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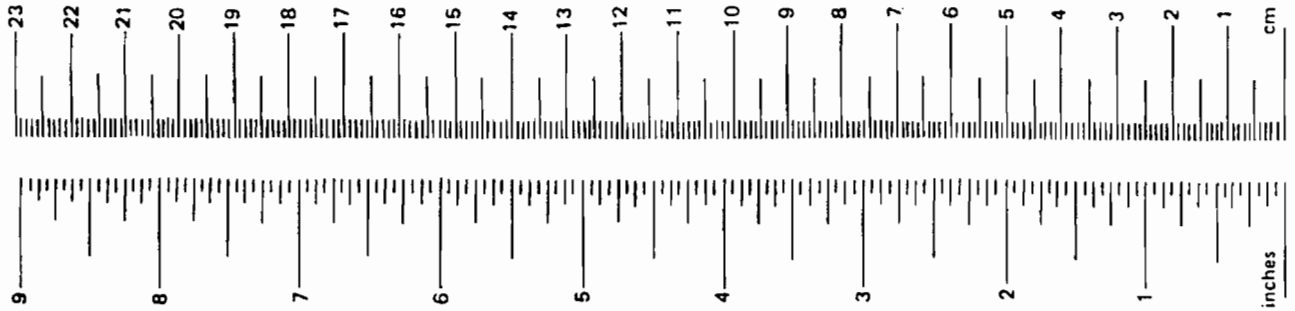
Passenger Rail Two Car Impact Test Volume III - Test Procedures Instrumentation and Data

Office of Research and
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| 16. Abstract <p>A full-scale impact test was performed April 4, 2000, at the Federal Railroad Administration's Transportation Technology Center near Pueblo, Colorado by Transportation Technology Center, Inc., a subsidiary of the Association of American Railroads. The test was performed using two Budd Company Pioneer-type commuter passenger cars coupled together. The purpose of the test was to measure strains, accelerations, and displacements during the impact and validate the computational and kinematic models of the vehicle impacting a rigid barrier. The test also showed the influence of the lead car on the secondary collision environment of the trailing car.</p> <p>Other test objectives were to determine the crash-force pulse shape throughout the vehicle and to provide a greater understanding of occupant kinematics in crash situations. Simula Technologies Inc. provided the occupant kinematic experiments, including a number of instrumented Anthropomorphic Test Devices in different seat configurations.</p> <p>This report describes the test cars and the methodology used to carry out the impact test, together with a description of all the instrumentation used to measure the structural deformation of the car during the impact.</p> <p>The impact was recorded by a number of high speed film and video cameras. The report contains a description of the cameras used, their position, and the subsequent film analysis carried out to measure the displacement and velocity of the test cars during the impact.</p> <p>The strain, acceleration, velocity, and displacement time histories from all the transducers, during the impact, are presented in the report including the load/time history in the coupler.</p> <p>The speed of the test cars at impact with the rigid barrier was 26.25 mph and the amount of crush of the lead car was about 5.5 feet.</p> | | | |
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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 |

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 |



* 1 in. = 2.54 cm (exactly)

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Dave Tyrell, Program Manager, Volpe National Transportation Systems Center, coordinated technical requirements. Caroline Van Ingen-Dunn, Senior Engineer, Simula Technologies, Inc., implemented the occupant protection tests. Ed Murphy, Chief Mechanical Officer, Southeastern Pennsylvania Transit Authority (SEPTA), arranged for the donation of the cars in the test effort. Doug Karan of Amtrak arranged for the donation of the inter-city passenger seats. Gordon Campbell, Senior Engineer, LDK Engineering, Inc., arranged for a copy of the Pioneer car structural drawings from Bombardier, Inc. Tom Peacock of the American Public Transportation Association coordinated the test with members of the passenger rail transportation industry.

EXECUTIVE SUMMARY

A full-scale rigid barrier impact test was performed April 4, 2000, at the Federal Railroad Administration's Transportation Technology Center, Pueblo, Colorado by Transportation Technology Center, Inc. (TTCI), a subsidiary of the Association of American Railroads. The test was performed on two Pioneer type commuter passenger cars coupled together. The purpose of the test was to measure strains, accelerations, displacements and the load in the coupler during the impact so that computational and kinematic models of the vehicle impacting a rigid barrier can be validated.

Further test objectives were to determine the crash-force pulse shape throughout the two vehicles and to provide a greater understanding of occupant kinematics in crash situations.

The test cars were structurally complete although the original seats were removed together with other underfloor ancillary equipment. The interior of the cars was modified with a number of prototype seats fitted in different configurations.

Approximately 10,000 pounds of ballast was added to each test car body. The coupler was left installed at the impact end of the lead car and an instrumented coupler was fitted between the two cars.

The impact test was performed by pushing the two coupled cars with a locomotive, releasing them at a pre-determined point at a pre-determined speed, and then letting them run down the inclined track into the barrier. The release distance, and the speed of the locomotive at release, was calculated from a series of speed calibration tests carried out prior to the actual impact test.

The report shows measurements taken before, during, and after impact which indicate that:

- The speed of the coupled test cars at impact was 26.25 mph. This was within 1 percent of the target speed of 26 mph.

- The amount of crush in the lead car was about 5.5 feet as measured from the reduction in length of the vehicle after the test. There was no permanent crush damage to the car body of the trailing car.
- The film analysis showed the lead car to have a maximum displacement at impact in the longitudinal direction of just over 6 feet, and the trailing car to have a maximum displacement of about 7 feet in the longitudinal direction. Both of these displacements include elastic deformation of the car body and substructure.
- The data acquisition system comprised 12 Data Bricks, each collecting 8 channels of data. All of the Data Bricks triggered and recorded data. All the strain gages provided some information before being damaged by the impact.
- The maximum longitudinal acceleration recorded on the center sill of the lead car was 190 g although the peak acceleration was reduced to 50 g when filtered to SAE CFC 60.
- The maximum longitudinal acceleration recorded on the center sill of the trailing car was 110 g although the peak acceleration was reduced to 22 g when filtered to SAE CFC 60.
- A maximum vertical deflection of 5 inches was recorded across the secondary suspension at the right hand side of the A-end of the lead car. The maximum vertical deflection at the A-end of the trailing car was recorded as +3 inches on one side and -3 inches on the other side.
- The lead car B-end coupler moved almost 5 inches laterally in one direction while the trailing car A-end coupler moved almost 10 inches in the opposite direction.
- A peak load of 872,000 pounds was measured in the instrumented coupler between the two cars.
- Ten high speed film cameras and ten video cameras recorded the impact. All but one of the cameras worked successfully.

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1.0 INTRODUCTION AND OBJECTIVE

A full-scale impact test on April 4, 2000, using two Budd Company Pioneer-type commuter passenger cars coupled together, was performed at the Federal Railroad Administration's Transportation Technology Center, Pueblo, Colorado. The purpose of the test was to measure strains, accelerations, and displacements during the impact so that computational and kinematic models of the vehicle impacting a rigid barrier can be validated. The test also showed the influence of the lead car on the secondary collision environment of the trailing car.

Further test objectives were to determine the crash-force pulse shape throughout both vehicles and to provide a greater understanding of occupant kinematics in crash situations.

2.0 DESCRIPTION OF TEST CARS

The test was conducted using two Budd Company Pioneer-type commuter passenger cars provided by the Southeastern Pennsylvania Transportation Authority (SEPTA).

The car bodies were structurally complete. The original seats were removed, as was other underfloor and ancillary equipment. The interiors of both cars were modified with a number of prototype seats fitted in different configurations. Approximately 10,000 pounds of concrete were added to each car body, mostly under the floor in the



Figure 1. Test Cars

center of the car. The coupler was left installed at the impact end and an instrumented coupler was fitted between the two cars. The cars were steam cleaned. The test cars just before impact are shown in Figure 1.

The trucks fitted to the test car were not equipped with motors. The secondary air suspension was pumped up to its normal inflated height before impact and adjusted so that both cars were at the same height.

The brakes were primed so that they would come on if the brake pipe was cut on impact. A cutter device was fitted to the front of the vehicle, which ensured that the brake pipe was cut on impact with the barrier and an orifice was installed in the pipe so that the brake action would be delayed. The purpose of this device was to ensure that the vehicle would impact the wall, roll back, and then stop without rolling forward into the wall again.

3.0 TEST METHODOLOGY

The test was performed at the Federal Railroad Administration's (FRA) Transportation Technology Center (TTC), Pueblo, Colorado according to the procedures outlined in the test implementation plan for two-car dynamic crush test, Appendix A of this report.

The inclined tangent track leading to the impact barrier has a constant gradient of 0.86 percent and is parallel to another track, the Precision Test Track (PTT), which has exactly the same gradient. The barrier itself, constructed of reinforced concrete and steel, has an estimated weight of 1,350 tons and is capable of withstanding an impact force of 3,000,000 pounds (13.4 MN). The front face of the barrier is 2-foot thick reinforced concrete faced with a 3-inch thick steel plate. A front view of the barrier is shown in Figure 2a and a schematic of the impact barrier is shown in Figure 2b .

The impact test was performed by pushing the test cars with a locomotive, releasing it at a pre-determined point and then letting it run down the inclined track and into the barrier. The release distance, and the speed of the locomotive at release, was calculated from a series of speed calibration tests carried out on the PTT track and on the track leading to the barrier. The target speed for this test was 26 mph.

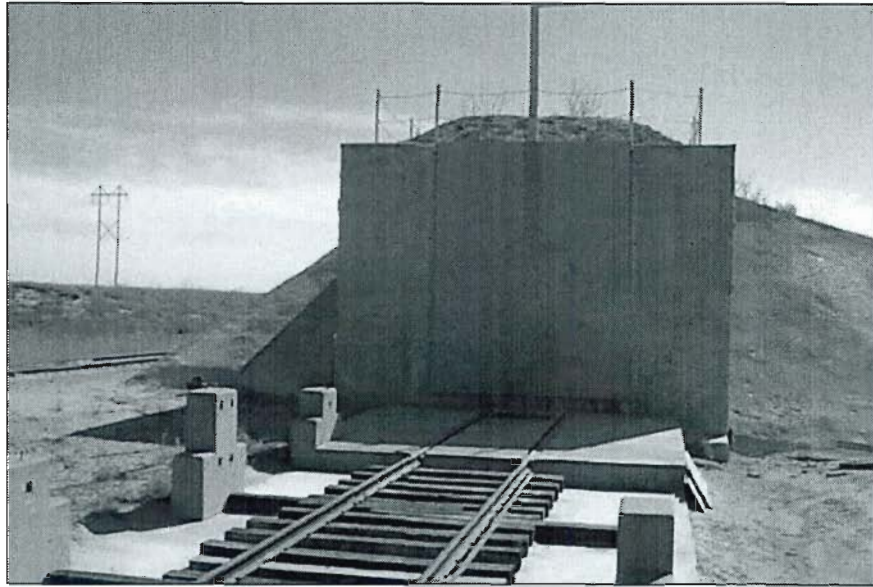


Figure 2a. Impact barrier at the TTC

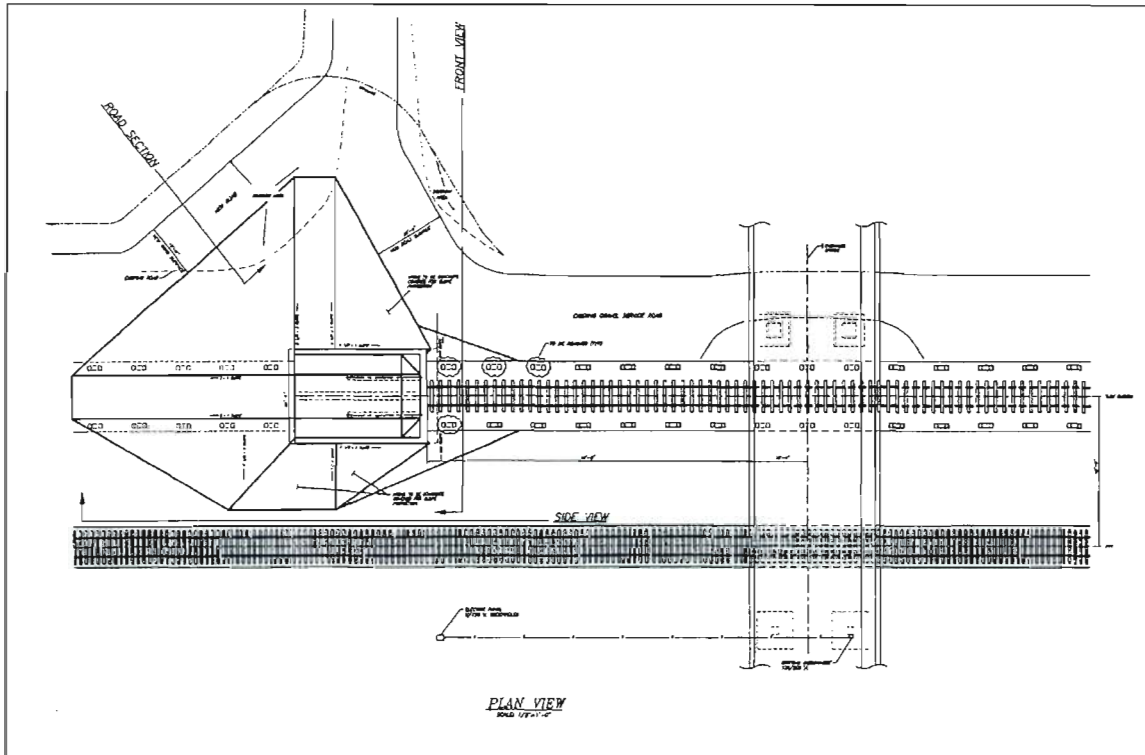


Figure 2b. Crash Wall — Plan View

4.0 RESULTS

4.1 ITEMS MEASURED BEFORE THE TEST

4.1.1 Longitudinal and Vertical Distances

(Note: A-end = Leading End, B-end = Trailing End)

| | | |
|--|-------|----------------|
| Length of leading car from buffer beam to buffer beam | | = 84.23 feet |
| Length of trailing car from buffer beam to buffer beam | | = 84.19 feet |
| Longitudinal distance from buff stop to body bolster, Lead Car | A-end | = 6.64 feet |
| | B-end | = 6.62 feet |
| Longitudinal distance from buff stop to body bolster, Trailing Car | A-end | = 6.74 feet |
| | B-end | = 6.77 feet |
| Longitudinal distance between body bolsters on Lead Car | | = 61.99 feet |
| Longitudinal distance between body bolsters on Trailing Car | | = 61.83 feet |
| Vertical distance between mid point of Lead Car (center sill) and a line extending between body bolsters | | = 9.53 inches |
| Vertical distance between mid point of Trailing Car (center sill) and a line extending between body bolsters | | = 9.60 inches |
| Vertical distance between buffer beam and a line extending between body bolsters, Lead Car | A-end | = 18.90 inches |
| | B-end | = 18.59 inches |
| Vertical distance between buffer beam and a line extending between body bolsters, Trailing Car | A-end | = 18.05 inches |
| | B-end | = 18.03 inches |

4.1.2 Weight of Test Cars

The test cars were weighed just before the impact test using the TTC computerized scale. The test cars were uncoupled from the locomotive for these measurements and each truck, in turn, was moved onto the weighbridge. The measured test car weight included the weight of the car body, trucks, added weight, anthropomorphic dummies, seats, and all instrumentation:

Lead car (No. 248)

| | |
|-----------------|-----------------|
| Weight of A-end | = 34,403 pounds |
| Weight of B-end | = 37,305 pounds |
| Total weight | = 71,708 pounds |

Trailing Car (No.245)

| | |
|-----------------|-----------------|
| Weight of A-end | = 36,398 pounds |
| Weight of B-end | = 41,059 pounds |
| Total weight | = 77,457 pounds |

(The accuracy of the weigh-bridge is ± 50 pounds; therefore the accuracy of the vehicle weight is ± 100 pounds.)

4.1.3 WEATHER CONDITIONS

The weather conditions just before the test :

- Temperature 69°F
- Wind speed 7 mph from the SW

4.2 ITEMS MEASURED DURING THE TEST

4.2.1 SPEED

The car was accelerated from rest by a locomotive and released at a point 1,550 feet from the barrier. The speed of the test car just before impact, as measured by the laser based speed trap, was:

| | |
|----------|------------------------|
| Laser 1 | 38.54 ft/s |
| Laser 2 | 38.45 ft/s |
| Average: | 38.50 ft/s = 26.25 mph |

The amount of energy (E) absorbed by the vehicle on impact with a rigid barrier can be calculated from the speed of the cars just before impact, $V_0 = 38.50$ ft/s, and the mass of the cars, $m_L = 71,708$ lbs. and $m_T = 77,457$ lbs.

$$E = \frac{1}{2} \cdot m_L \cdot V_0^2 + \frac{1}{2} \cdot m_T \cdot V_0^2$$

$$E = 1.65 \times 10^6 \text{ ft.lbs.} + 1.78 \times 10^6 \text{ ft.lbs.} = 3.43 \times 10^6 \text{ ft.lbs. (4.65 MJ)}$$

4.2.2 STRAINS

The Test Implementation Plan in Appendix A shows the positions of the strain gages. The strain time histories for the lead car, A-end, over the range -0.1 s to 0.2 s are presented in Figures 3-25. In these figures positive values represent compression.

The Society of Automobile Engineers (SAE) frequency class indicating the filter frequency used for processing the recorded data is shown on each figure. SAE frequency classes are defined in SAE J211/1 (R) "Instrumentation for Impact Testing – Part 1 Electronic Instrumentation" (Reference 1). For the strain results, SAE Class 1000 is equivalent to the raw data.

The data acquisition system for both strains and accelerations comprised 12 Data Bricks each collecting 8 channels of data. When the system was triggered on impact with the wall, each Data Brick stored 0.1 s of information before the impact and 1.4 s of information after the impact.

The strain time histories for the lead car, A-end, over the complete range recorded by the Data Bricks; i.e., -0.1 s to 1.4 s, are presented in Appendix B.

The strain time histories for the lead car, B-end, over the complete range recorded by the Data Bricks; i.e., -0.1 s to 1.4 s, are presented in Appendix C.

The strain time histories for the trailing car, A-end, over the complete range recorded by the Data Bricks; i.e., -0.1 s to 1.4 s, are presented in Appendix D.

4.2.3 ACCELERATIONS

The positions of the accelerometers are shown in the Test Implementation Plan (Appendix A). The acceleration time histories for the lead car, over the full range -0.1 s to 1.4 s, are presented in Figures 26-48. These results are recorded acceleration time histories filtered according to SAE CFC 1000 specifications.

The acceleration time histories for the trailing car, filtered according to SAE CFC 1000, are presented in Figures 49-62.

The accelerations for the lead car, filtered to SAE CFC 60, are presented in Figures 63-85 and for the trailing car in Figures 86-99. The algorithm defining SAE CFC 60 is given in Appendix C of SAE J211/1 (R). Essentially SAE CFC 60 is a low-pass filter with a cut-off frequency of 100 Hz.

Low pass-filtered acceleration time histories, with a cutoff frequency $F_c = 25$ Hz, are presented in Appendix E for the lead car and in Appendix F for the trailing car.

4.2.4 DISPLACEMENTS

The vertical displacement across the secondary suspension was measured using string potentiometers between the car body and the truck. The unfiltered results are plotted in Figures 100-103 for the lead car and in Figures 104-107 for the trailing car.

The displacements (in each direction) between the lead car B-end coupler and the car body, and the trailing car A-end and the car body were also measured using string potentiometers. The unfiltered results are plotted in Figures 108-113.

4.2.5 LONGITUDINAL VELOCITY AND DISPLACEMENT

The x-axis acceleration time histories of the center sill accelerometers have been integrated to give velocity and plotted against time for the lead car in Figures 114-118, and for the trailing car in Figures 119-122.

These same acceleration time histories have been double integrated to give crush displacement and plotted against time for the lead car in Figures 123-127, and for the trailing car in Figures 128-131.

4.2.6 LONGITUDINAL FORCE IN COUPLER

The coupler at the B-end of the lead car was strain gaged and calibrated so that the longitudinal force in the coupler could be measured. The coupler force time history through the impact is presented in Figure 132 and shows a peak load of 872,000 pounds occurring at 0.0662 second after the initial contact with the wall.

4.2.7 TAPE SWITCHES

A tape switch was attached to each corner post of the lead car so that the time of contact with the wall could be recorded. Plots of time histories of these tape switches are presented in Figures 133 (right) and 134 (left). These plots show that the right corner post contacted the wall at 0.04391 second and the left corner post contacted the wall at 0.04319 second.

Tape switches were also attached to the coupler pocket — one across the top edge of the coupler pocket to measure vertical movement, and one on each side of the of the coupler pocket to measure lateral movement. The coupler pockets at the A-end and B-end of the lead car were instrumented in this way, as well as the coupler pocket at the A-end of the trailing car. See Figures 135 to 143.

For the coupler at the A-end of the lead car, first contact in the vertical direction occurred at 0.01586 second and in the lateral direction (right) at 0.01766 second.

For the coupler at the B-end of the lead car, contact with the left side of the coupler pocket occurred at 0.3391 second.

For the coupler at the A-end of the trailing car, contact with the right side of the coupler pocket occurred at 0.299 second.

4.2.8 HIGH-SPEED AND VIDEO PHOTOGRAPHY

The impact test was visually recorded with 10 high-speed film cameras and 10 video cameras. Camera coverage was selected to provide views of both the left and right sides of the vehicle, overhead views, an underside view, an onboard view, and an overall view of the impact. (Camera coverage is depicted in Figure 6-3-1 of the Test Implementation Plan – Appendix A). The side views and overhead views had redundant coverage to obtain photo documentation in the event of an individual camera failure.

All the high-speed and video cameras worked successfully with the exception of the Milliken camera on the west side of the barrier.

4.2.9 FILM ANALYSIS

The film analysis described in this section was conducted on film from the high-speed fixed cameras on the east side of the barrier, on the west side of the coupler, and from the overhead camera.

For the analysis, the film was projected frame-by-frame onto a digitizer pad. The location of three vehicle-mounted and three ground-based targets was selected with the crosshairs of a cursor, and corresponding x and y coordinates were stored in a computer. The analysis was started before impact and continued through maximum crush to the vehicle rebound. The average position of the onboard targets relative to the ground-based targets was computed using the equation:

$$d = \frac{s_1 + s_2 + s_3 - s_4 - s_5 - s_6}{3}$$

where d is the relative position, and s_1 through s_6 are the locations of the three onboard and three ground-based targets, respectively.

Vehicle speed was computed using the equation:

$$v_i = \frac{d_i - d_{i+1}}{\Delta t}$$

where the subscripts represent the film frame number, and Δt is the time duration between frames.

Film speed was obtained directly from the 100-Hertz timing marks on the film. The nominal speed of the fixed cameras was 500 frames per second.

