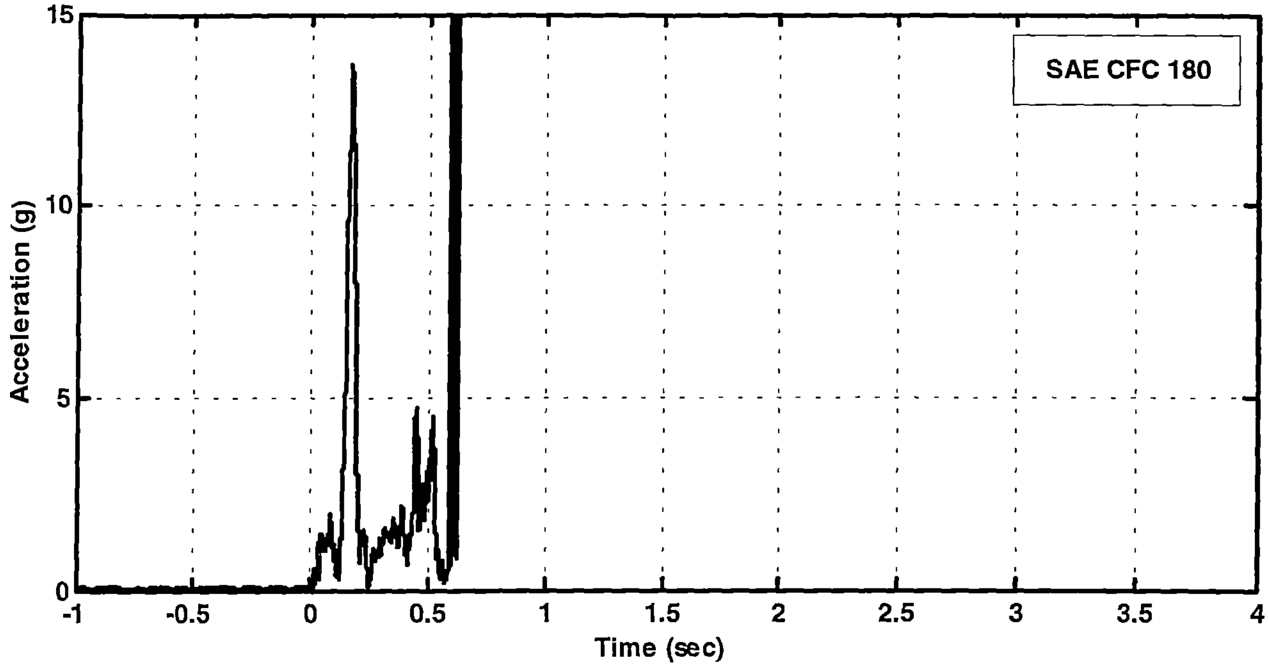

Figure G7. Anthropomorphic test device, chest acceleration, vector sum
Channel Name: ATD_CXYZ