Car body displacement was set to zero at impact. The displacement data is relatively smooth in its raw, as collected, form. Figures 144-147 show the absolute carbody displacements in the longitudinal, lateral, and vertical directions. These plots show the maximum displacement in the longitudinal direction to be about 6 feet for the lead car and 7 feet for the trailing car.

The maximum lateral displacement of the lead car, B-end is shown from Figure 145 to be about 1 foot while the maximum lateral displacement of the trailing car, A-end is about 8 inches in the opposite direction.

Figure 148 shows the relative longitudinal displacement between the lead car and the trailing car. Figure 149 shows both the longitudinal displacement and the vertical displacement of the A-end (Impact End) of the lead car. The maximum vertical displacement is about 8 inches.

The raw velocity data was computed as indicated above. Smoothed data was low-pass filtered with a phaseless 4th-order Butterworth filter having a cutoff frequency of approximately 23 Hz. Phaseless filtering introduces no time lags into the filtered data, so the time relationship with other events and measurements in the crash test is maintained. Before smoothing, the velocity at impact was set to 38.5 ft/s, the average velocity obtained from the laser speed traps.

The raw velocity data is presented in Appendix G.

Figure 150 shows the longitudinal velocity of the lead car and Figure 157 shows a comparison between the B-end of the lead car and the A-end of the trailing car. Figure 152 shows the longitudinal velocity of the trailing car relative to the lead car.

A comparison between the vertical velocity of the A-end and B-ends of the lead car is shown in Figure 153 and between the B-end of the lead car and the A-end of the trailing car in Figure 154.

Finally, the vertical velocity between the trailing car relative to the lead car is presented in Figure 155 and the lateral velocity between the trailing car relative to the lead car in Figure 156.

4.3 ITEMS MEASURED AFTER THE TEST

(A-end = Leading End, B-end = Trailing End)

| | | |
|--|-------|--|
| Length of leading car from buffer beam to buffer beam | | = 78.71 ft (Difference = 5.52 ft) |
| Length of trailing car from buffer beam to buffer beam | | = 84.19 ft (Difference = 0.0 ft) |
| Long. distance from buff stop to body bolster , Lead Car | A-end | = not measured |
| Long. distance from buff stop to body bolster , Lead Car | B-end | = 6.66 ft (Difference = -0.04 ft.) |
| Long. distance, buff stop to body bolster, Trailing Car | A-end | = 6.75 ft (Difference = -0.01 ft.) |
| Long. distance, buff stop to body bolster , Trailing Car | B-end | = 6.76 ft (Difference = 0.01 ft.) |
| Long. distance between body bolsters on Lead Car | | = 62.02 ft (Difference = - 0.02 ft.) |
| Long. distance between body bolsters on Trailing Car | | = 61.83 ft (Difference = 0.0 ft.) |
| Vertical distance between mid-point of Lead Car (center sill) and a line extending between body bolsters | | = 9.75 ins (Difference = -0.22 in.) |
| Vertical distance between mid point of Trailing Car (center sill) and a line extending between body bolsters | | = 9.38 ins (Difference = 0.22 in.) |
| Vertical distance between buffer beam and a line extending between body bolsters, Lead Car, A-end | | = 12.13 ins (Difference = 6.77 in.) |
| Vertical distance between buffer beam and a line extending between body bolsters, Lead Car, B-end | | = 13.88 ins (Difference = 4.71 in.) |
| Vertical distance between buffer beam and a line extending between body bolsters, Trailing Car, A-end | | = 17.88 ins (Difference = 0.17 in.) |
| Vertical distance between buffer beam and a line extending between body bolsters, Trailing Car, B-end | | = 17.88 ins (Difference = 0.15 in.) |

5.0 CONCLUSIONS

- The speed of the test car at impact with the barrier was 26.25 mph. This was within 1 percent of the desired speed of 26 mph.
- The amount of crush in the lead car was about 5.5 feet as measured from the reduction in length of the vehicle after the test. The film analysis showed a maximum displacement in the longitudinal direction of just over 6 feet. The accelerometer data, double integrated, also shows a maximum displacement of about 6 feet. Both the film analysis and the double-integrated accelerometer data include elastic deformation of the car body. The test requirement was for at least 4 feet of crush.
- The maximum displacement of the trailing car in the longitudinal direction is shown to be about 7 feet.
- All the data bricks triggered and recorded data. All the strain gages provided some information.
- The maximum longitudinal acceleration recorded on the center sill of the lead car was 190 g at position 5 although when filtered to SAE CFC 60 the peak acceleration was reduced to 50 g.
- The maximum longitudinal acceleration recorded on the center sill of the trailing car was 110 g at position 1 although when filtered to SAE CFC 60 the peak acceleration was reduced to 22 g.
- The maximum lateral acceleration recorded on the center sill of the lead car was 300 g at position 2 although when filtered to SAE CFC 60 the peak acceleration was reduced to 18 g.
- The maximum lateral acceleration recorded on the center sill of the trailing car was 270 g at position 2 although when filtered to SAE CFC 60 the peak acceleration was reduced to 9 g.
- The maximum vertical acceleration recorded on the center sill of the lead car was 300 g at position 2 although when filtered to SAE CFC 60 the peak acceleration was reduced to 75 g.

- The maximum vertical acceleration recorded on the center sill of the trailing car was 130 g at position 2 although when filtered to SAE CFC 60 the peak acceleration was reduced to 14 g.
- The maximum vertical acceleration recorded on the A-bogie of the lead car was 250 g although when filtered to SAE CFC 60 the peak acceleration was reduced to 35 g. For the B-bogie the corresponding values were 160 g and 40 g.
- The maximum vertical acceleration recorded on the A-bogie of the trailing car was 100 g although when filtered to SAE CFC 60 the peak acceleration was reduced to 14 g. For the B-bogie the corresponding values were 40 g and 8 g.
- A maximum vertical deflection of 5 inches was recorded across the secondary suspension at the right hand side of the A-end of the lead car. The maximum vertical deflection at the A-end of the trailing car was recorded as + 3 inches on one side and - 3 inches on the other side.
- The string potentiometer measuring the longitudinal displacement of the A-end coupler on the trailing car failed. Apart from this, all the other coupler string potentiometers functioned correctly. The lead car B-end coupler moved 5 inches laterally in one direction while the trailing car B-end coupler moved almost 10 inches in the opposite direction.
- A peak load of 872,000 pounds was measured in the instrumented coupler between the two cars.
- Ten high speed film cameras and ten video cameras recorded the impact. All but one of the cameras worked successfully.
- The amount of energy absorbed by the two vehicles on impact with the barrier was calculated to be 3.43×10^6 ft. lbs. (4.65 MJ).