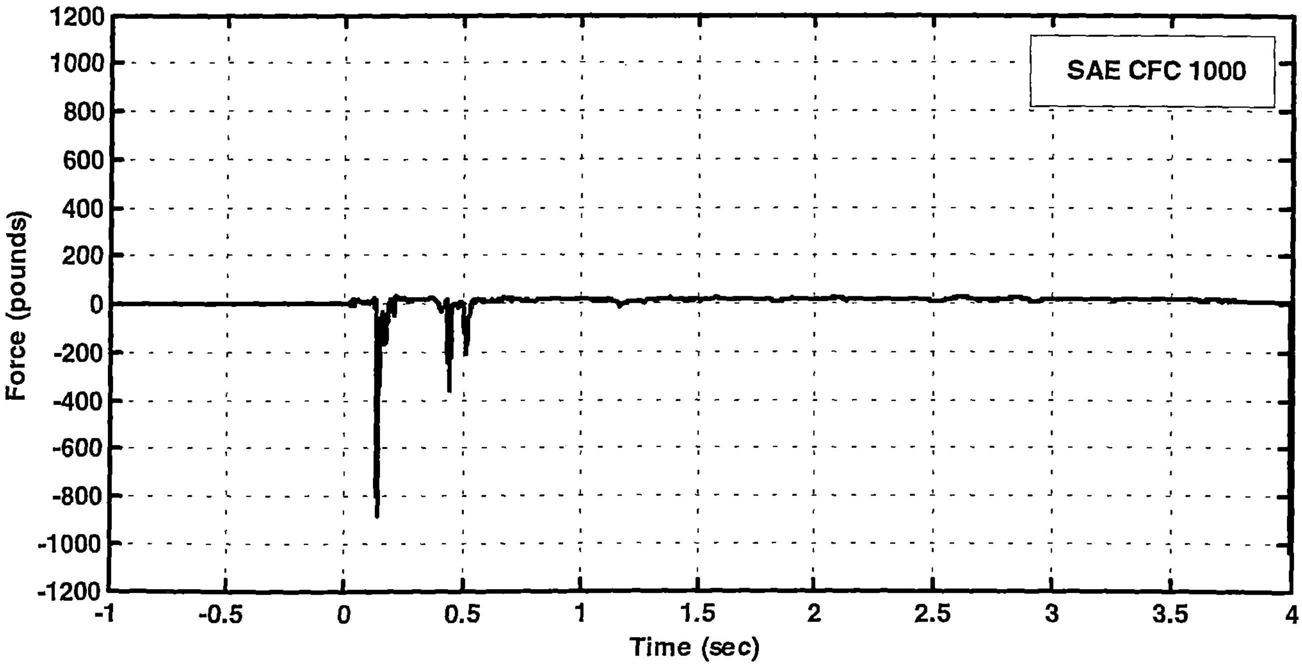

Figure G8. Anthropomorphic test device, left femur load
Channel Name: ATD_FL

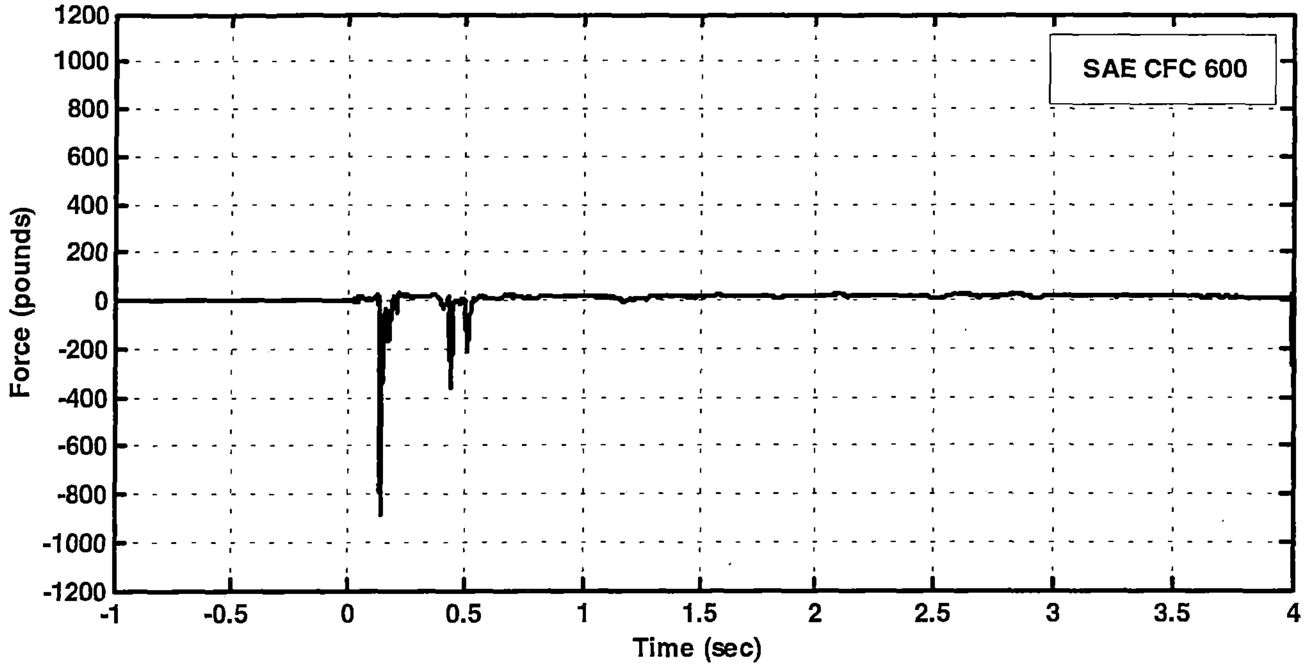

Figure G9. Anthropomorphic test device, left femur load
Channel Name: ATD_FL

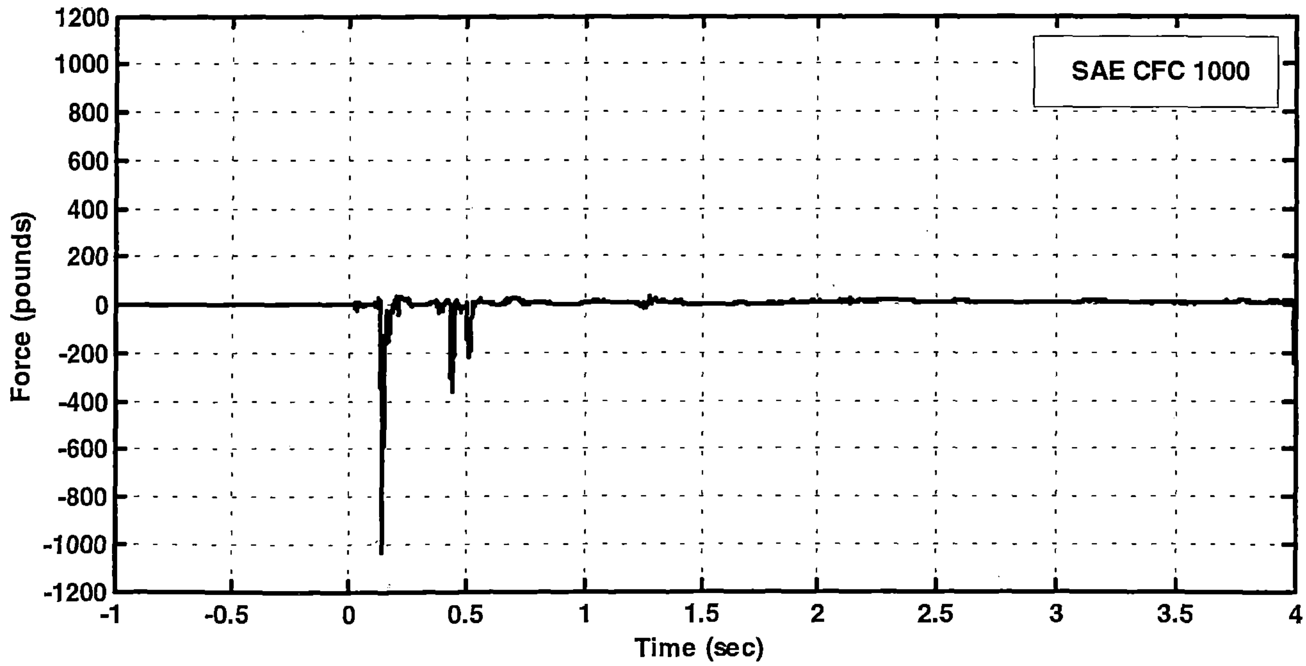

Figure G10. Anthropomorphic test device, right femur load
Channel Name: ATD_FR