Reference

1. SAE J211(R), "Instrumentation for Impact Test," Society of Automotive Engineers, March 1995.

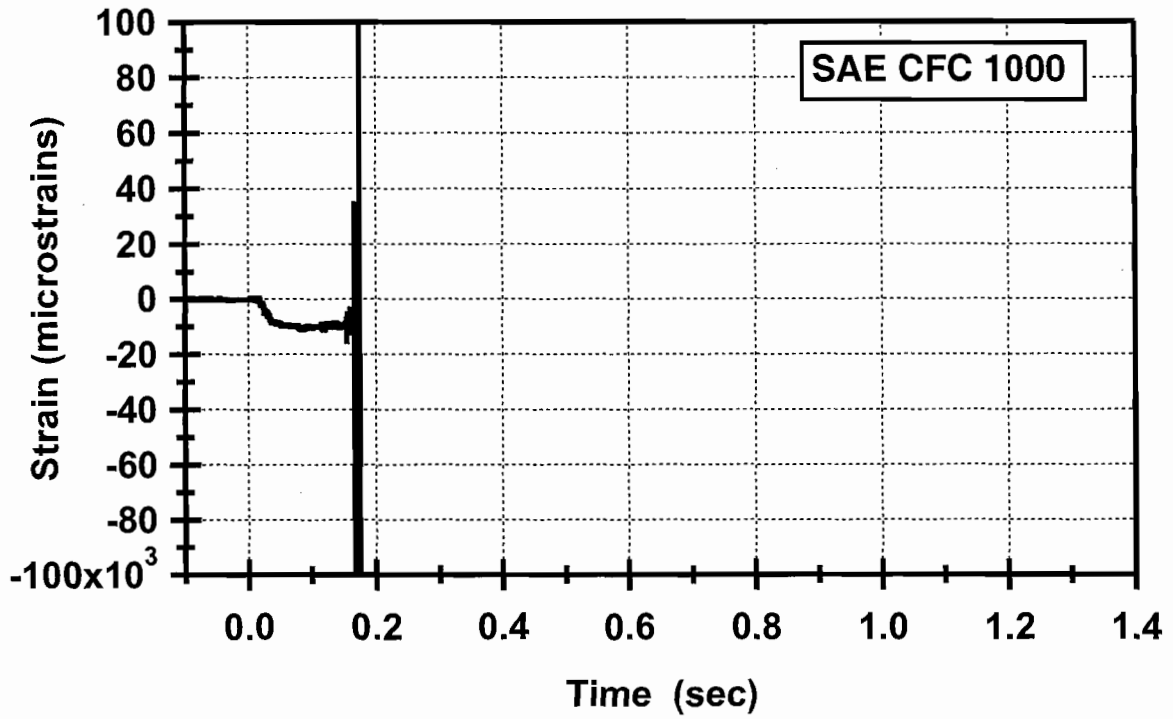


Figure 3. Strain Gage, Lead Car, A End, CS-R-1-U

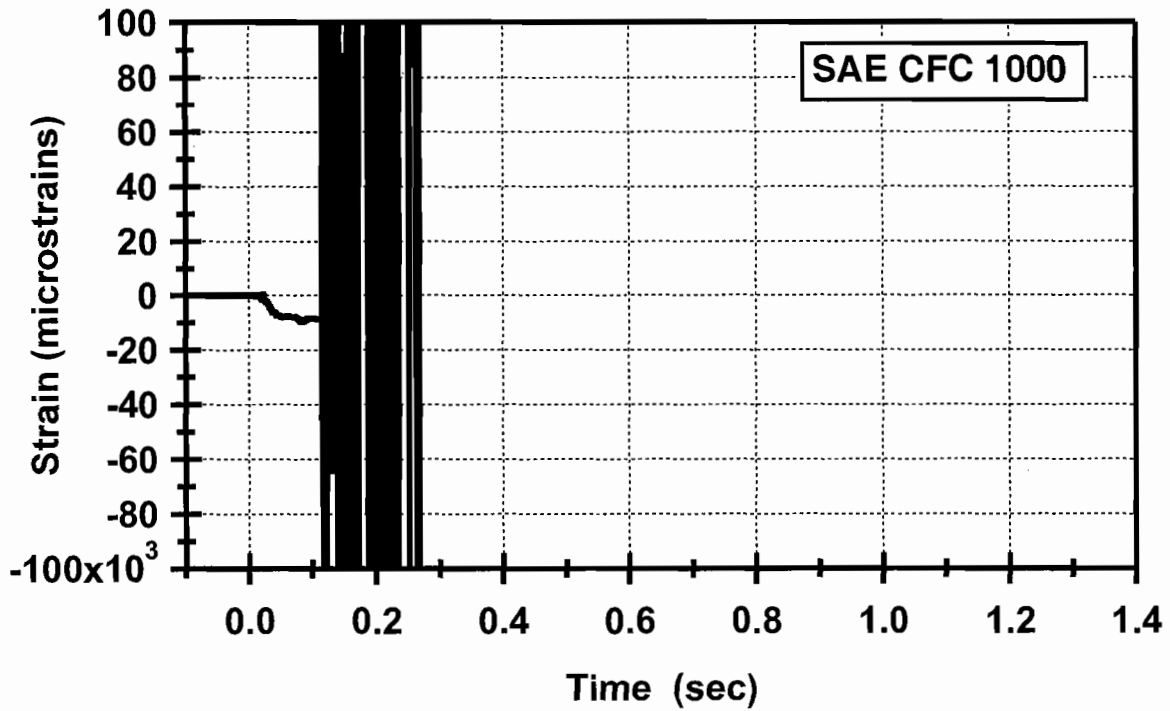


Figure 4. Strain Gage, Lead Car, A End, CS-R-2-U

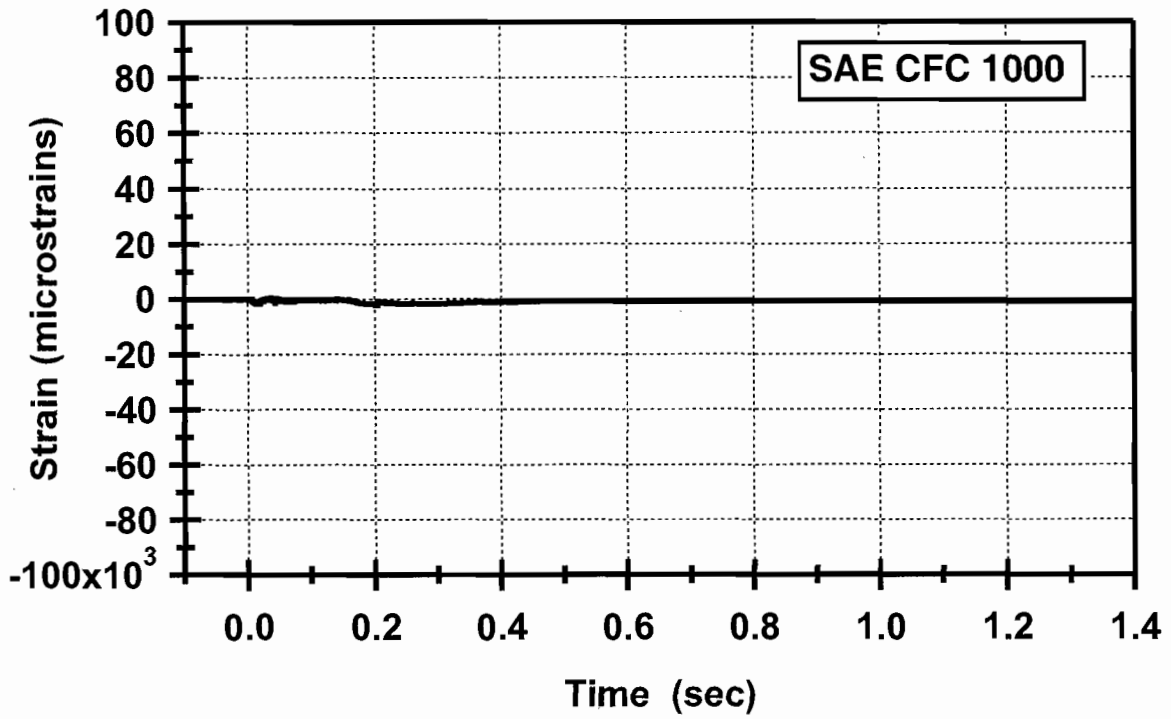


Figure 5. Strain Gage, Lead Car, A End, CS-R-6-U

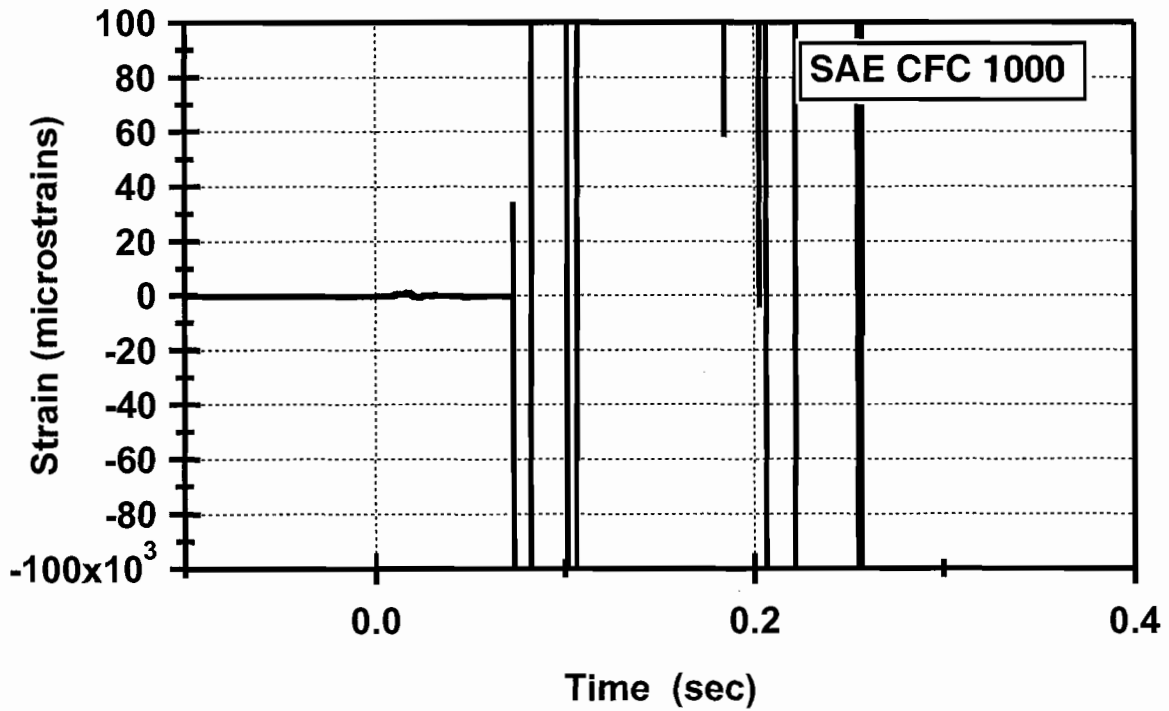


Figure 6. Strain Gage, Lead Car, A End, CS-L-1-U

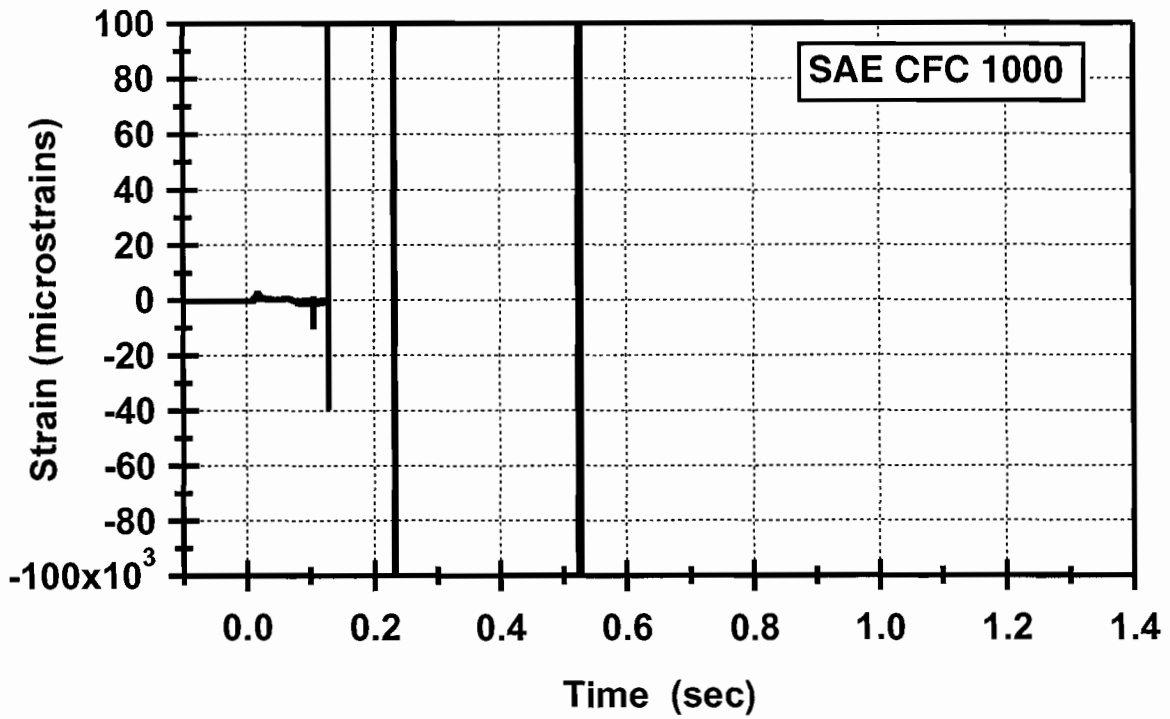


Figure 7. Strain Gage, Lead Car, A End, CS-L-2-U

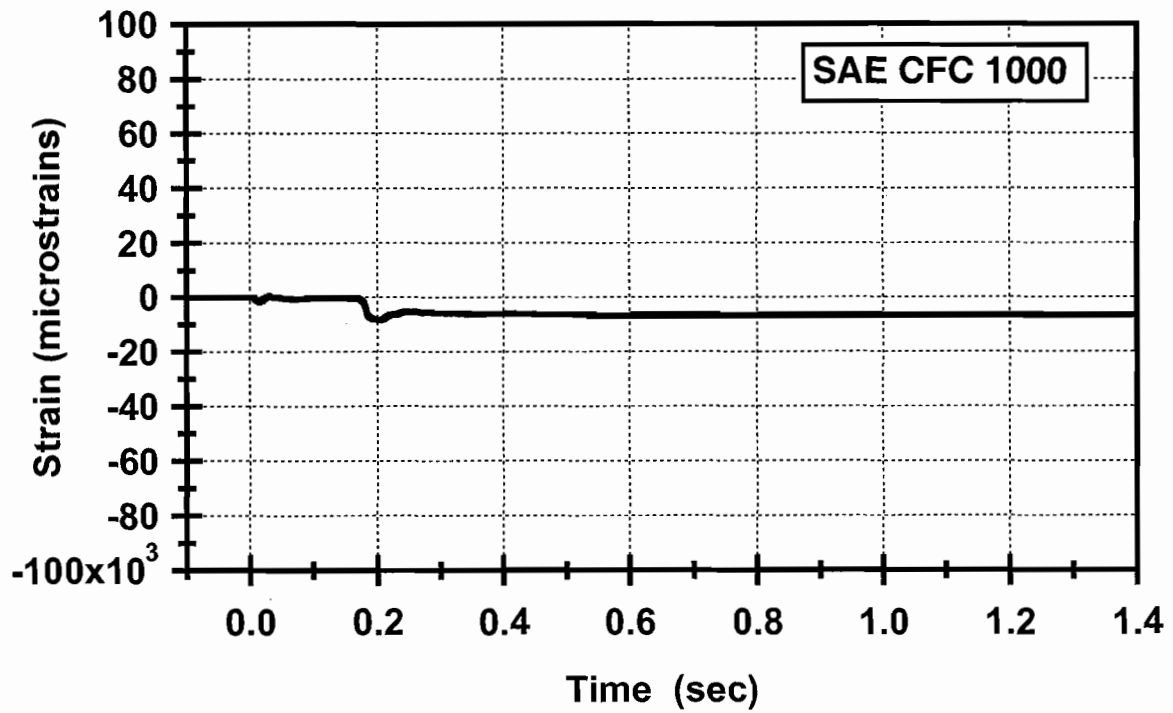


Figure 8. Strain Gage, Lead Car, A End, CS-L-6-U

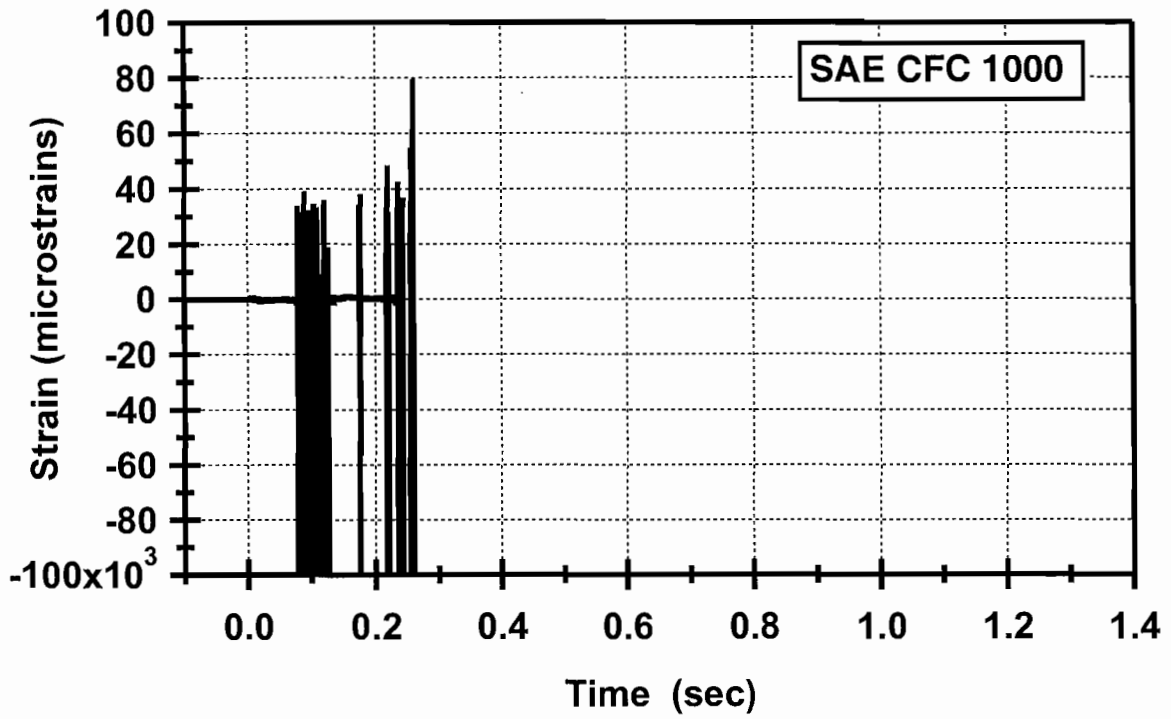


Figure 9. Strain Gage, Lead Car, A End, CS-L-1-L

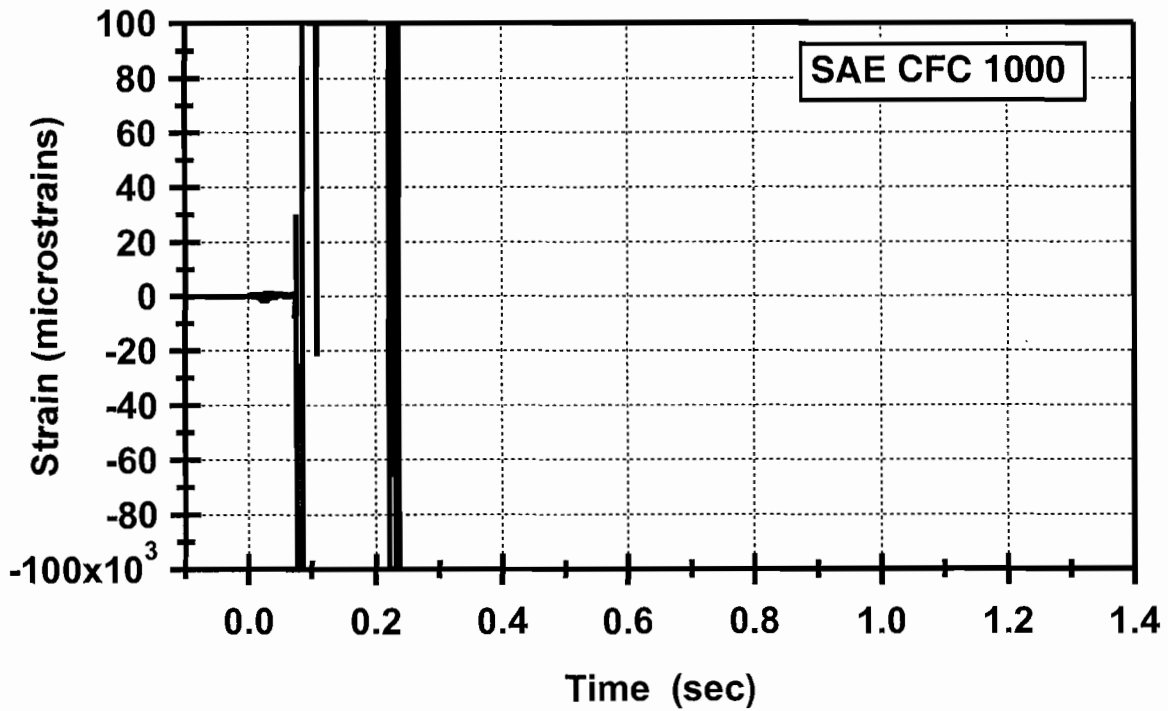


Figure 10. Strain Gage, Lead Car, A End, CS-L-2-L

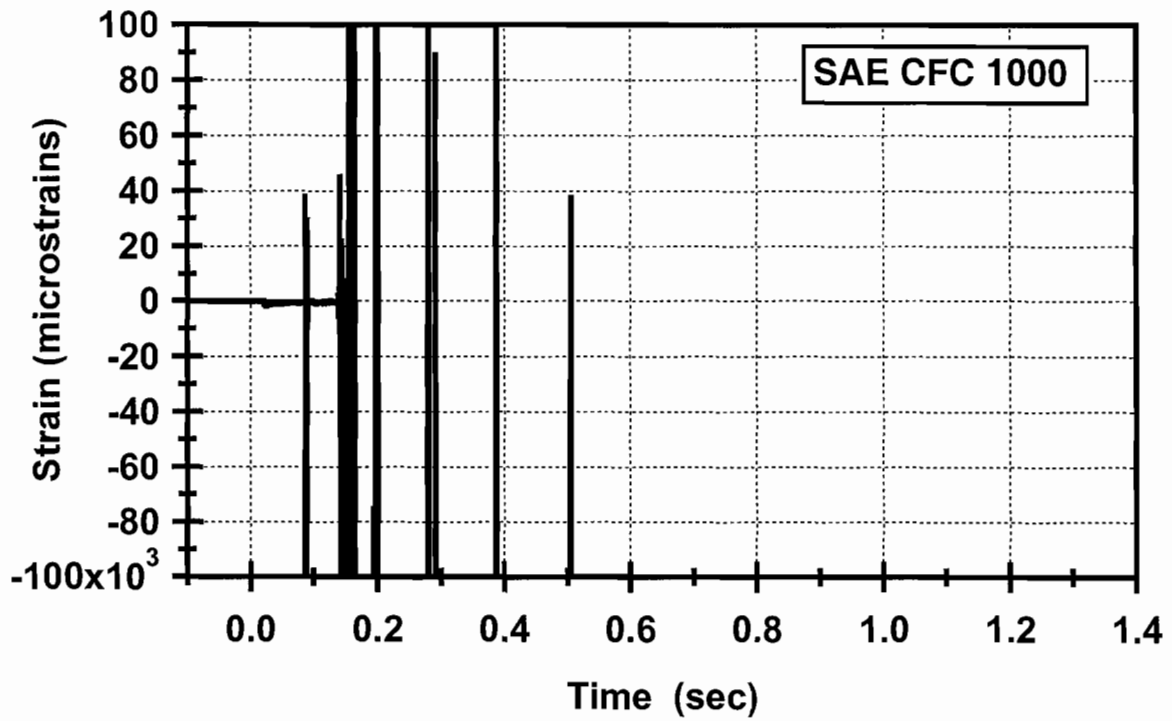


Figure 11. Strain Gage, Lead Car, A End, CS-R-1-L

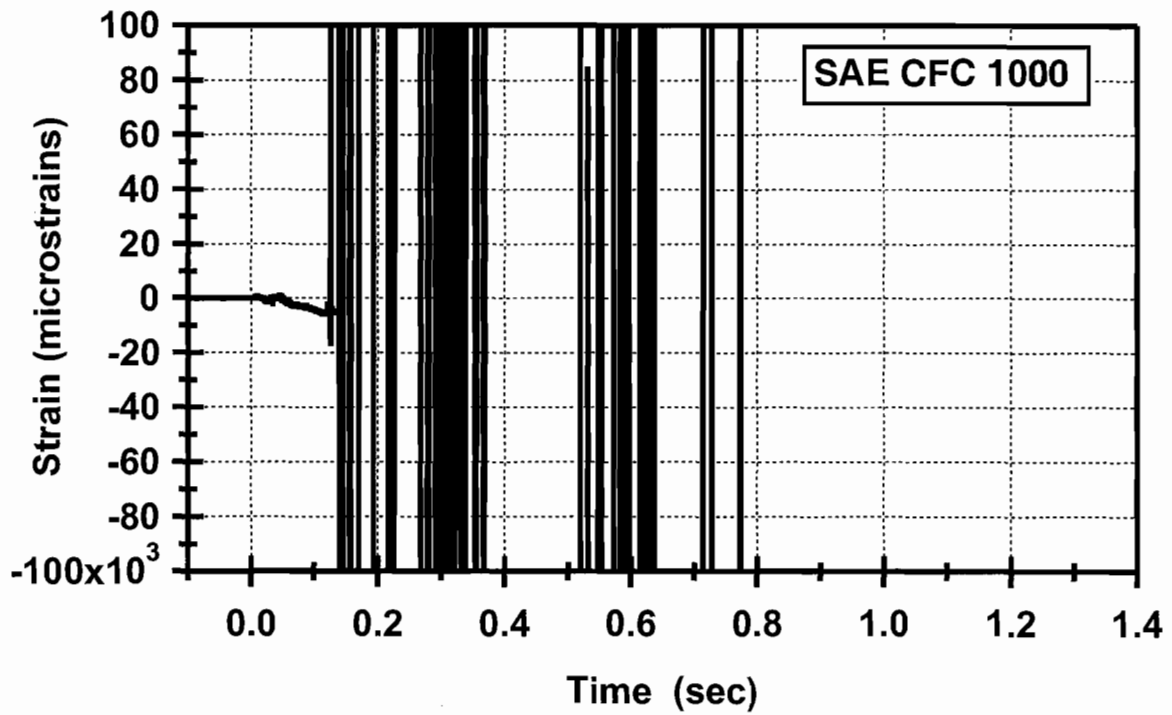


Figure 12. Strain Gage, Lead Car, A End, CS-R-2-L

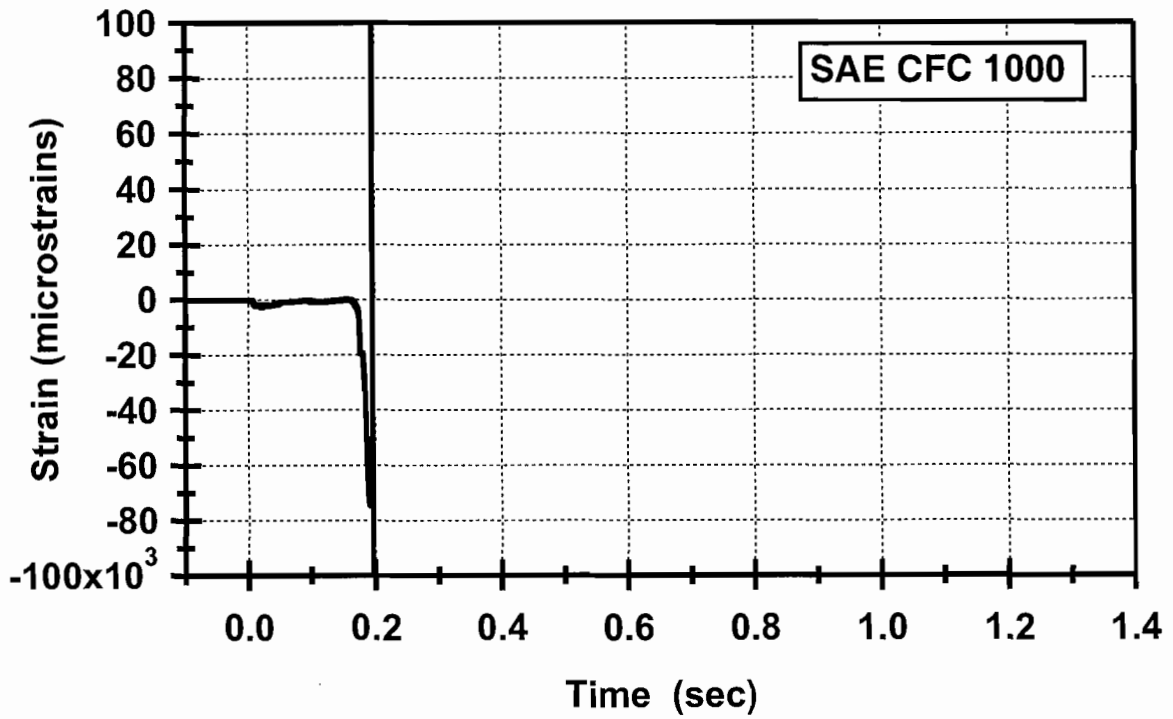


Figure 13. Strain Gage, Lead Car, A End, CS-B-6-C

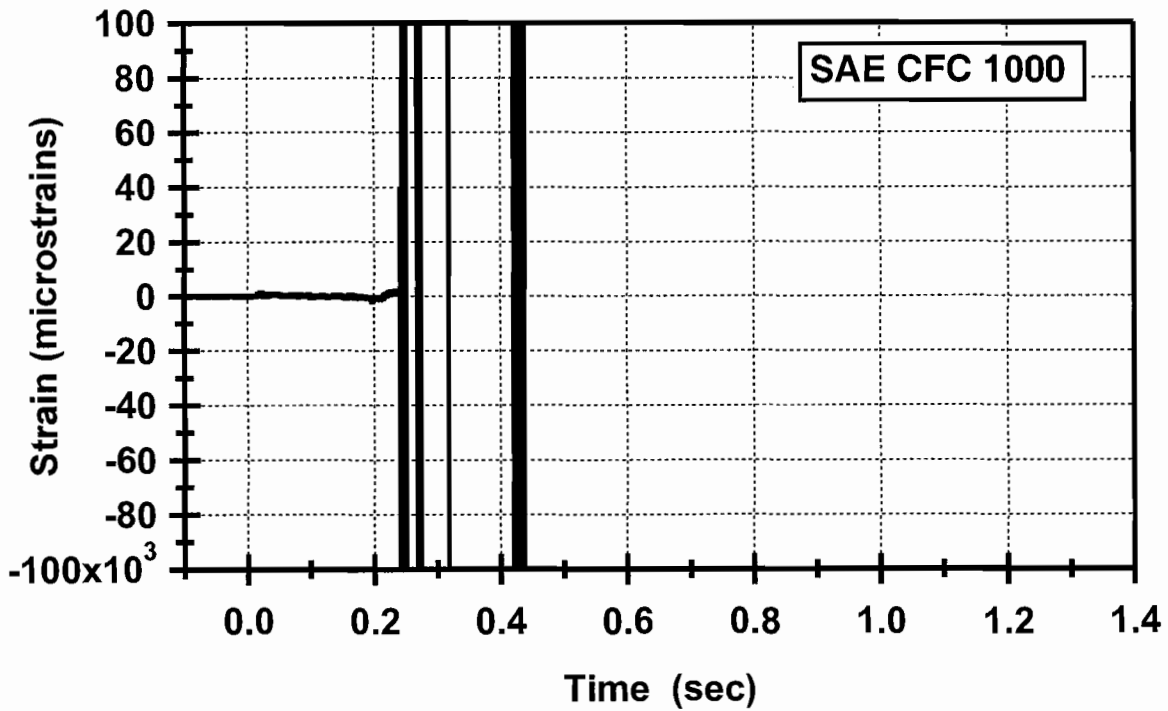


Figure 14. Strain Gage, Lead Car, A End, SS-L-1-U

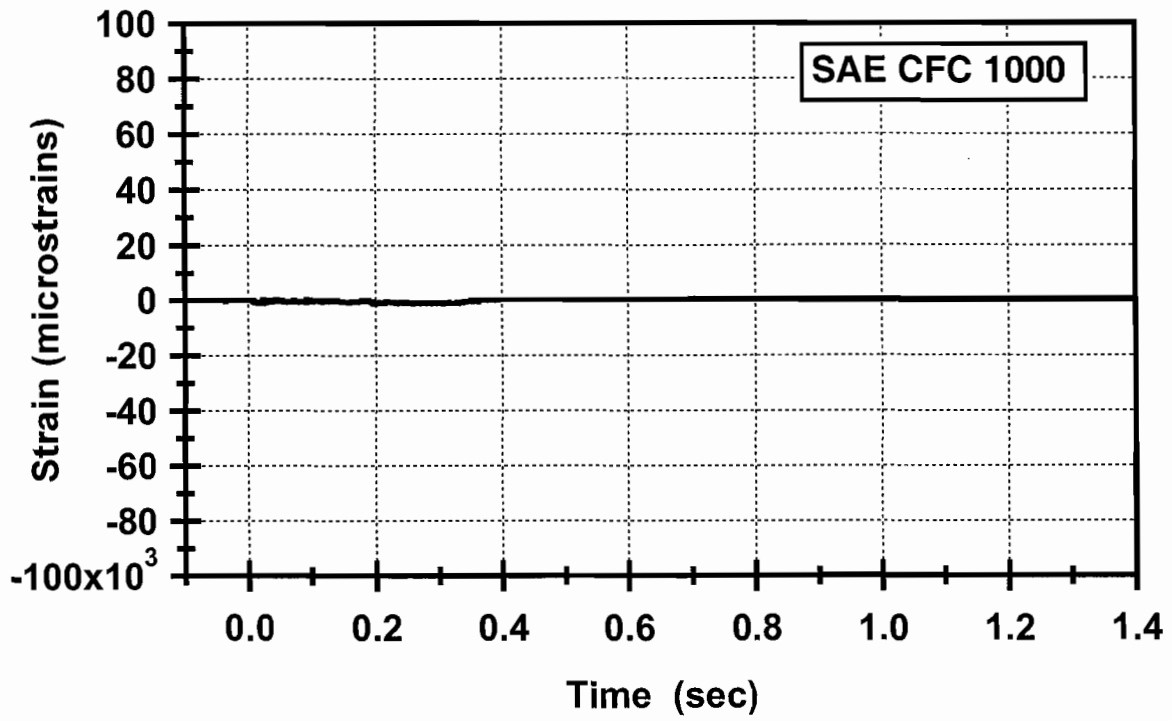


Figure 15. Strain Gage, Lead Car, A End, SS-L-2-U

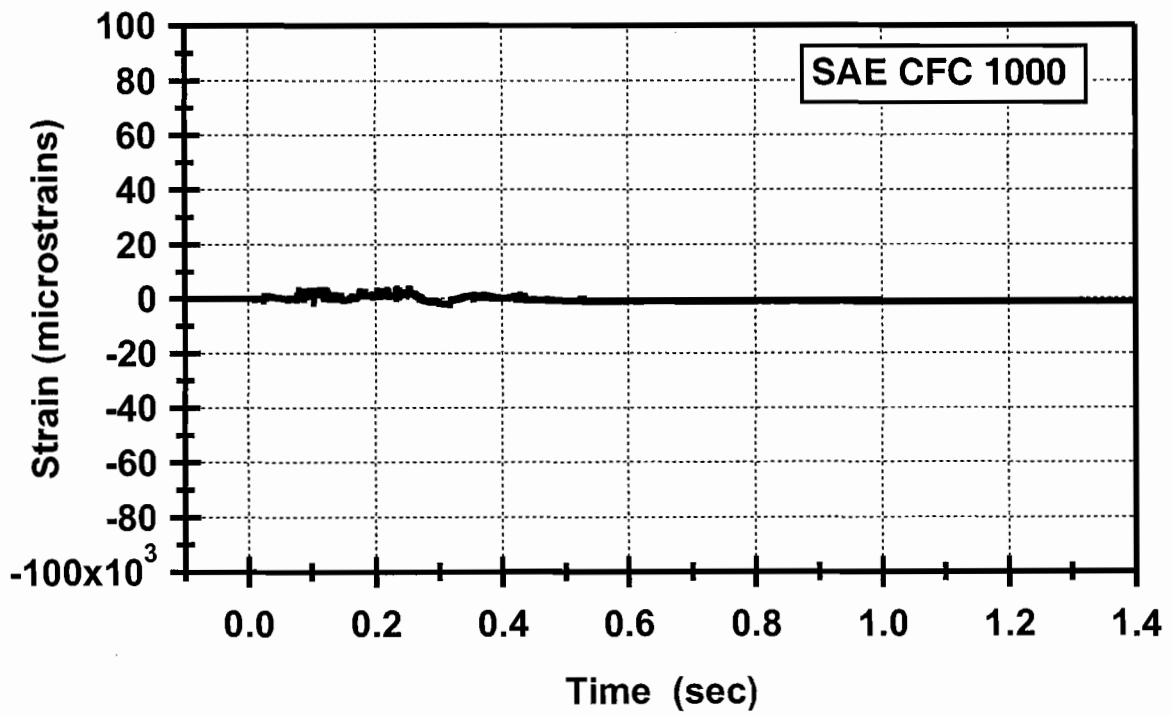


Figure 16. Strain Gage, Lead Car, A End, SS-L-1-L

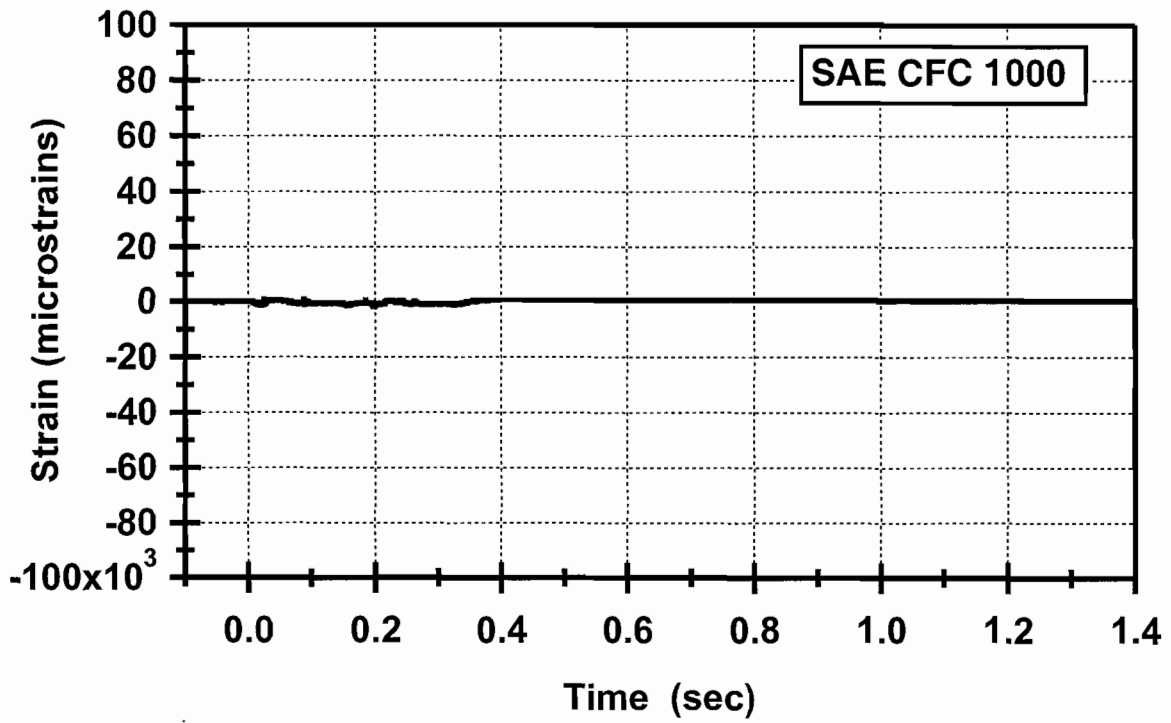


Figure 17. Strain Gage, Lead Car, A End, SS-L-2-L

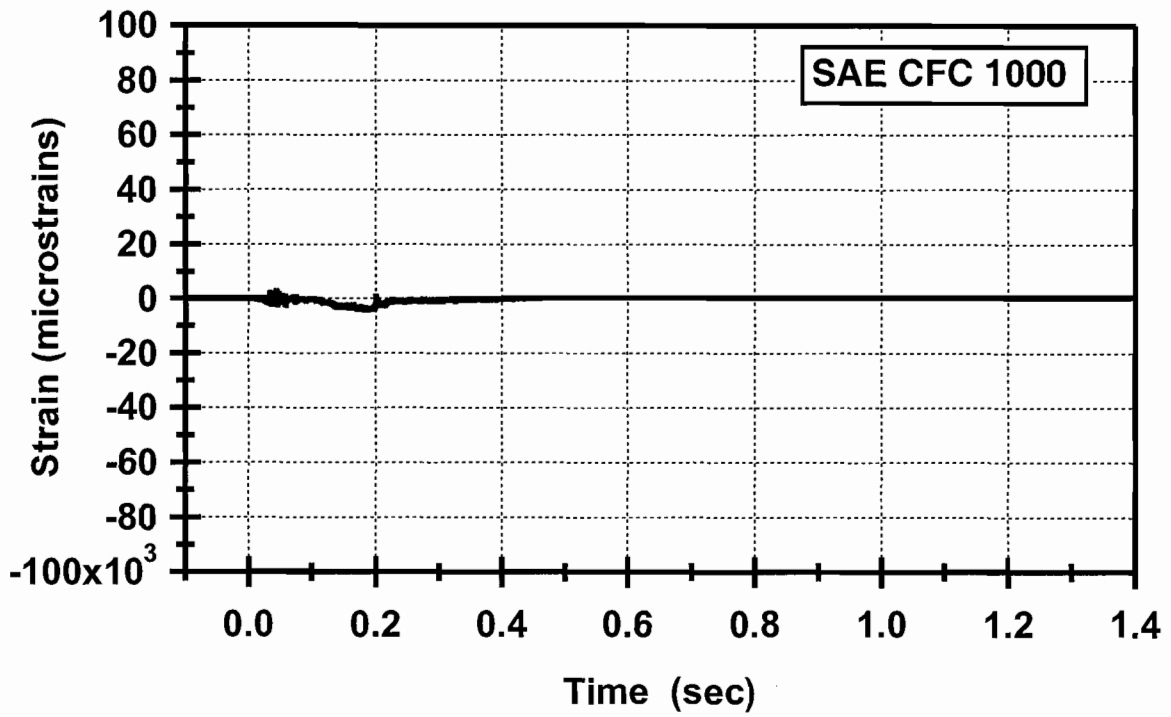


Figure 18. Strain Gage, Lead Car, A End, SS-R-1-U

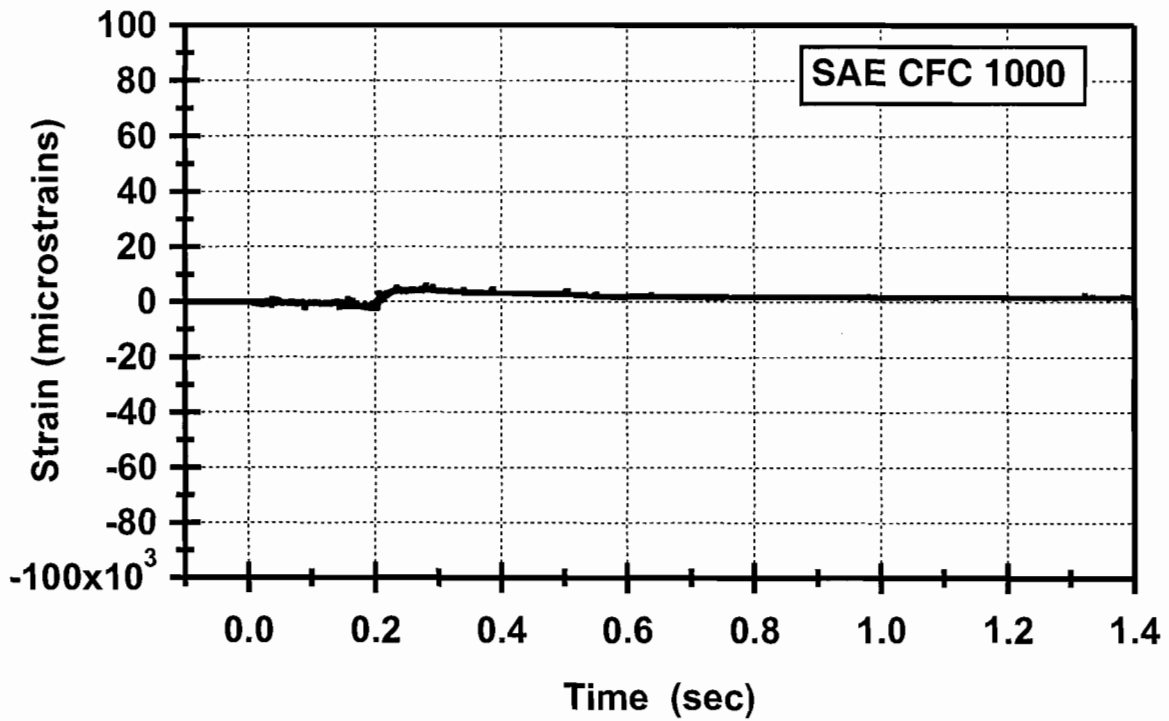


Figure 19. Strain Gage, Lead Car, A End, SS-R-2-U

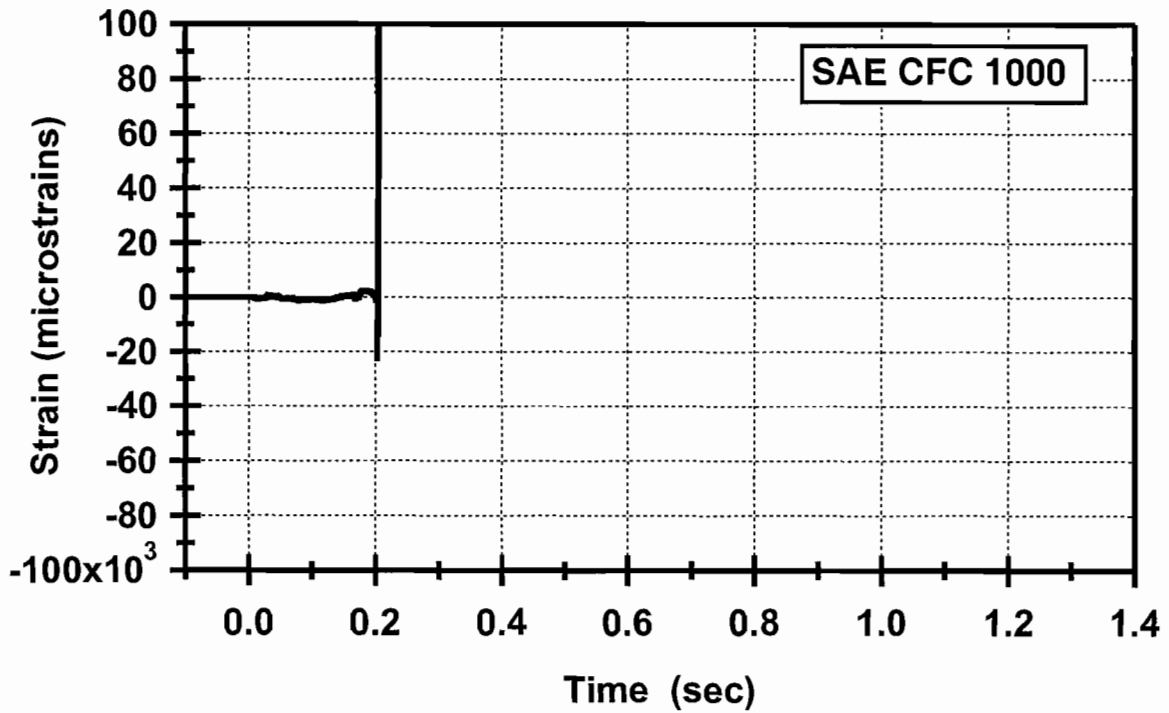


Figure 20. Strain Gage, Lead Car, A End, SS-R-1-L

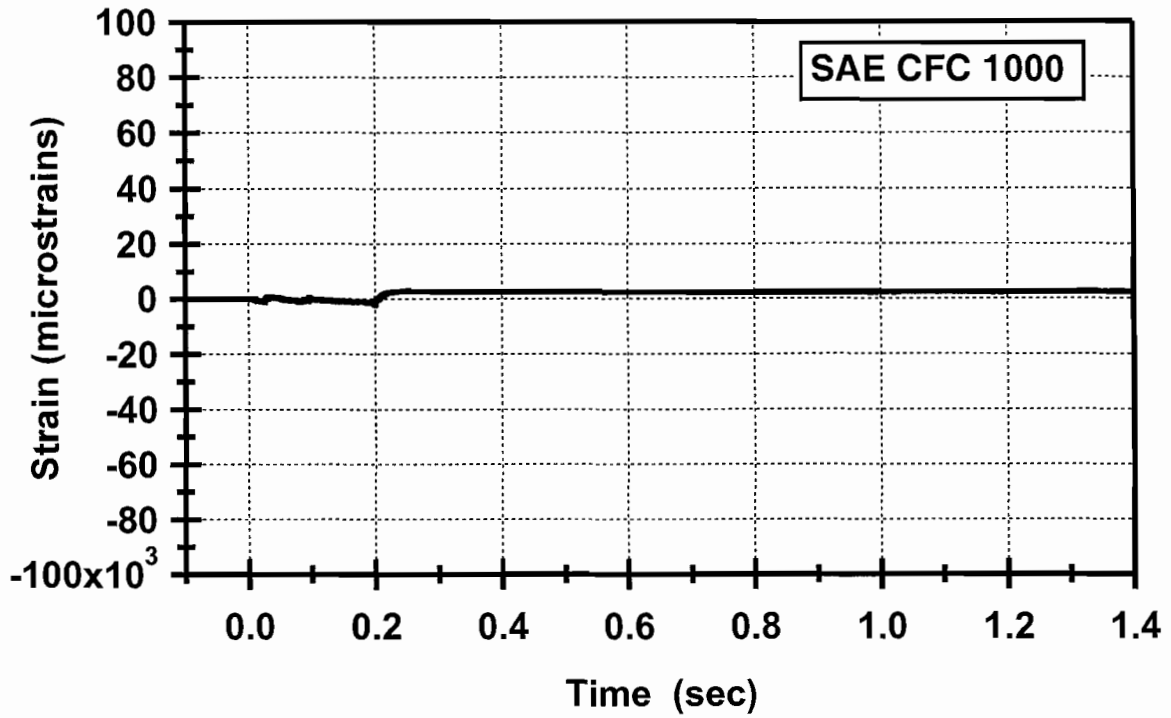