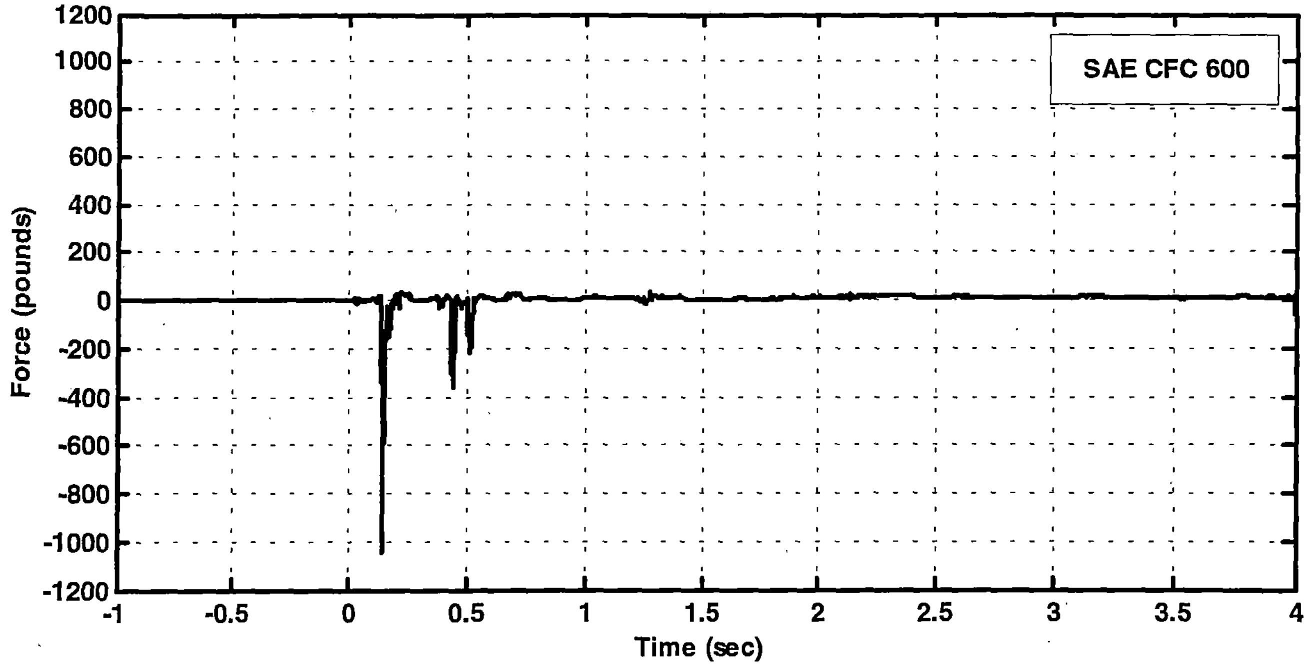

Figure G11. Anthropomorphic test device, right femur load
Channel Name: ATD_FR

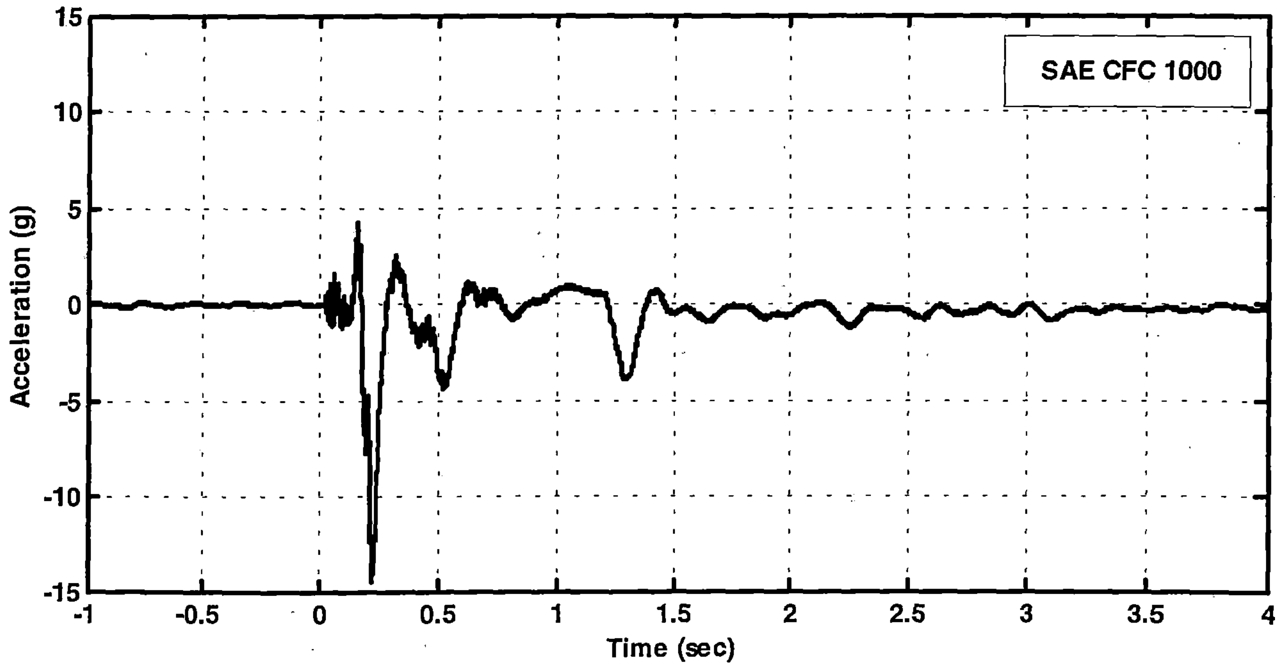

Figure G12. Anthropomorphic test device, head acceleration, x direction
Channel Name: ATD_HX

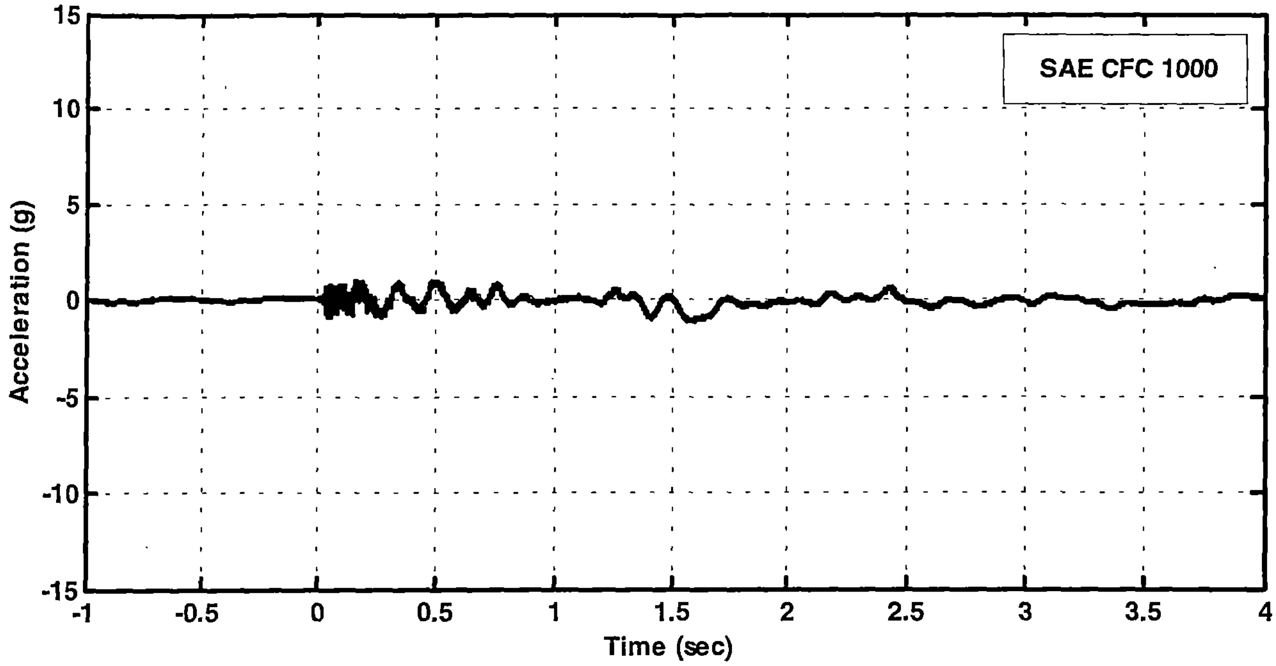

Figure G13. Anthropomorphic test device, head acceleration, y direction
Channel Name: ATD_HY