Figure 21. Strain Gage, Lead Car, A End, SS-R-2-L

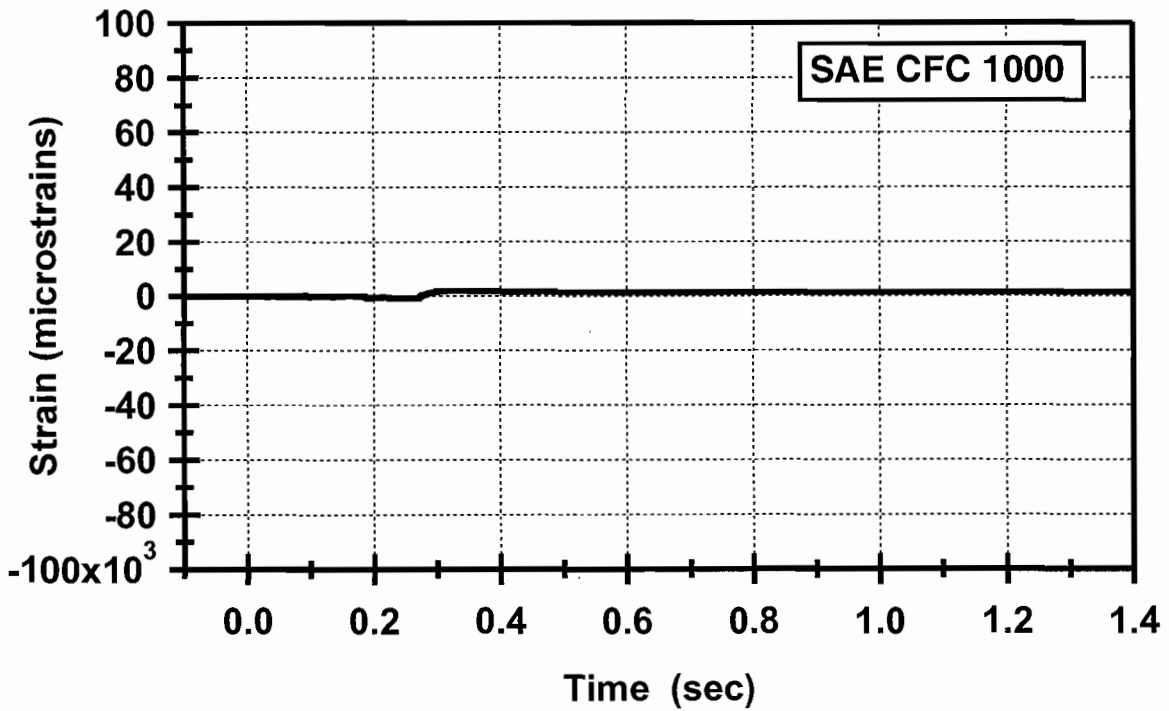


Figure 22. Strain Gage, Lead Car, A End, CR-L-2-U

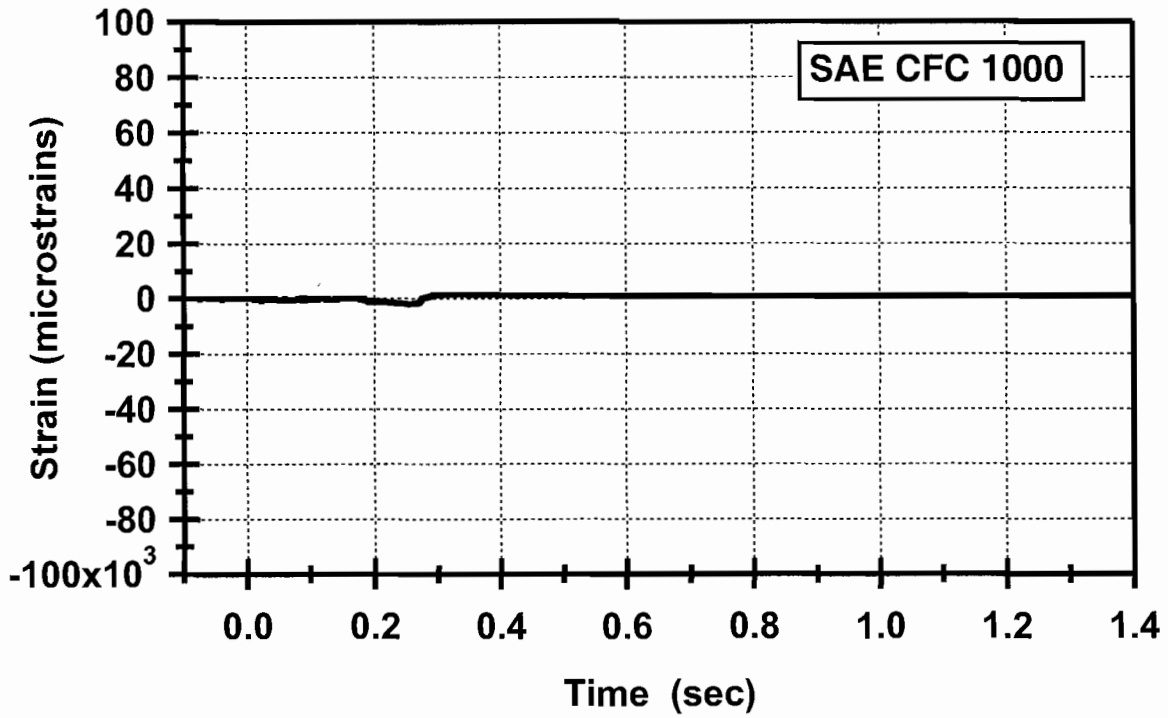


Figure 23. Strain Gage, Lead Car, A End, CR-L-2-L

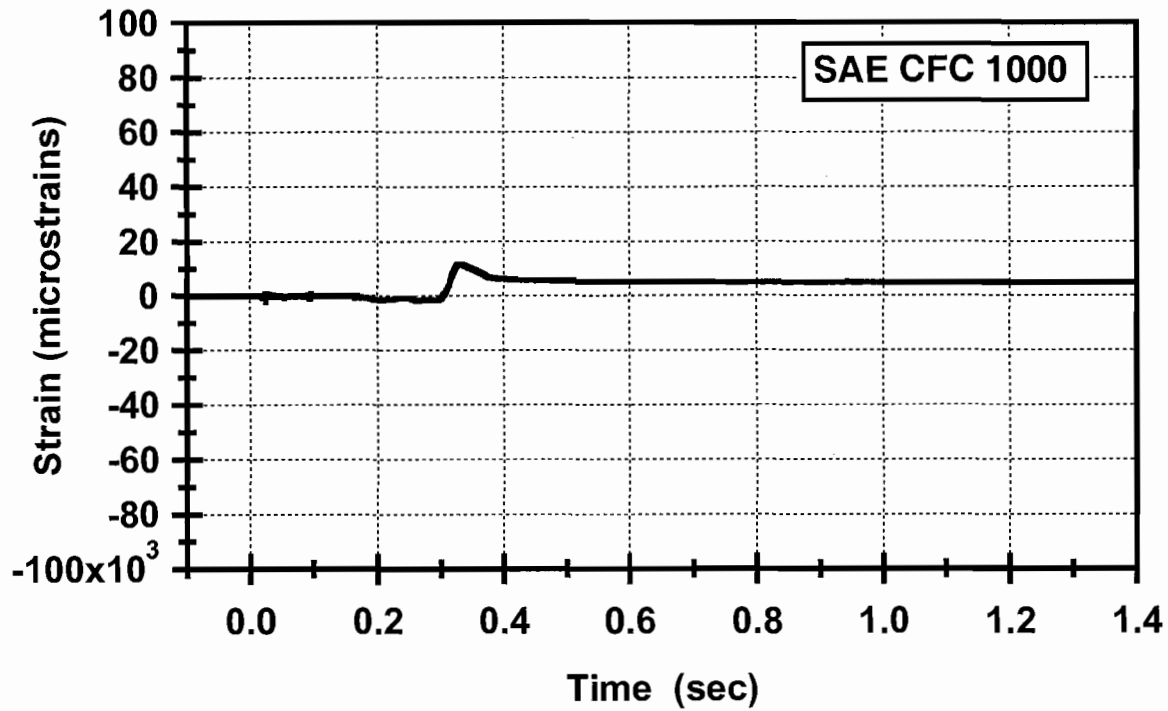


Figure 24. Strain Gage, Lead Car, A End, CR-R-2-U

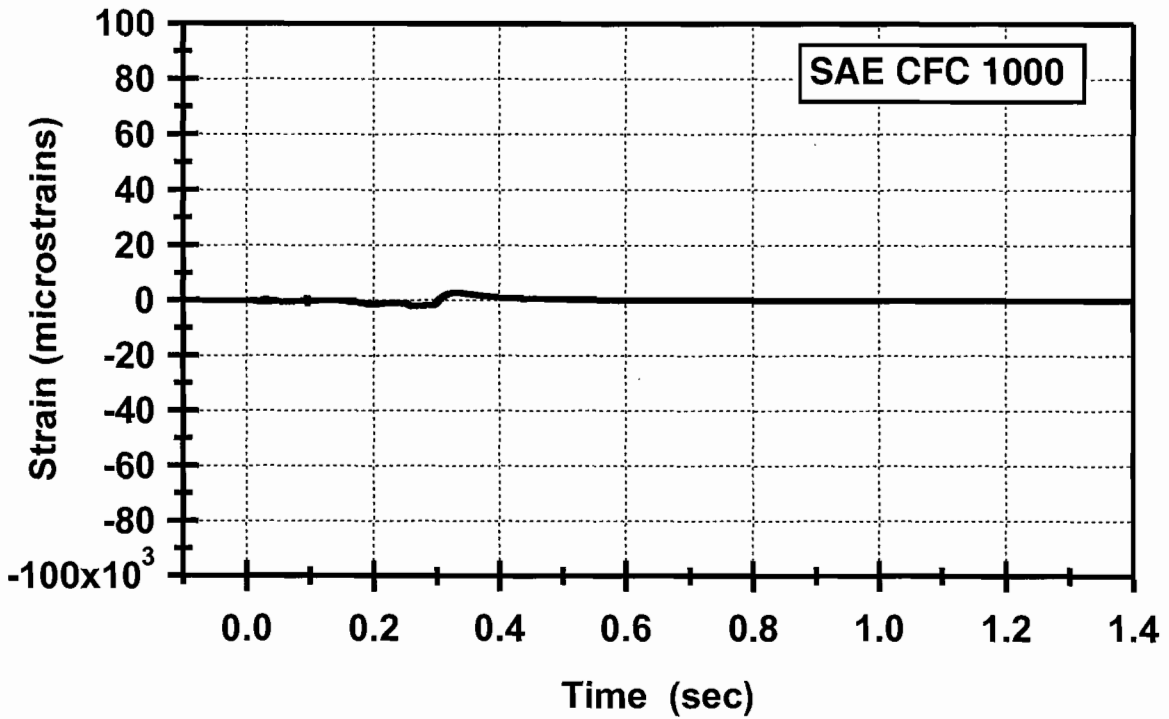


Figure 25. Strain Gage, Lead Car, A End, CR-R-2-L

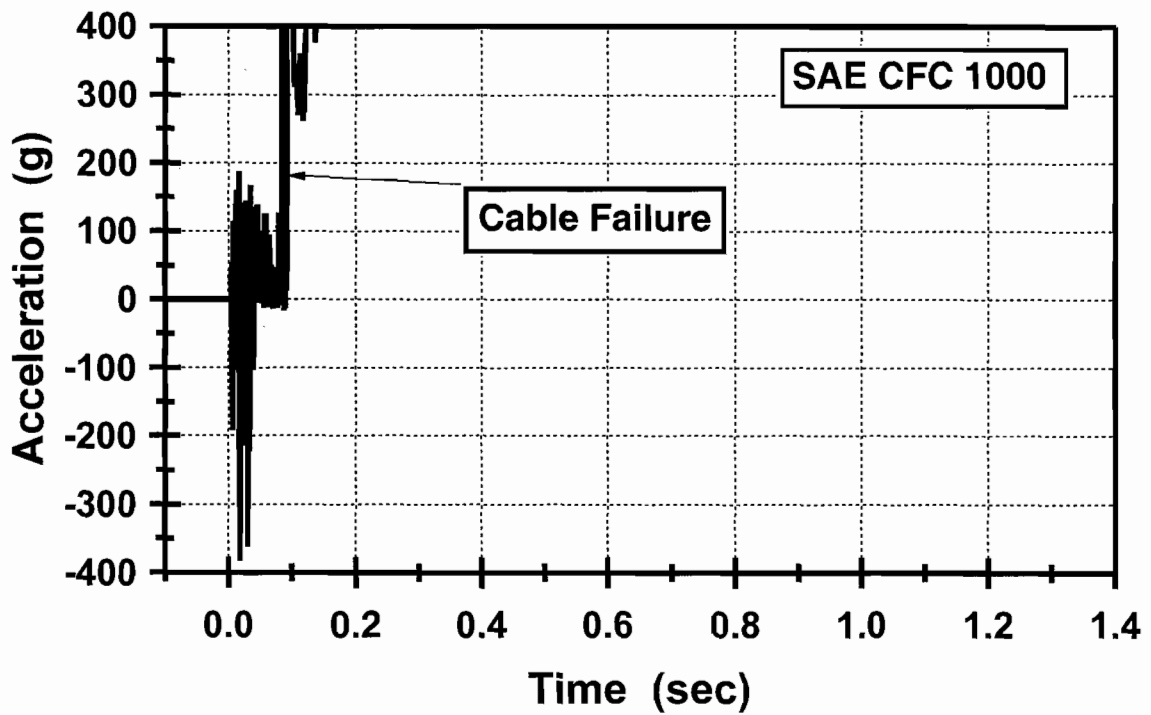


Figure 26. Accel., Lead Car, CS, Position 1, X-Axis

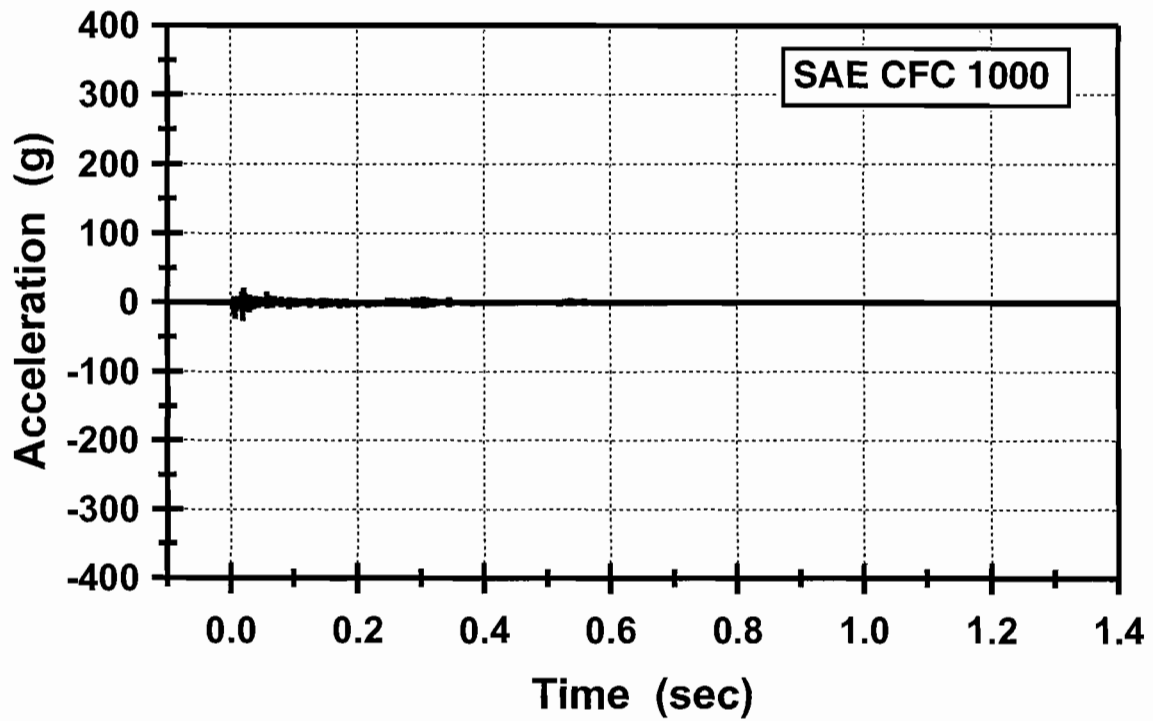


Figure 27. Accel., Lead Car, CS, Position 2, X-Axis

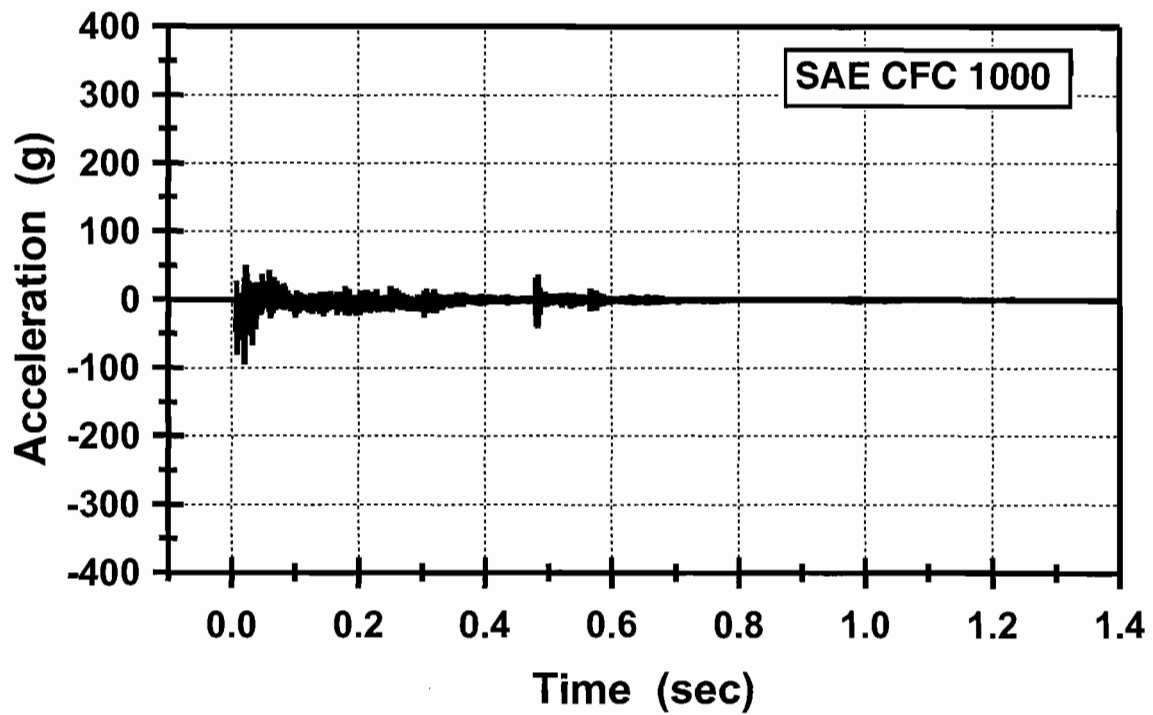


Figure 28. Accel., Lead Car, CS, Position 3, X-Axis

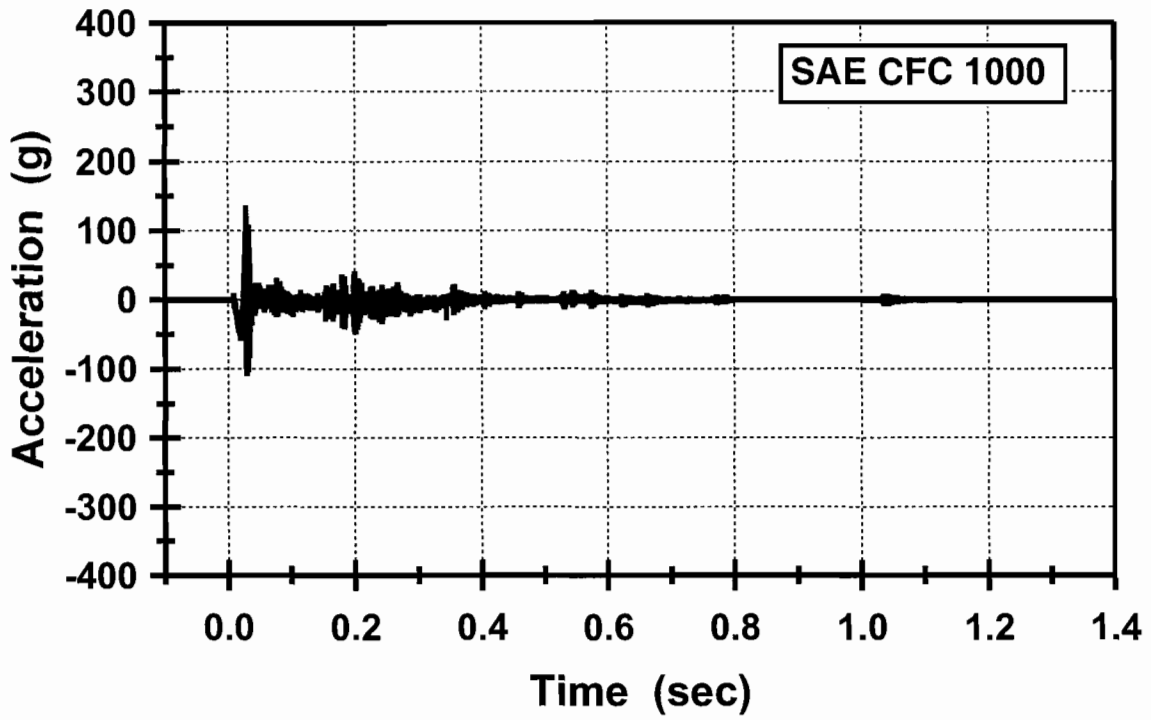


Figure 29. Accel., Lead Car, CS, Position 4, X-Axis

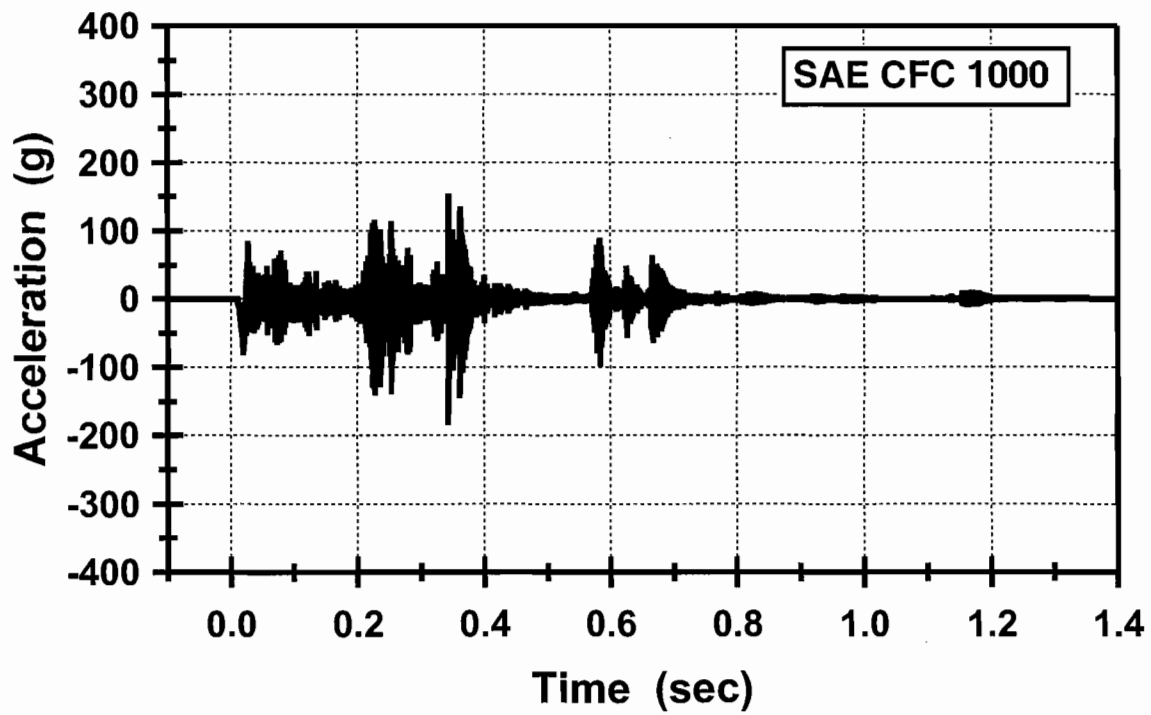


Figure 30. Accel., Lead Car, CS, Position 5, X-Axis