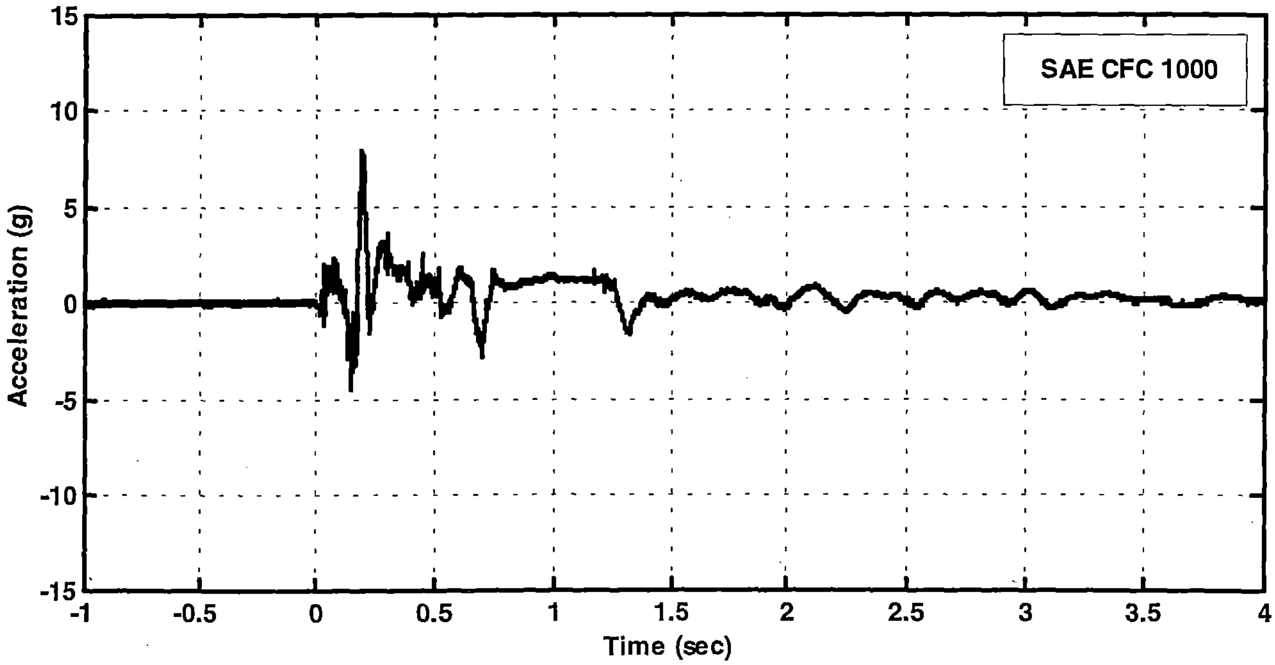

Figure G14. Anthropomorphic test device, head acceleration, z direction
Channel Name: ATD_HZ

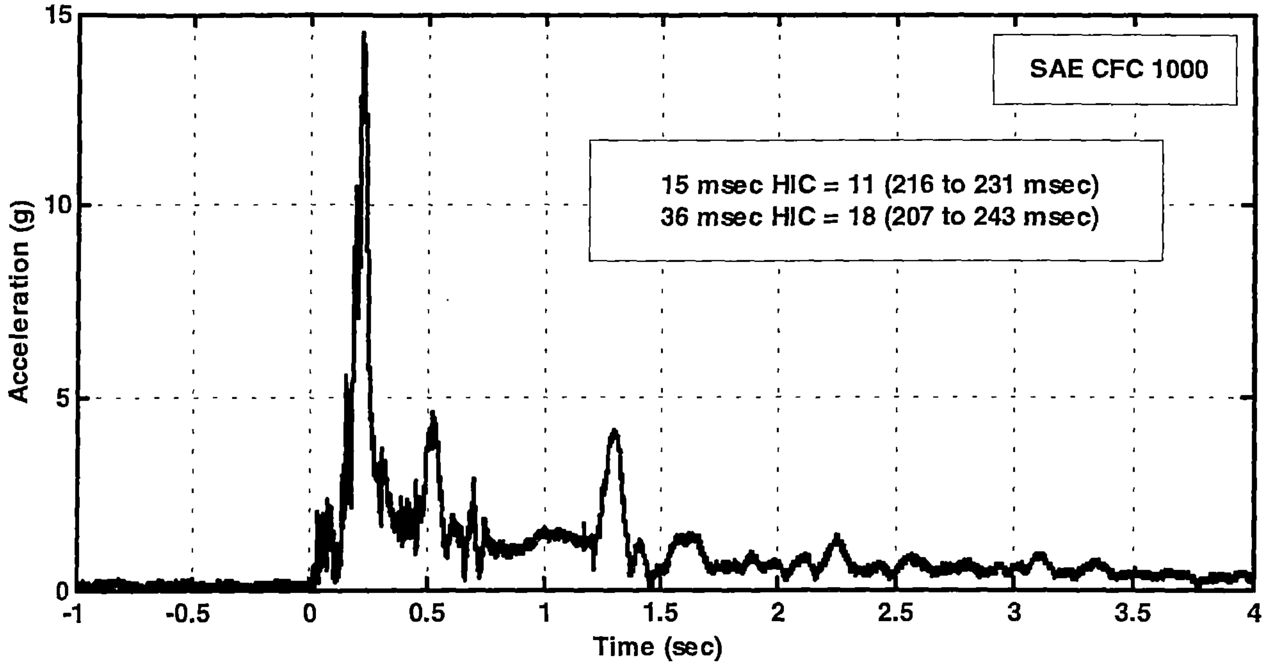

Figure G15. Anthropomorphic test device, head acceleration, vector sum
***Channel Name:* ATD_HXYZ**

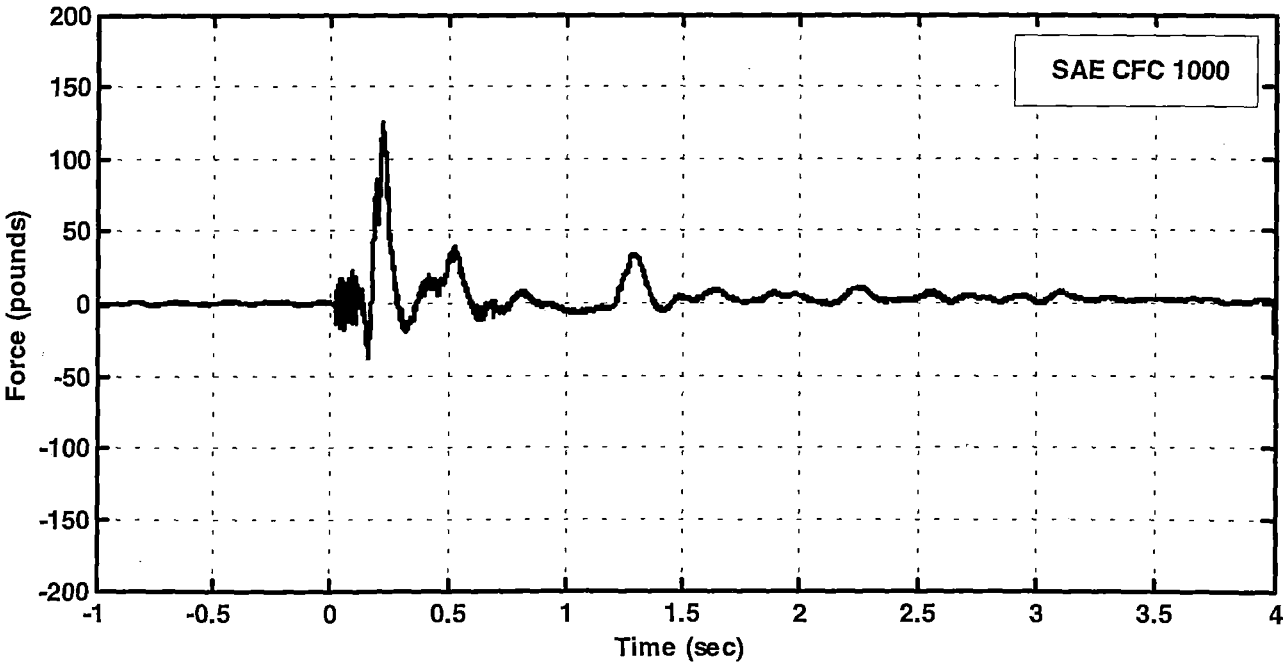

Figure G16. Anthropomorphic test device, neck load, x direction
***Channel Name:* ATD_NFx**

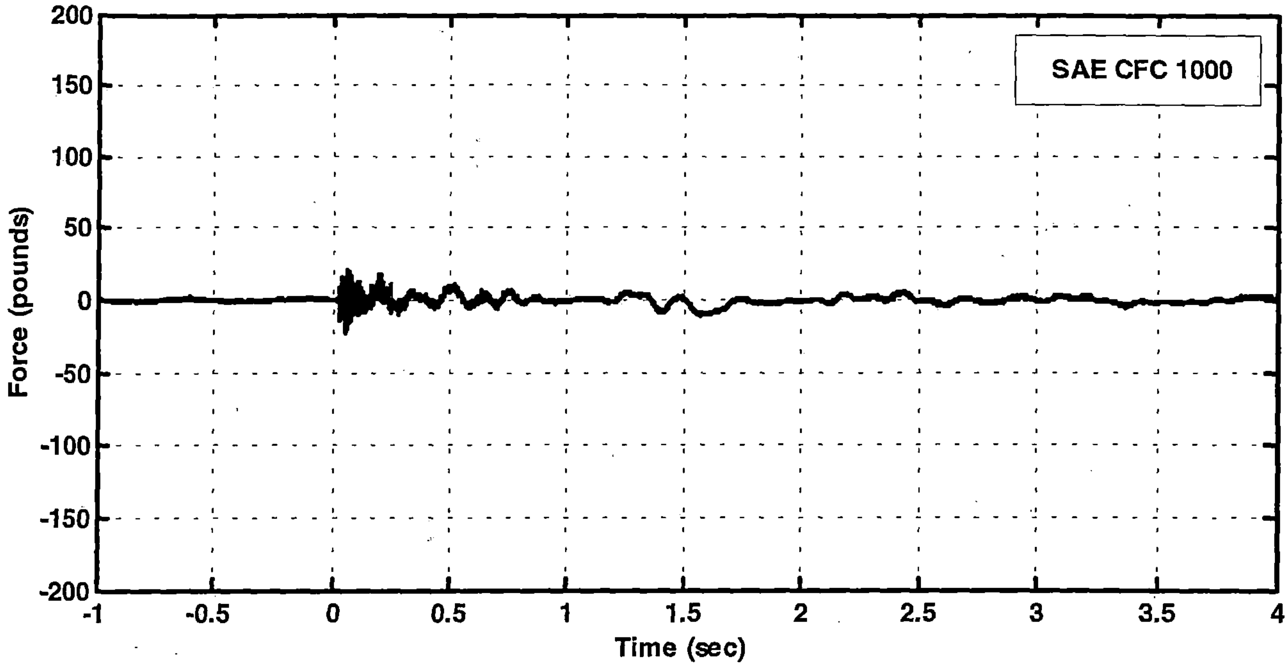

Figure G17. Anthropomorphic test device, neck load, y direction
Channel Name: ATD_NFy