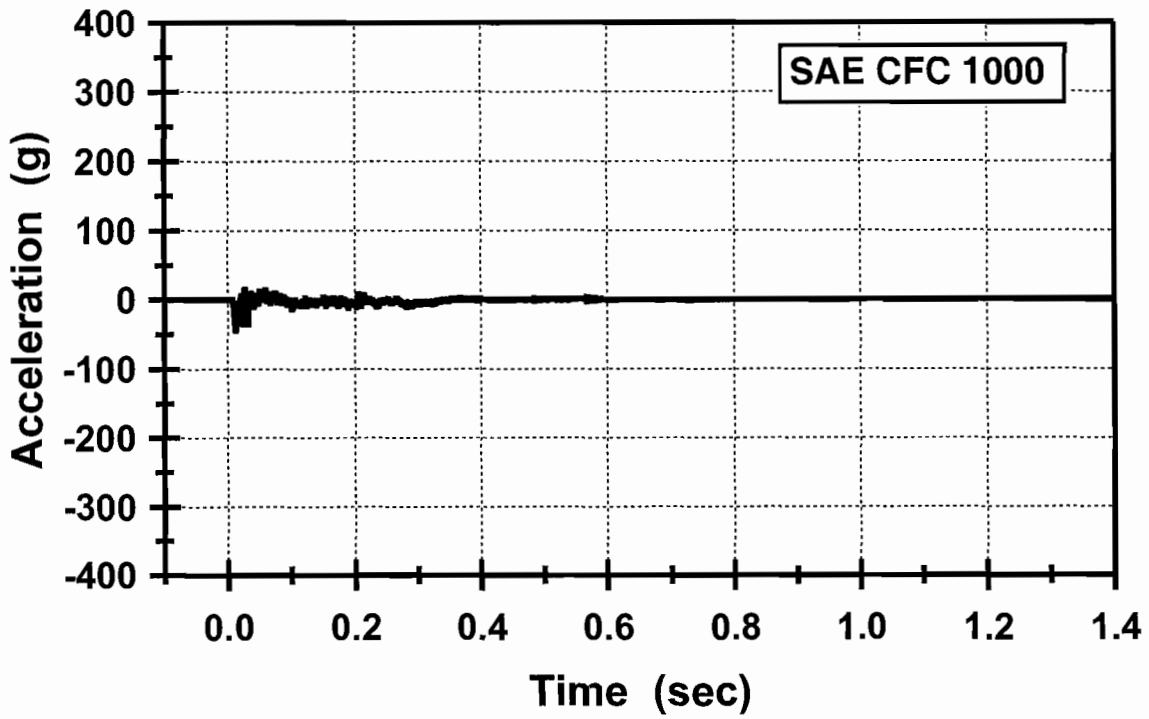


Figure 31. Accel., Lead Car, RS, Position 3, X-Axis

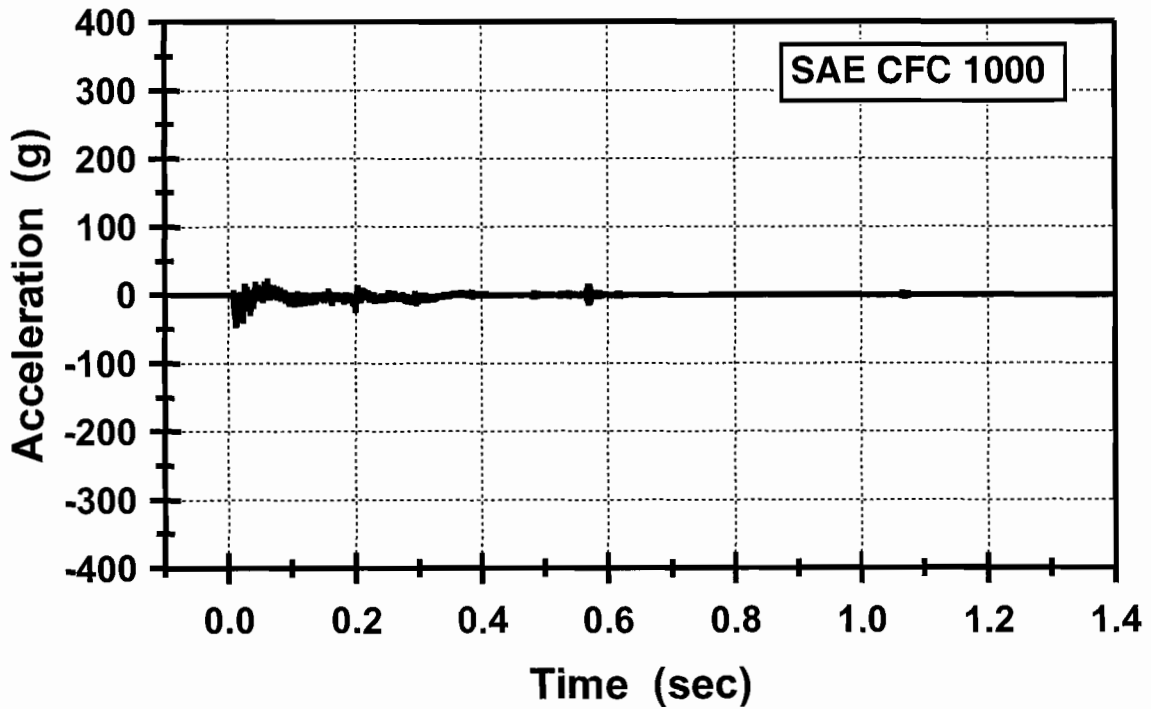


Figure 32. Accel., Lead Car, LS, Position 3, X-Axis

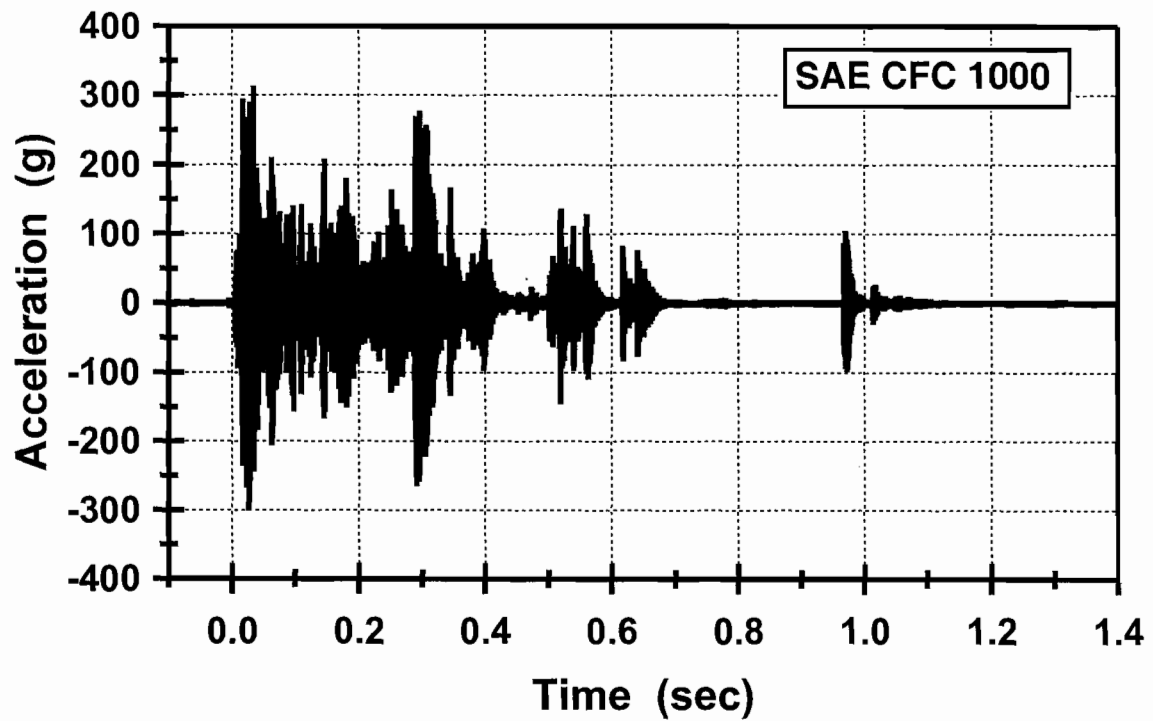


Figure 33. Accel., Lead Car, CS, Position 2, Y-Axis

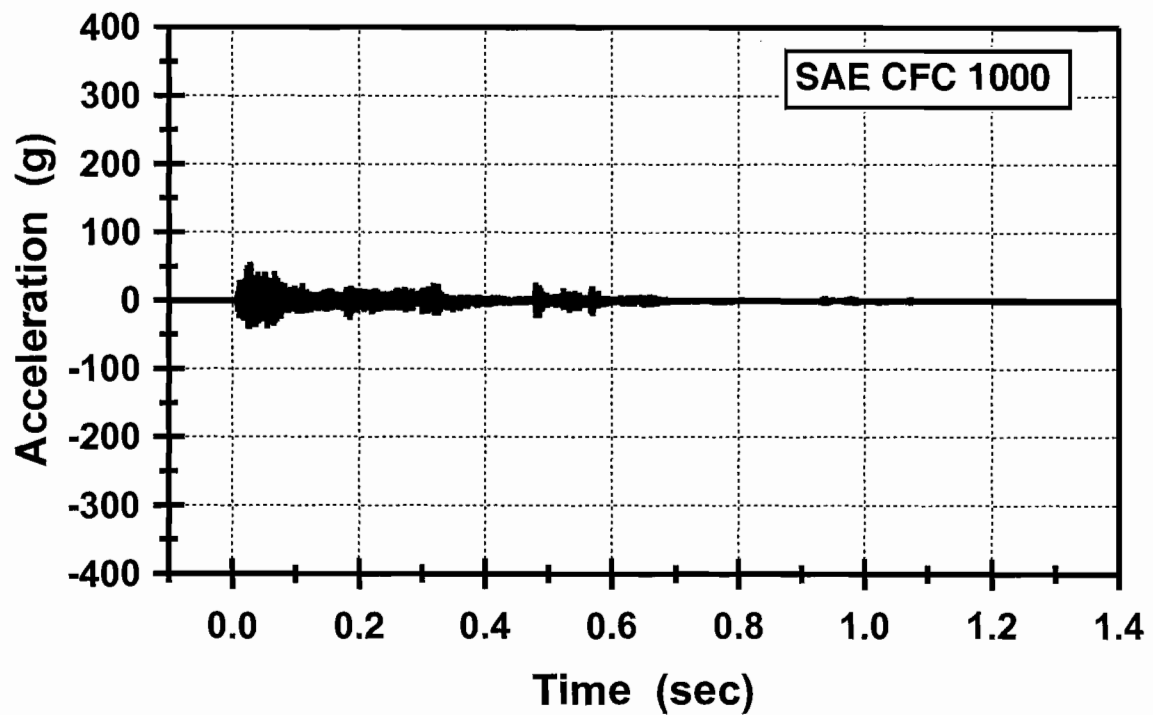


Figure 34. Accel., Lead Car, CS, Position 3, Y-Axis

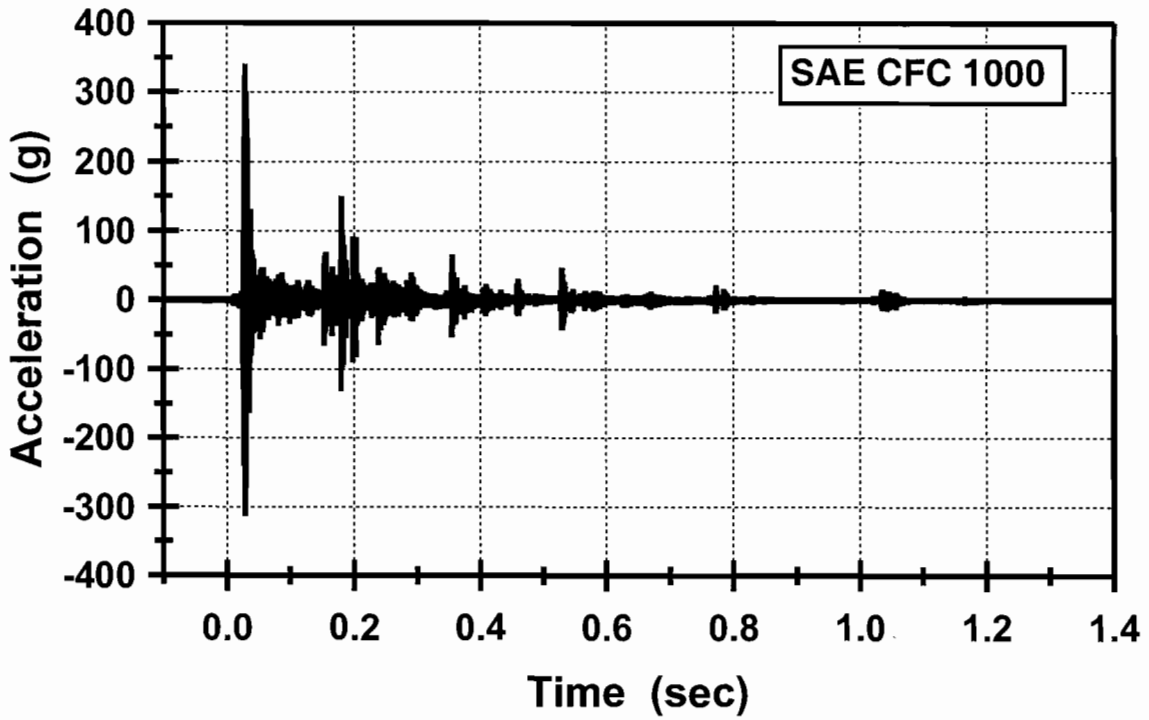


Figure 35. Accel., Lead Car, CS, Position 4, Y-Axis

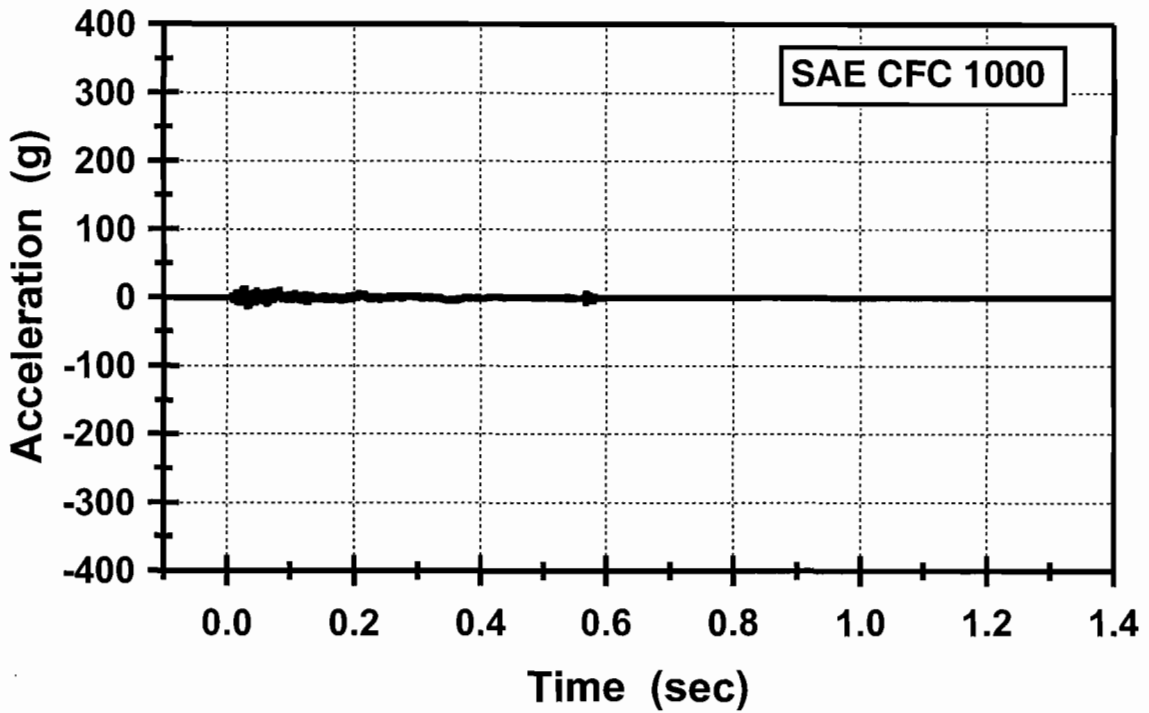


Figure 36. Accel., Lead Car, RS, Position 3, Y-Axis

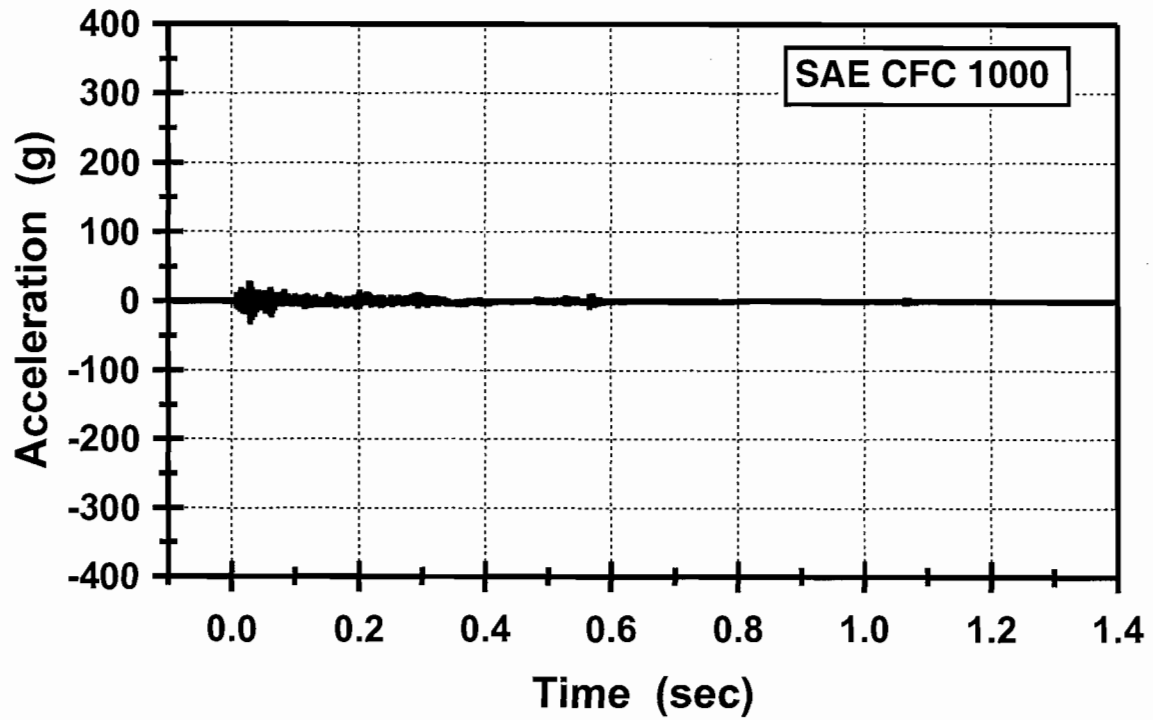


Figure 37. Accel., Lead Car, LS, Position 3, Y-Axis

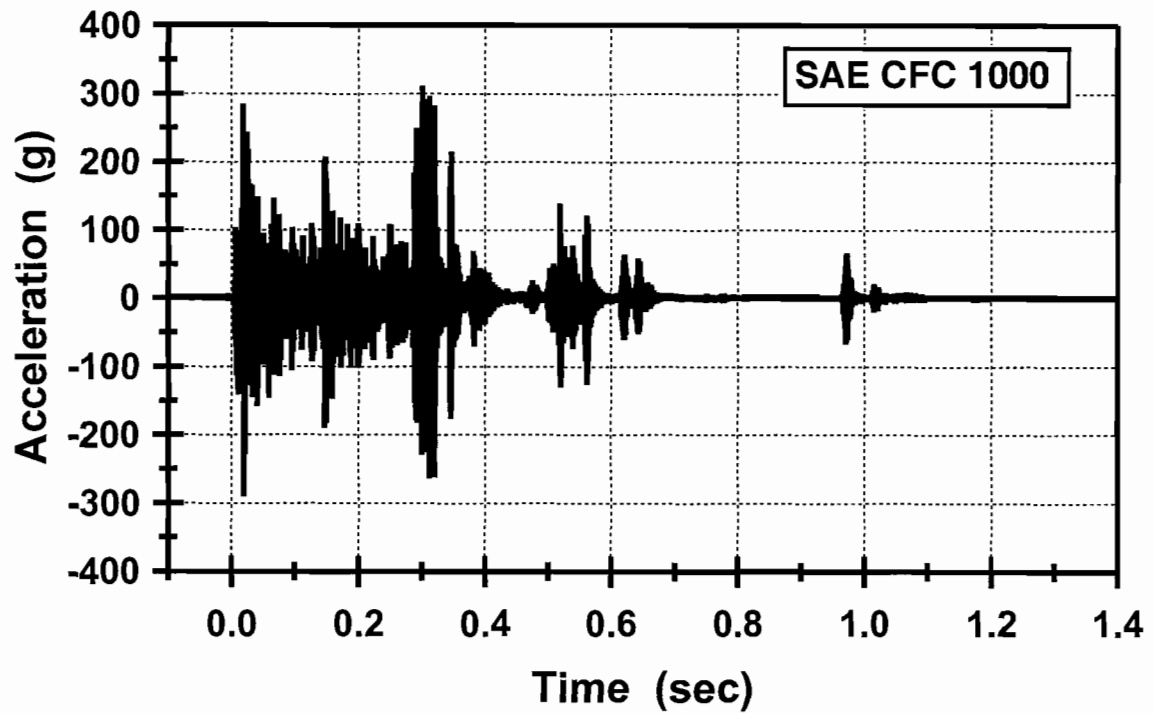


Figure 38. Accel., Lead Car, CS, Position 2, Z-Axis

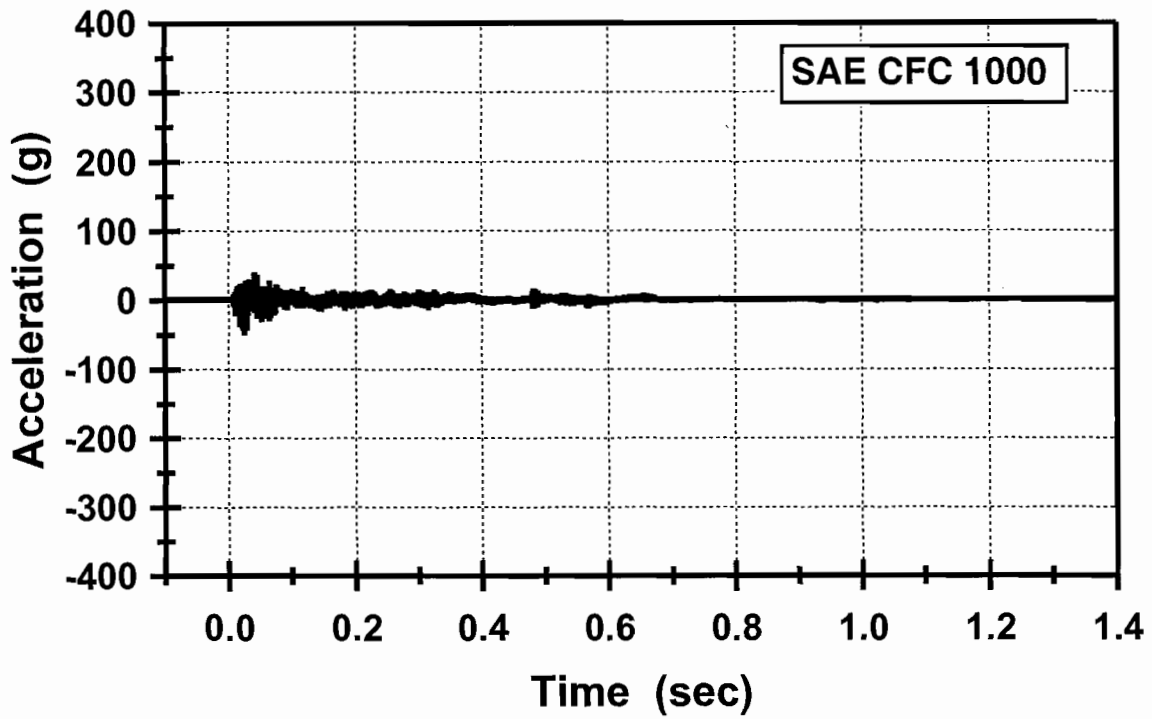


Figure 39. Accel., Lead Car, CS, Position 3, Z-Axis

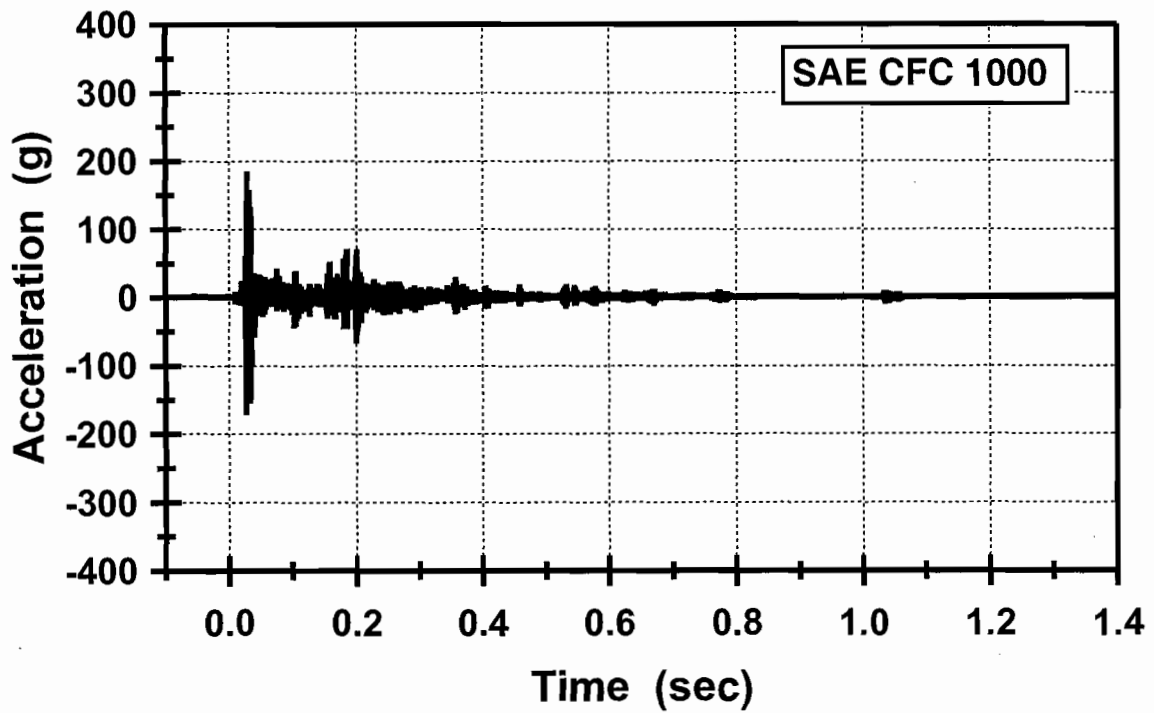


Figure 40. Accel., Lead Car, CS, Position 4, Z-Axis

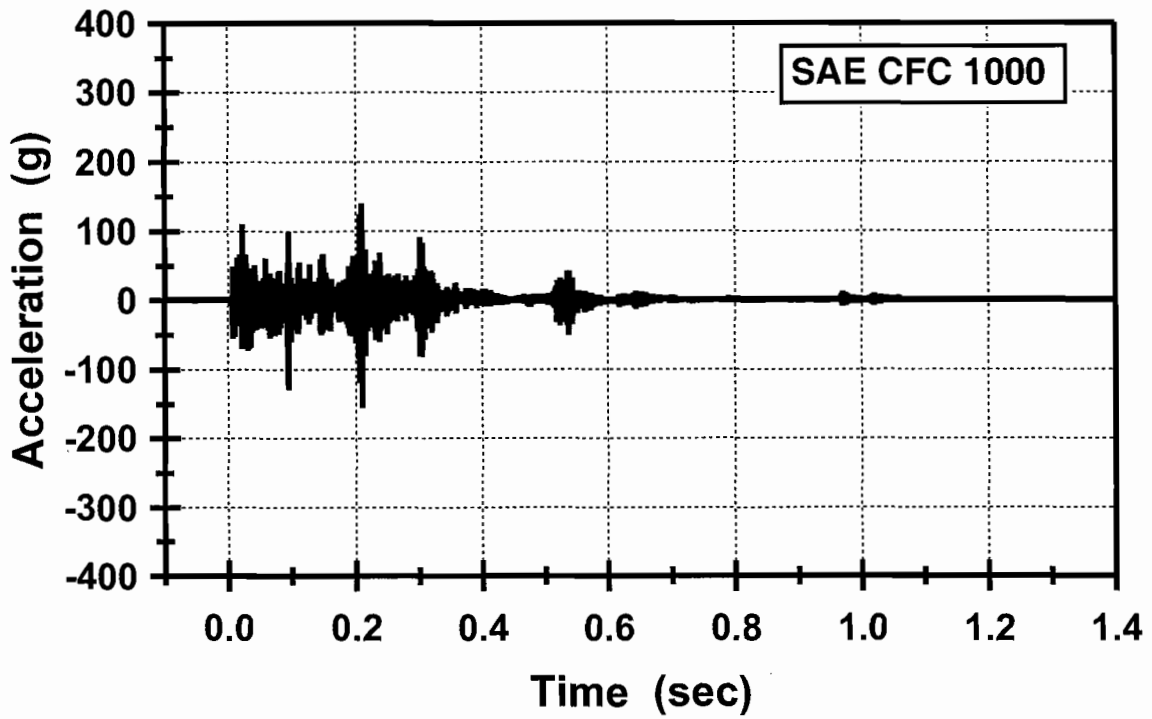


Figure 41. Accel., Lead Car, RS, Position 1, Z-Axis

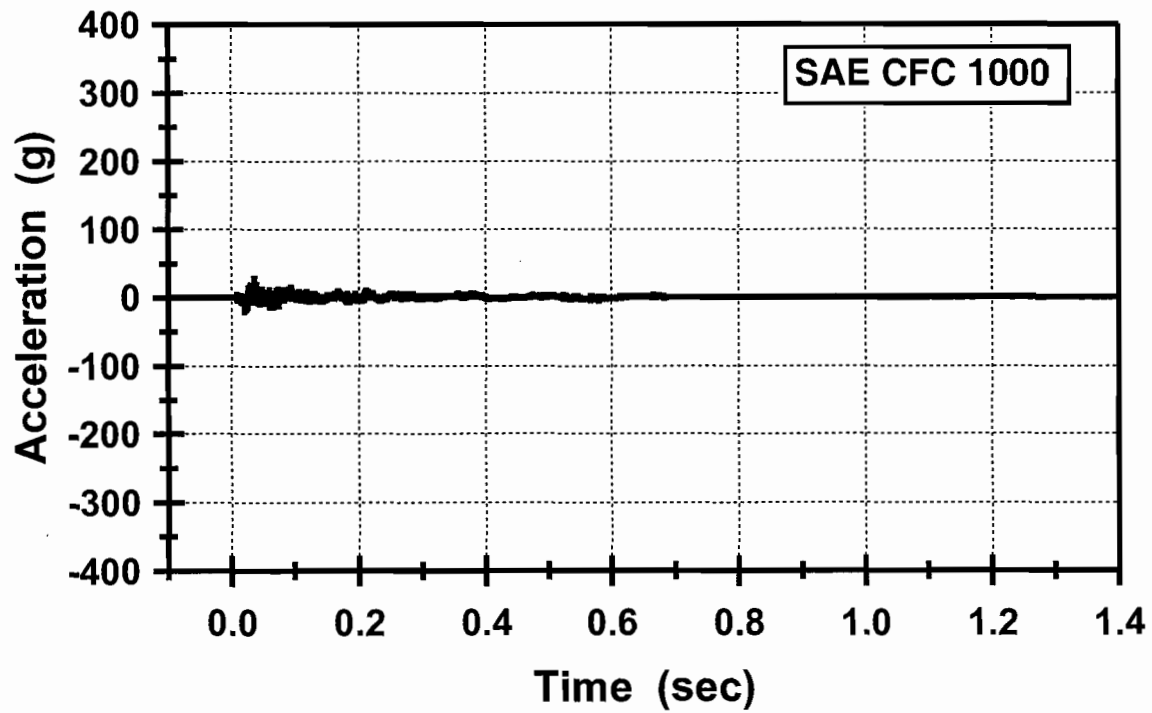


Figure 42. Accel., Lead Car, RS, Position 3, Z-Axis

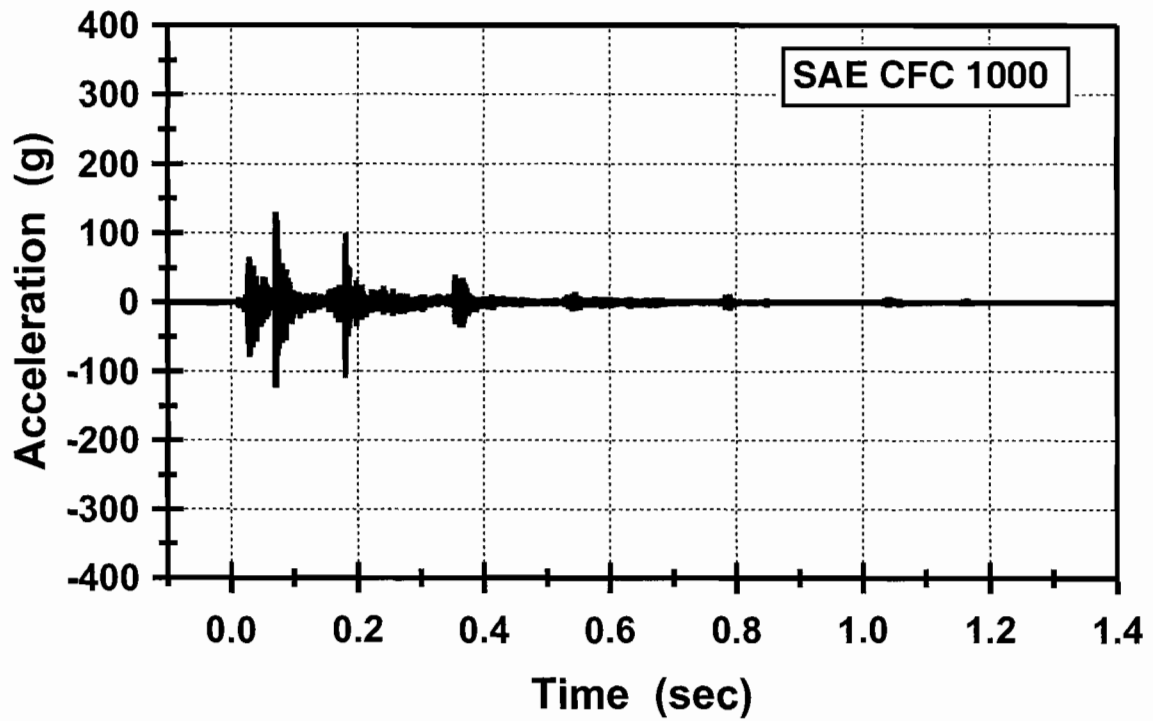


Figure 43. Accel., Lead Car, RS, Position 5, Z-Axis

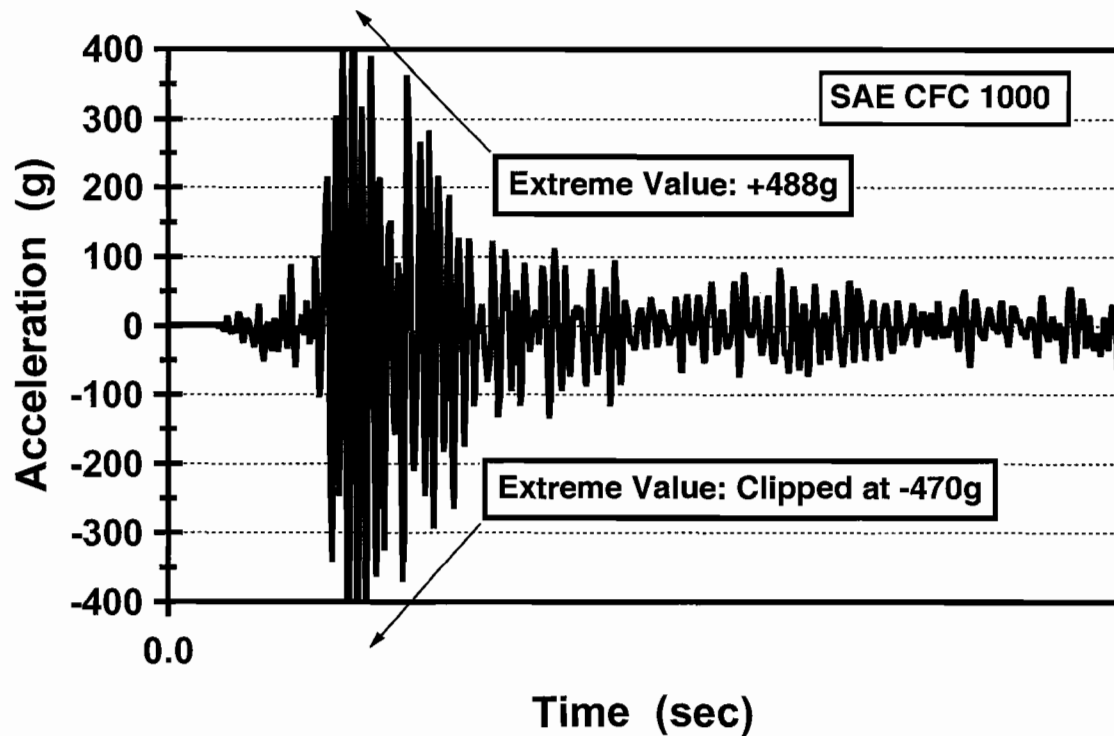


Figure 44. Accel., Lead Car, LS, Position 1, Z-Axis

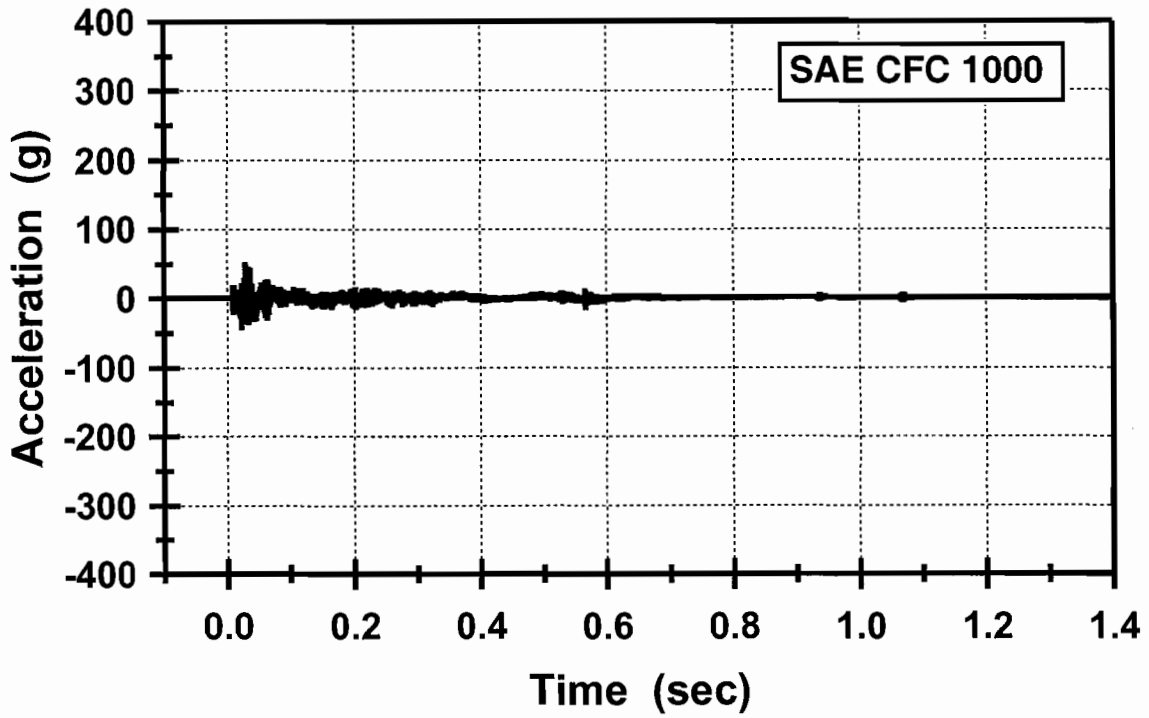


Figure 45. Accel., Lead Car, LS, Position 3, Z-Axis

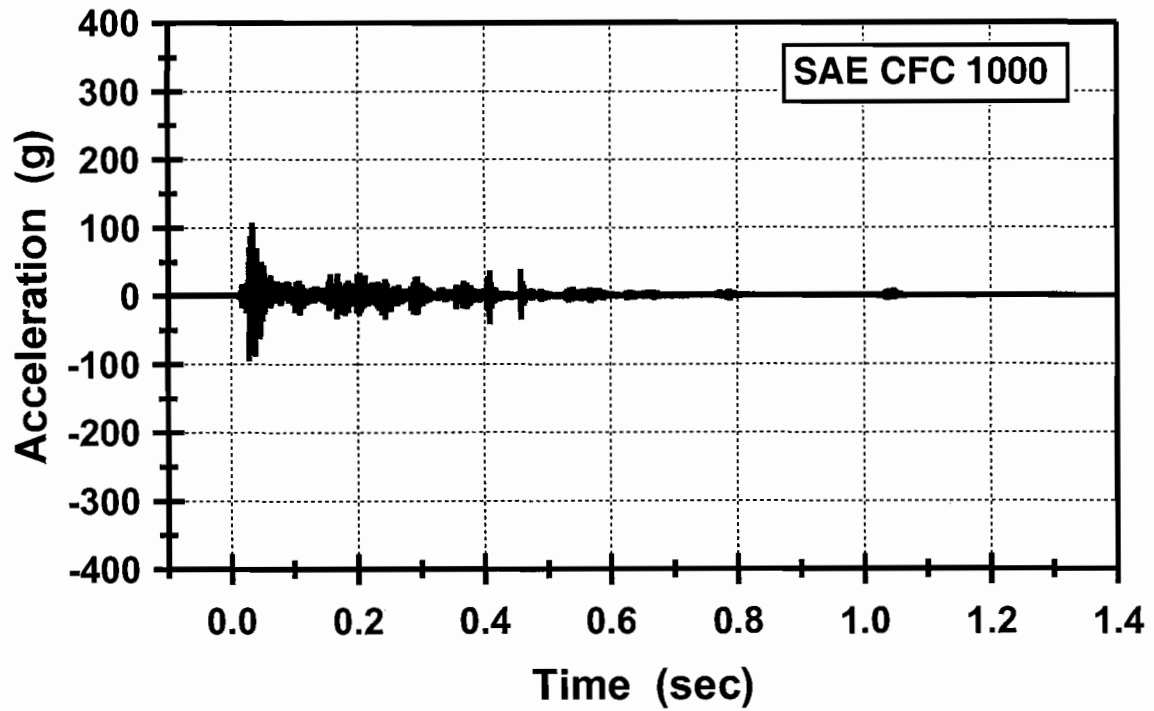


Figure 46. Accel., Lead Car, LS, Position 5, Z-Axis

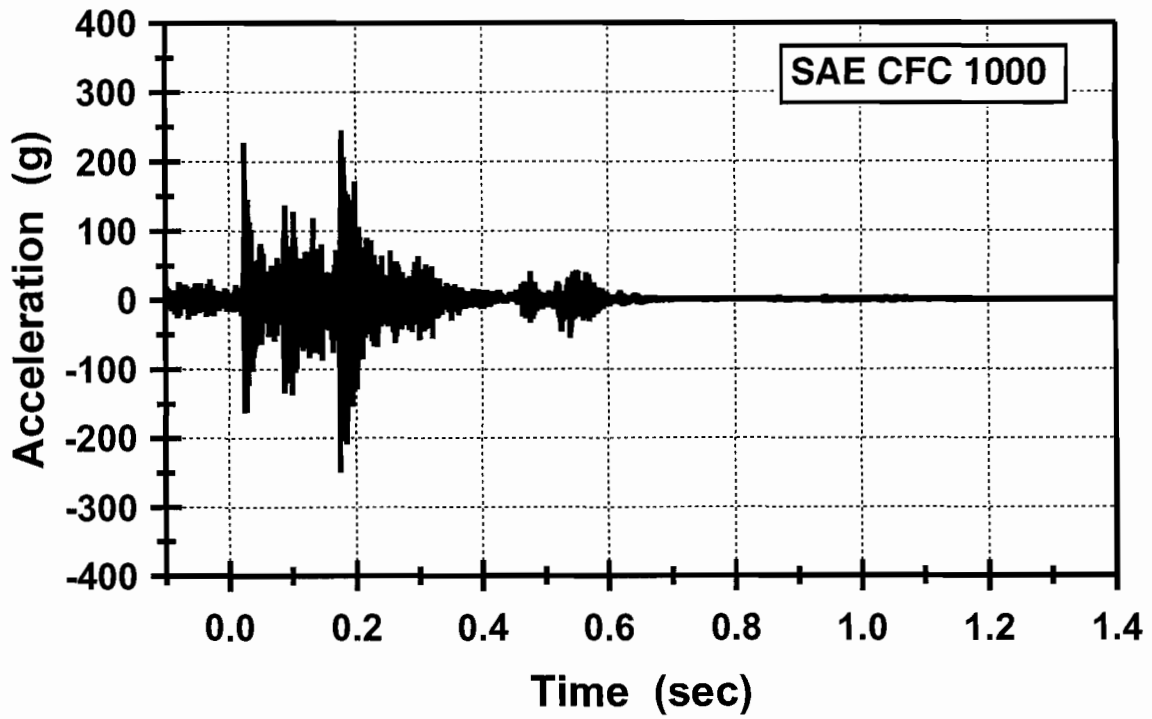


Figure 47. Accel., Lead Car, A End Bogie, Z-Axis

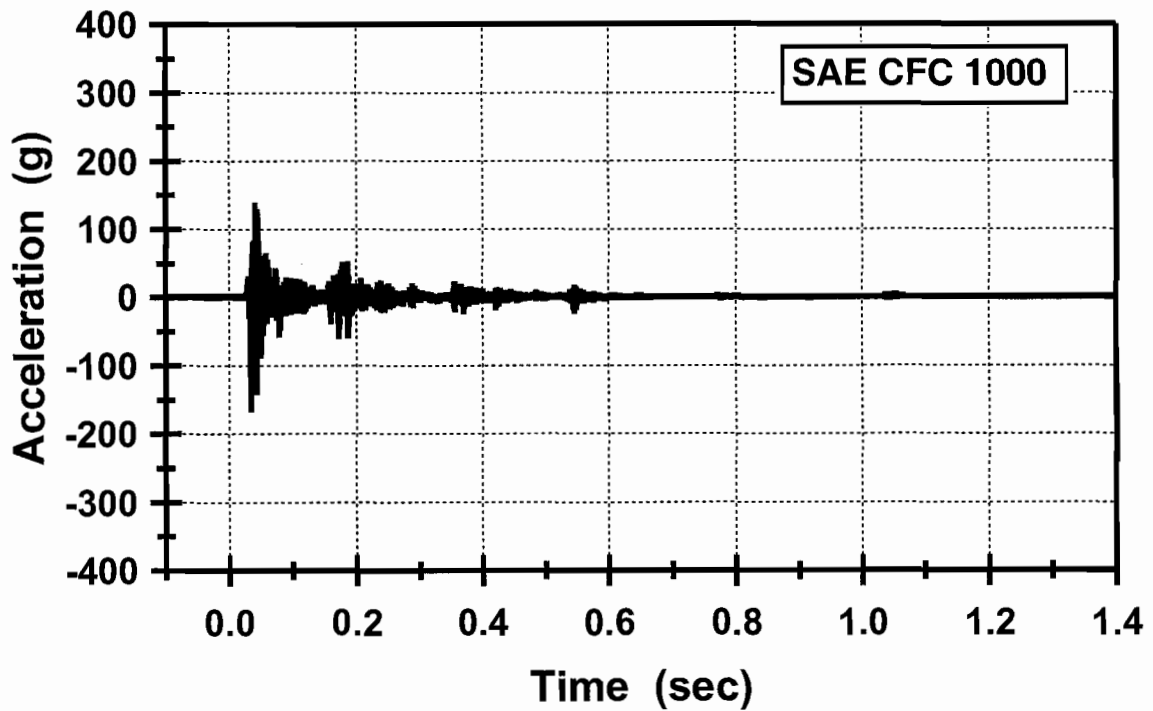


Figure 48. Accel., Lead Car, B End Bogie, Z-Axis

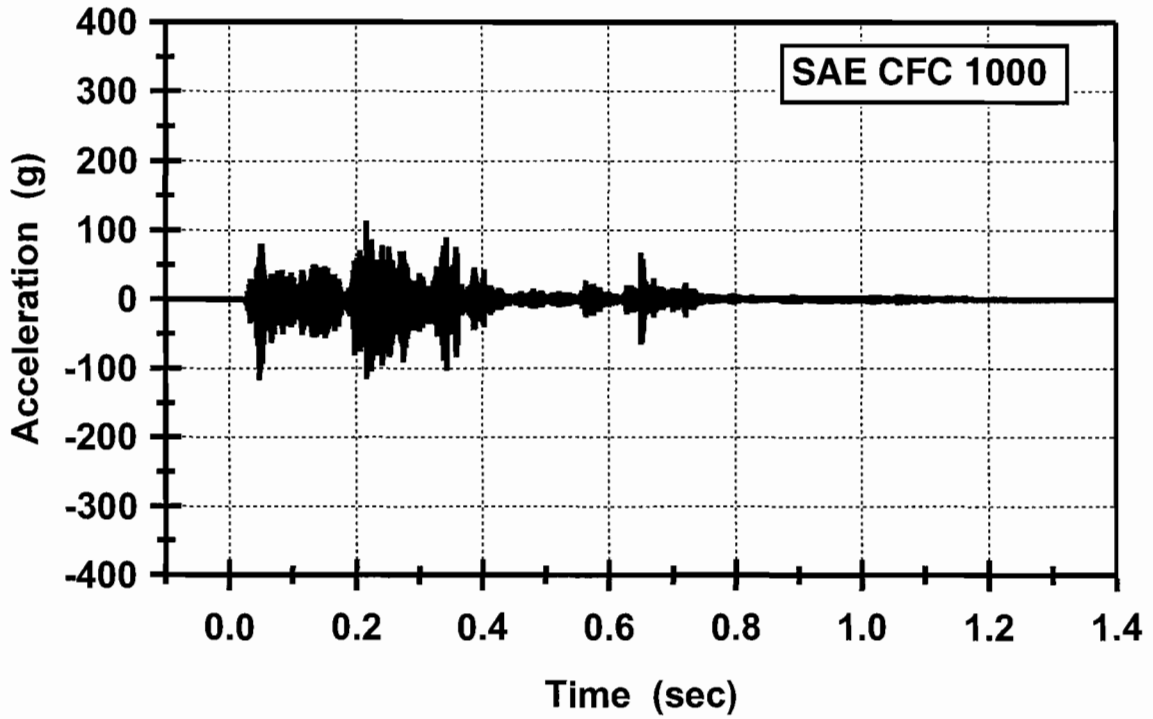


Figure 49. Accel., Trailing Car, CS, Position 1, X-Axis