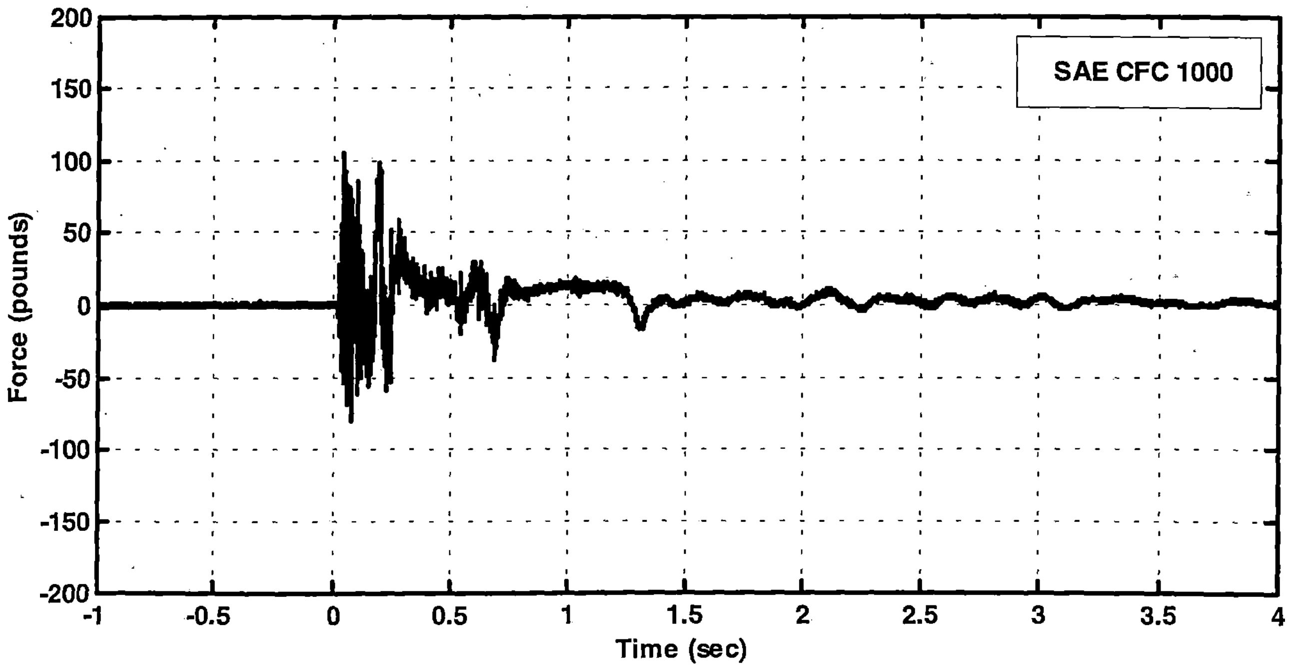

Figure G18. Anthropomorphic test device, neck load, z direction
Channel Name: ATD_NFz

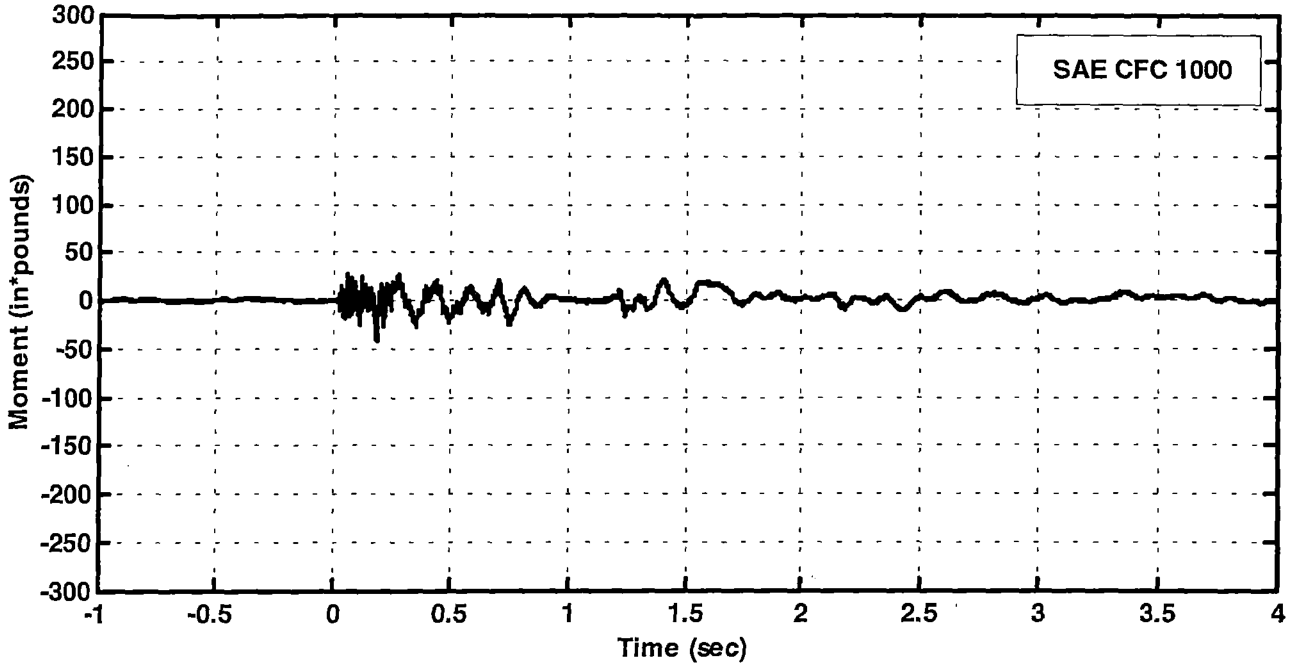

Figure G19. Anthropomorphic test device, neck moment, x direction
Channel Name: ATD_NMx

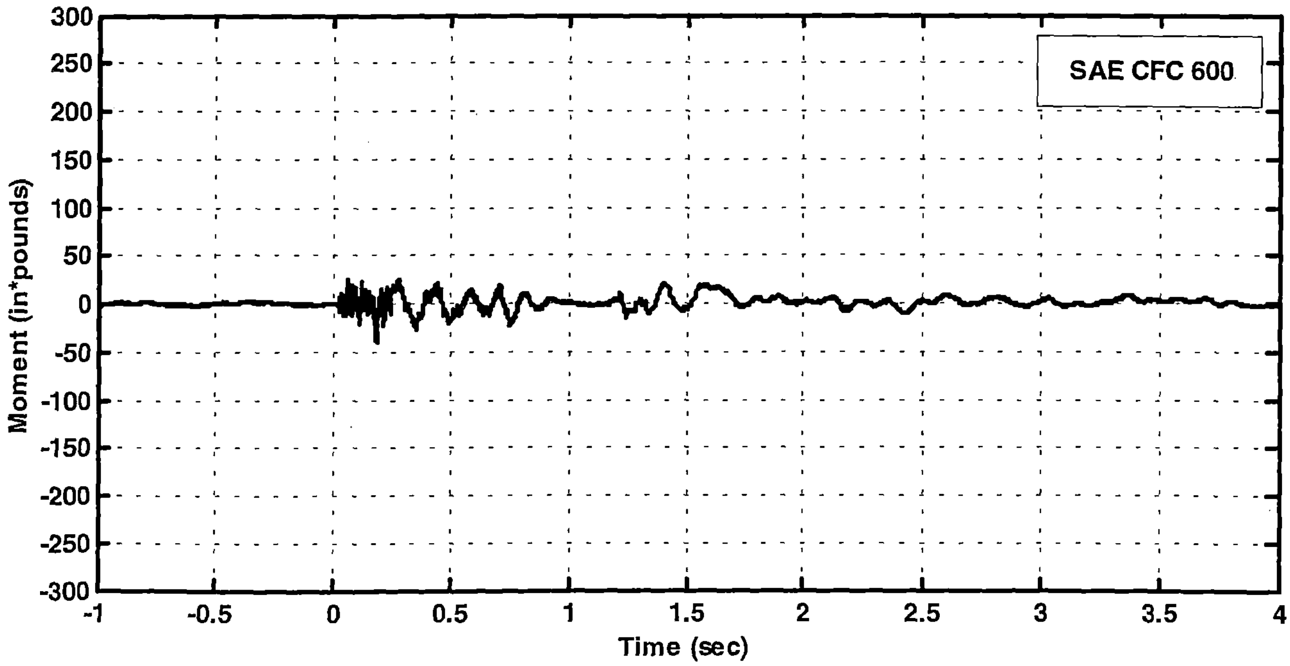

Figure G20. Anthropomorphic test device, neck moment, x direction
Channel Name: ATD_NMx

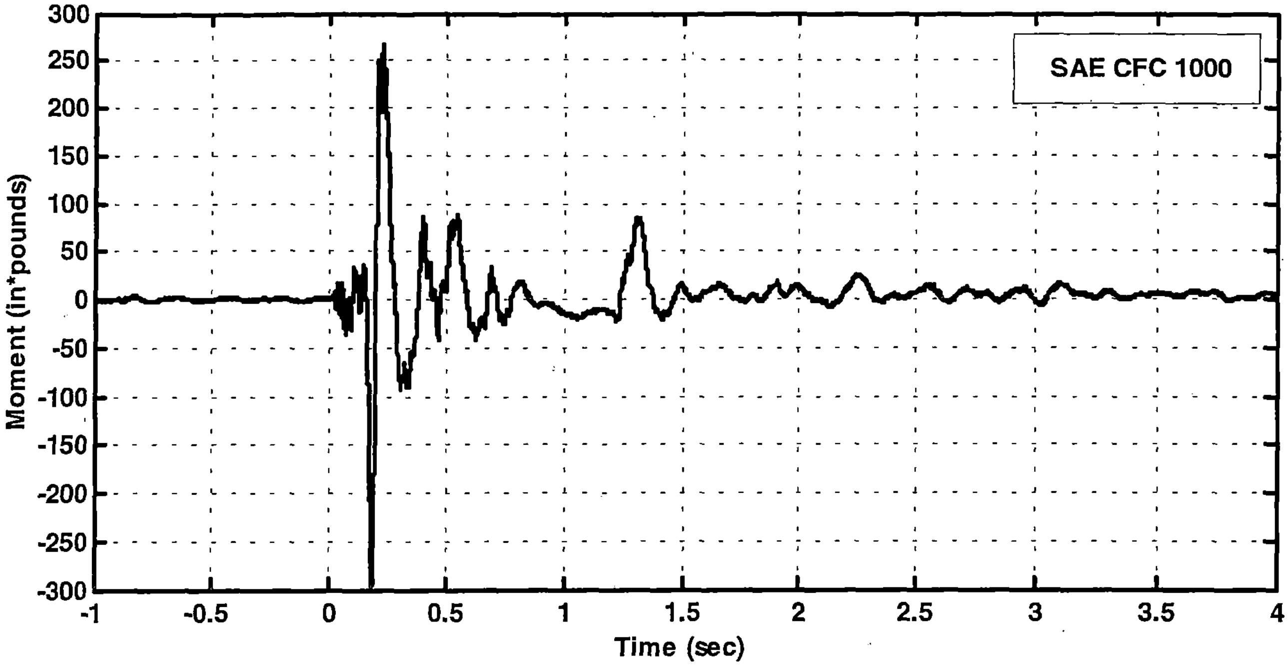

Figure G21. Anthropomorphic test device, neck moment, y direction
Channel Name: ATD_NMy

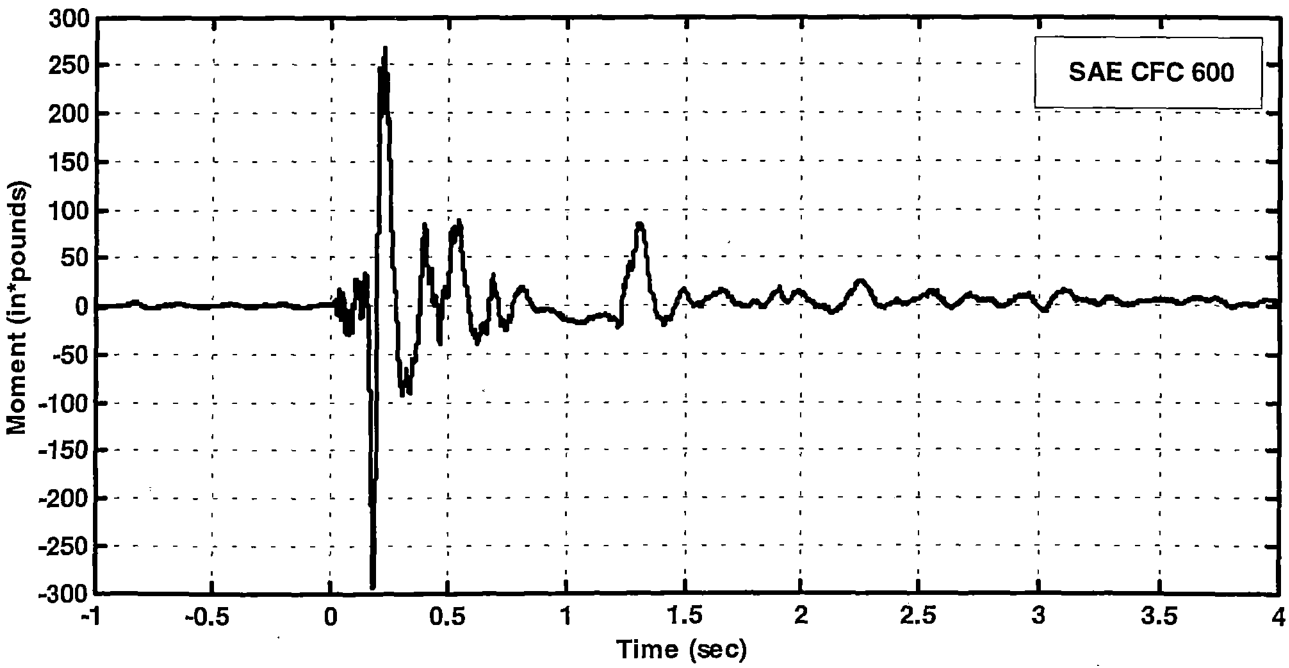

Figure G22. Anthropomorphic test device, neck moment, y direction
Channel Name: ATD_NMy

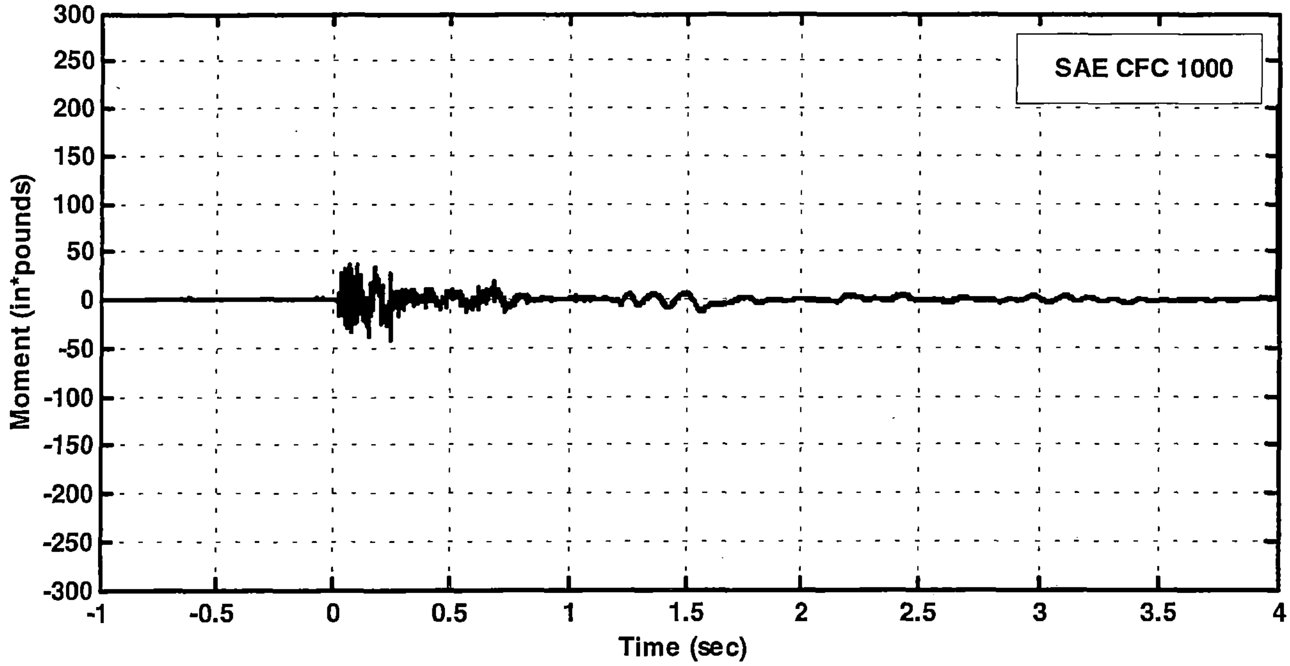

Figure G23. Anthropomorphic test device, neck moment, z direction
Channel Name: ATD_NMz

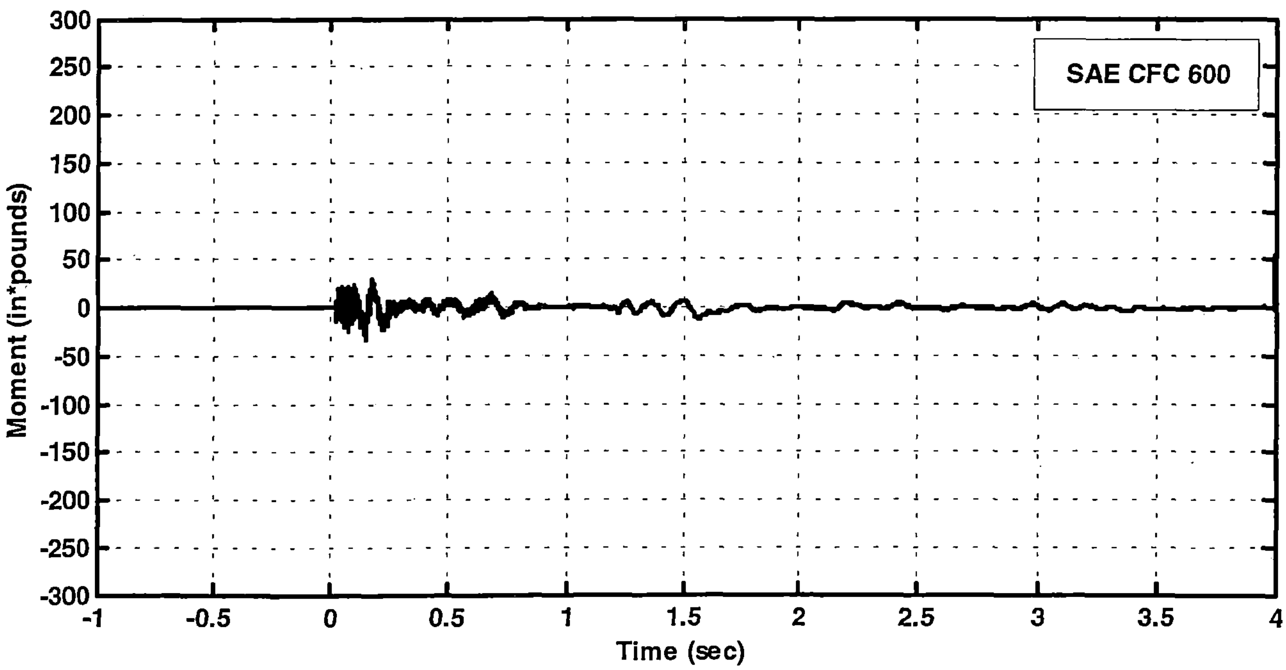

Figure G24. Anthropomorphic test device, neck moment, z direction
Channel Name: ATD_NMz