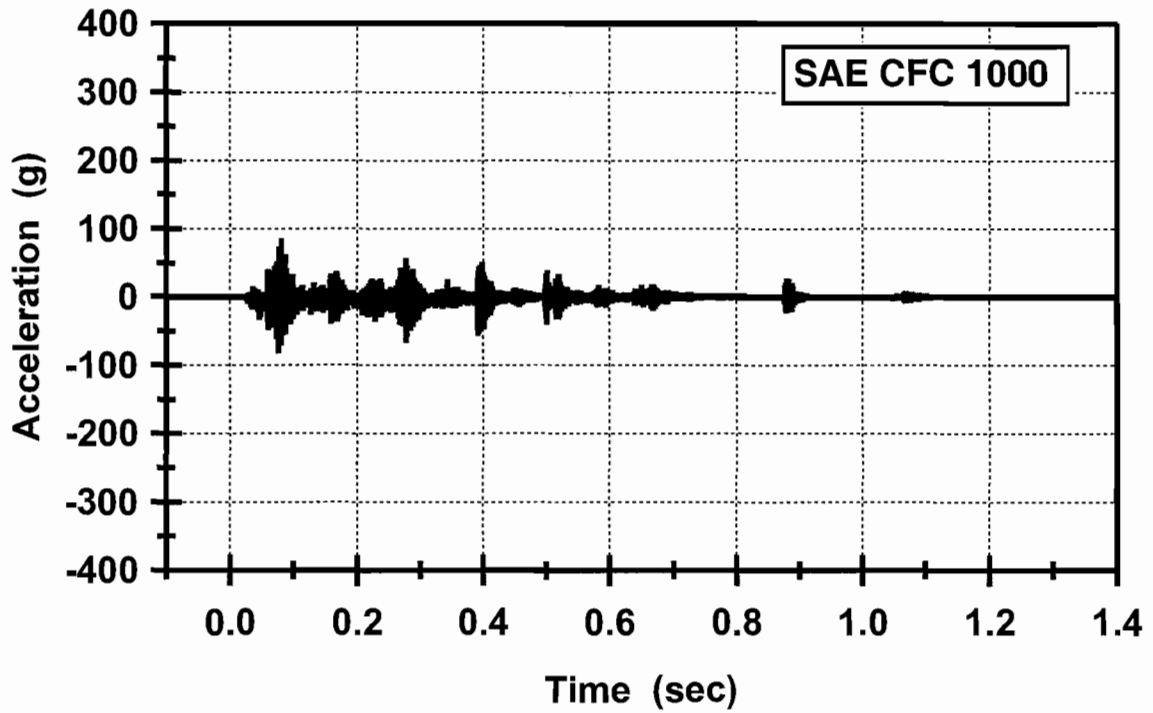


Figure 50. Accel., Trailing Car, CS, Position 2, X-Axis

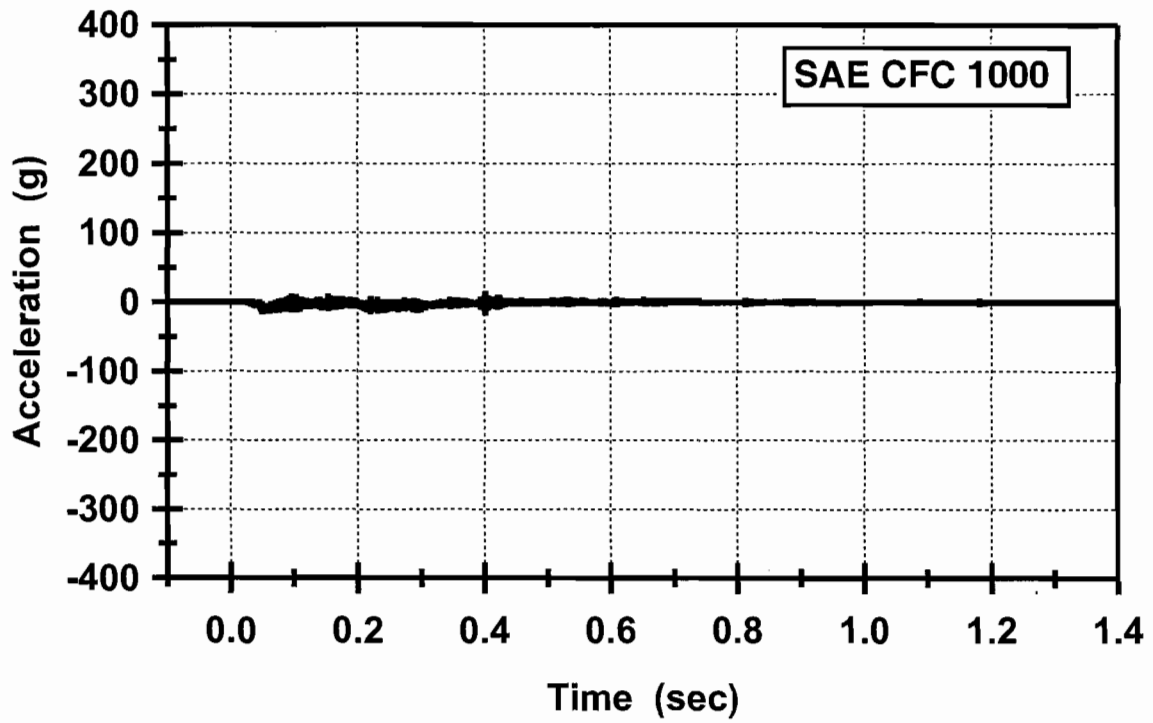


Figure 51. Accel., Trailing Car, CS, Position 3, X-Axis

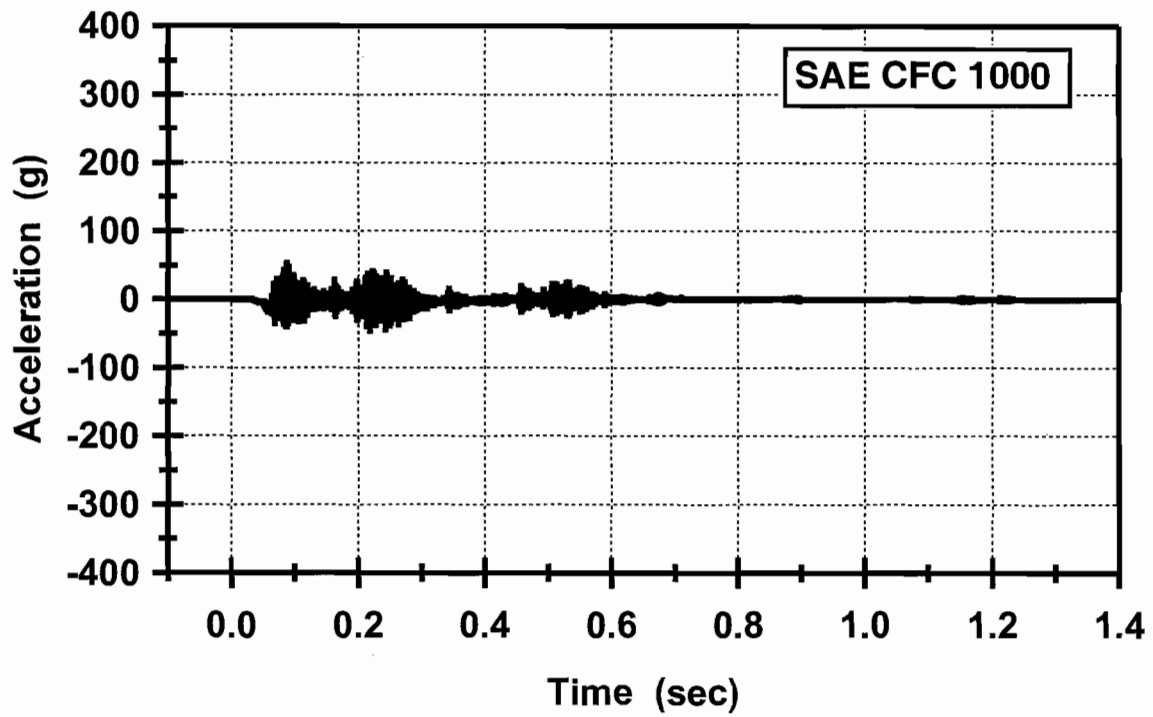


Figure 52. Accel., Trailing Car, CS, Position 4, X-Axis

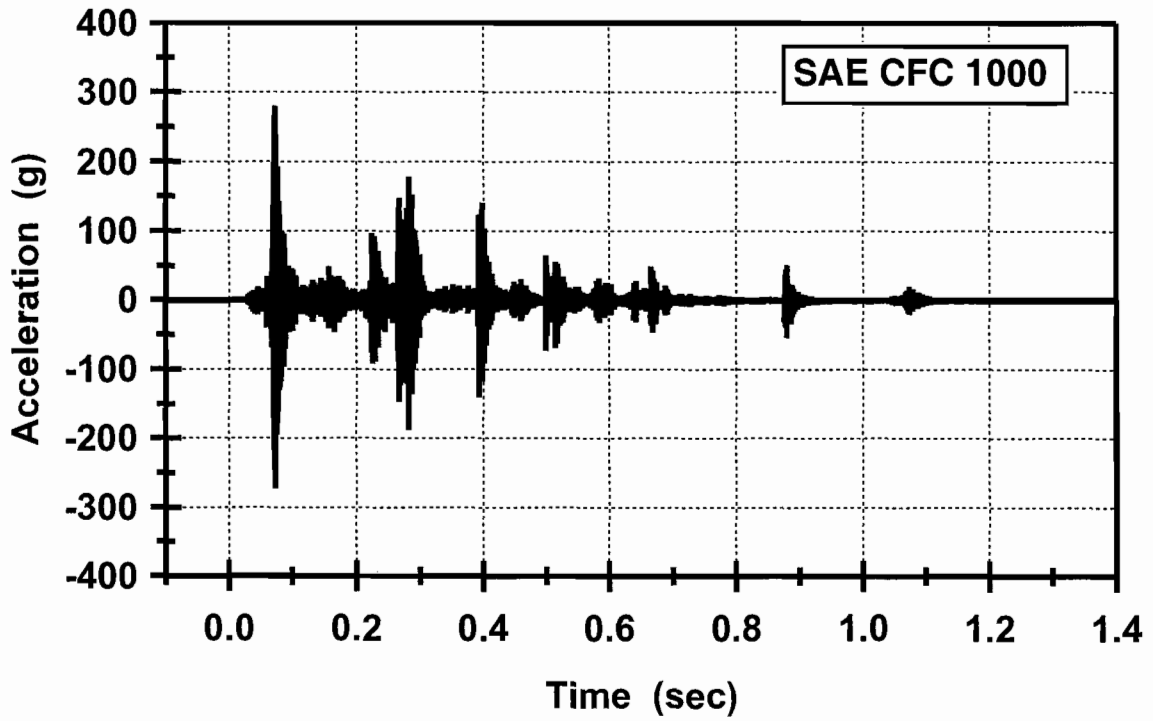


Figure 53. Accel., Trailing Car, CS, Position 2, Y-Axis

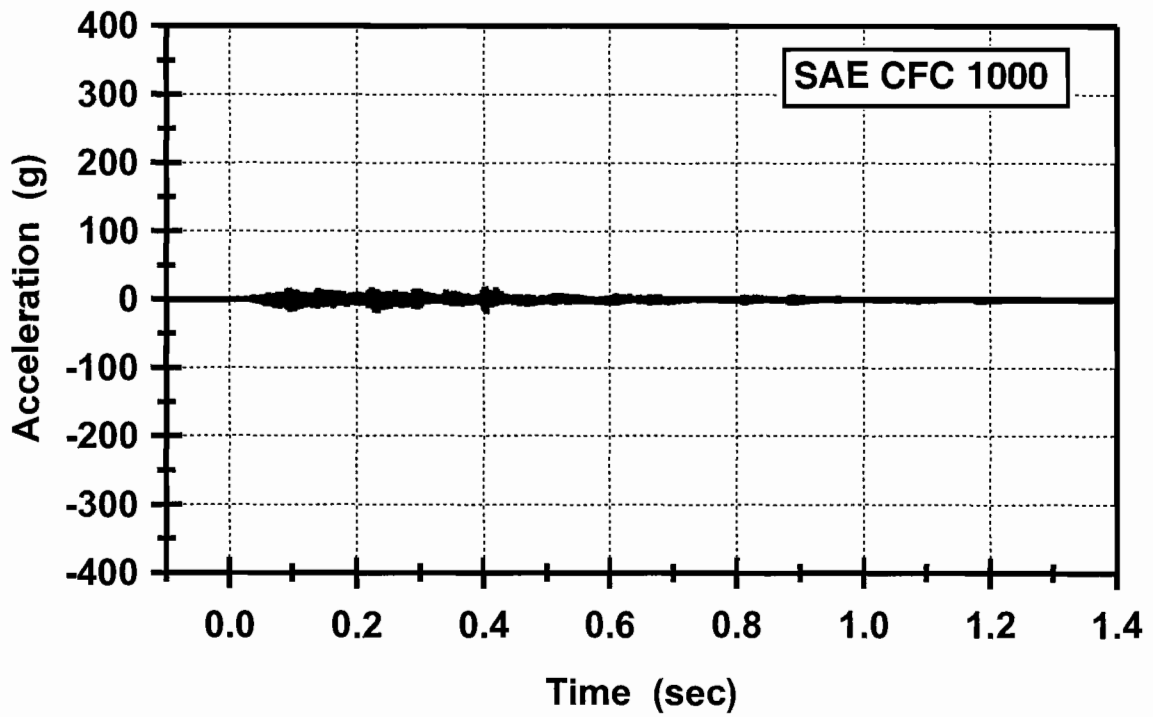


Figure 54. Accel., Trailing Car, CS, Position 3, Y-Axis

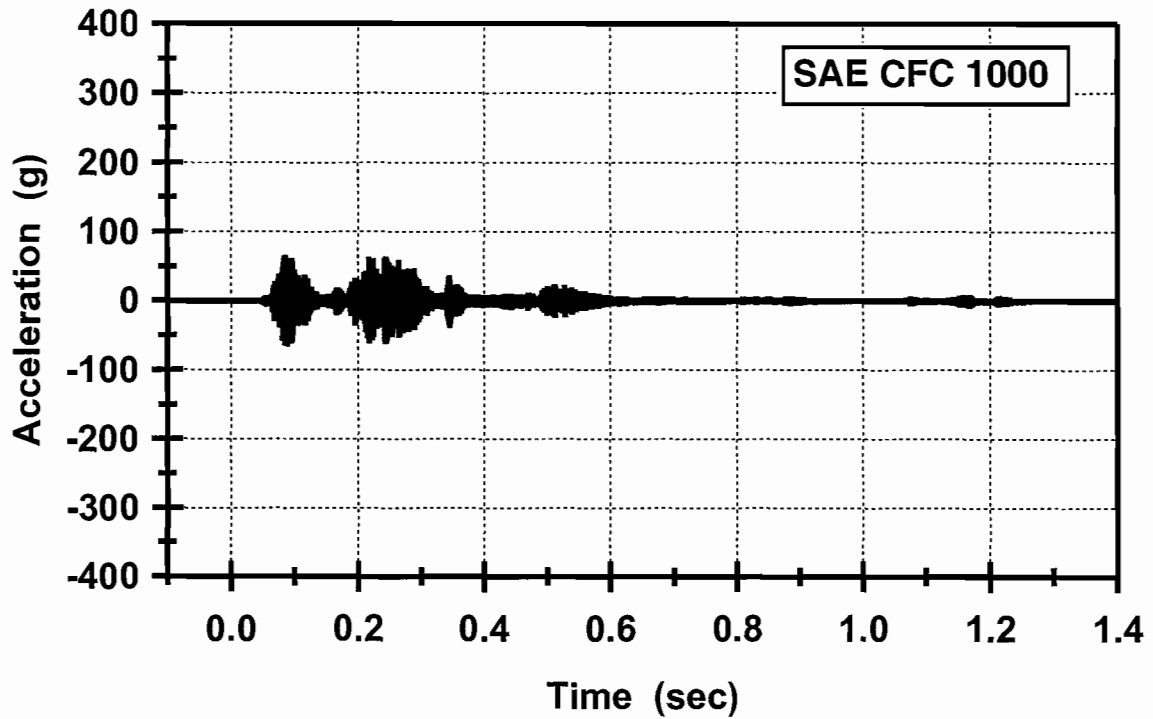


Figure 55. Accel., Trailing Car, CS, Position 4, Y-Axis

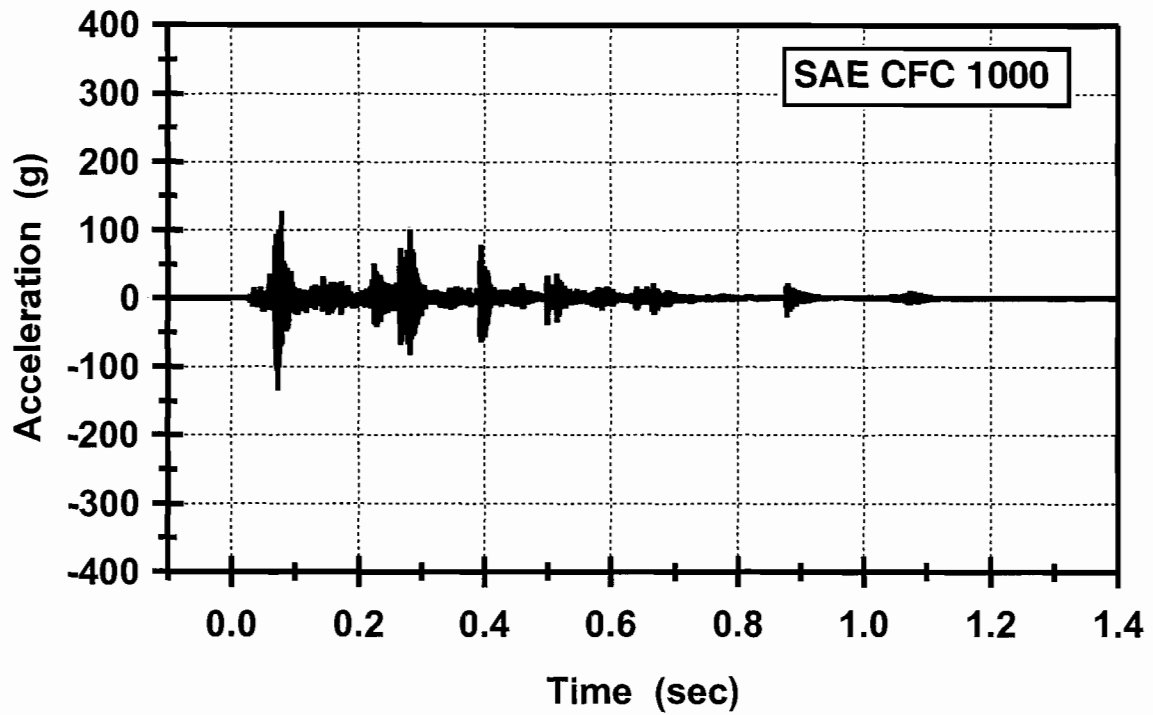


Figure 56. Accel., Trailing Car, CS, Position 2, Z-Axis

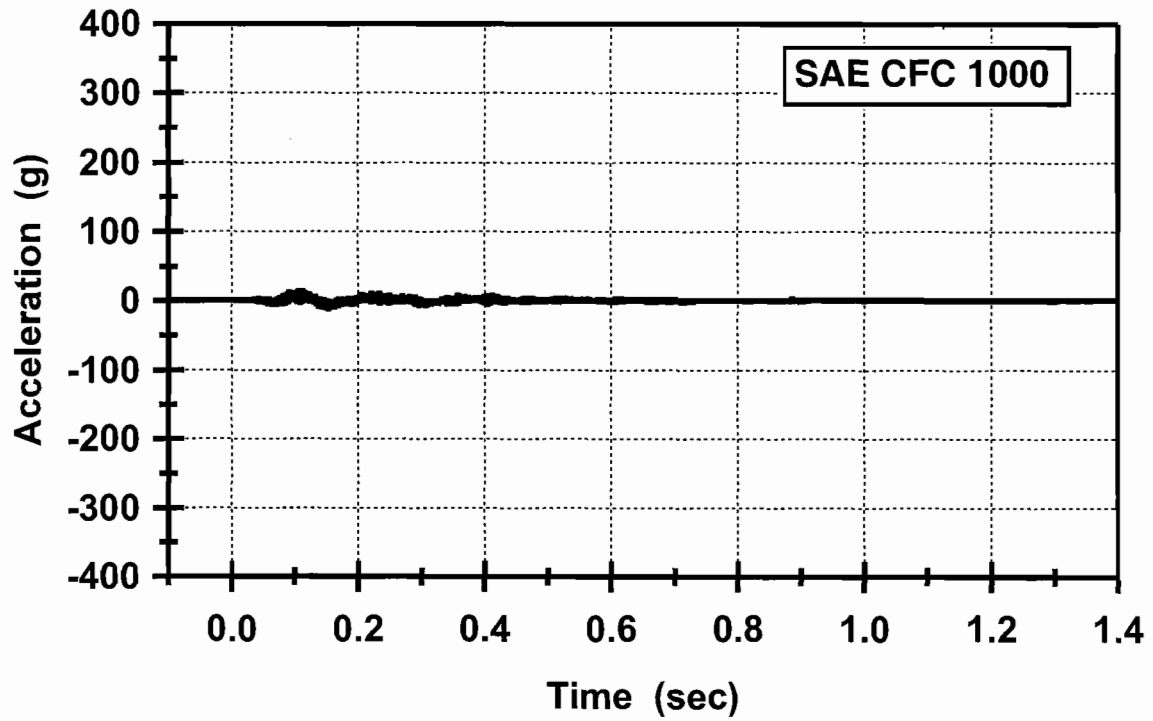


Figure 57. Accel., Trailing Car, CS, Position 3, Z-Axis

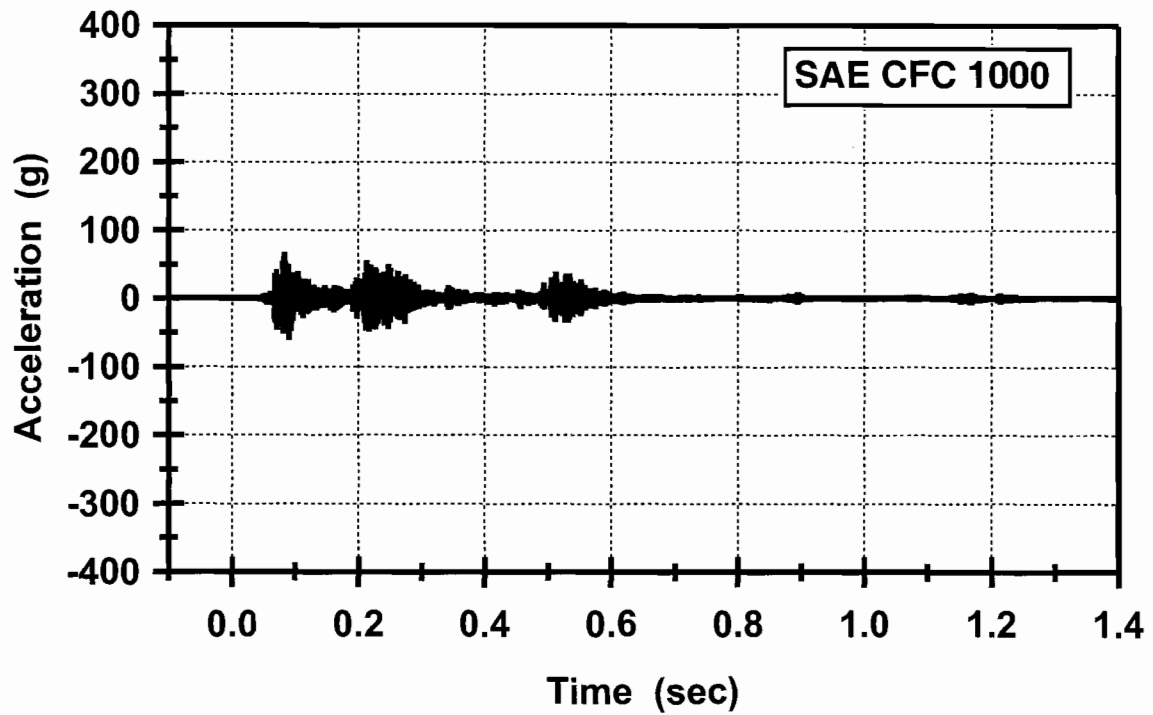


Figure 58. Accel., Trailing Car, CS, Position 4, Z-Axis

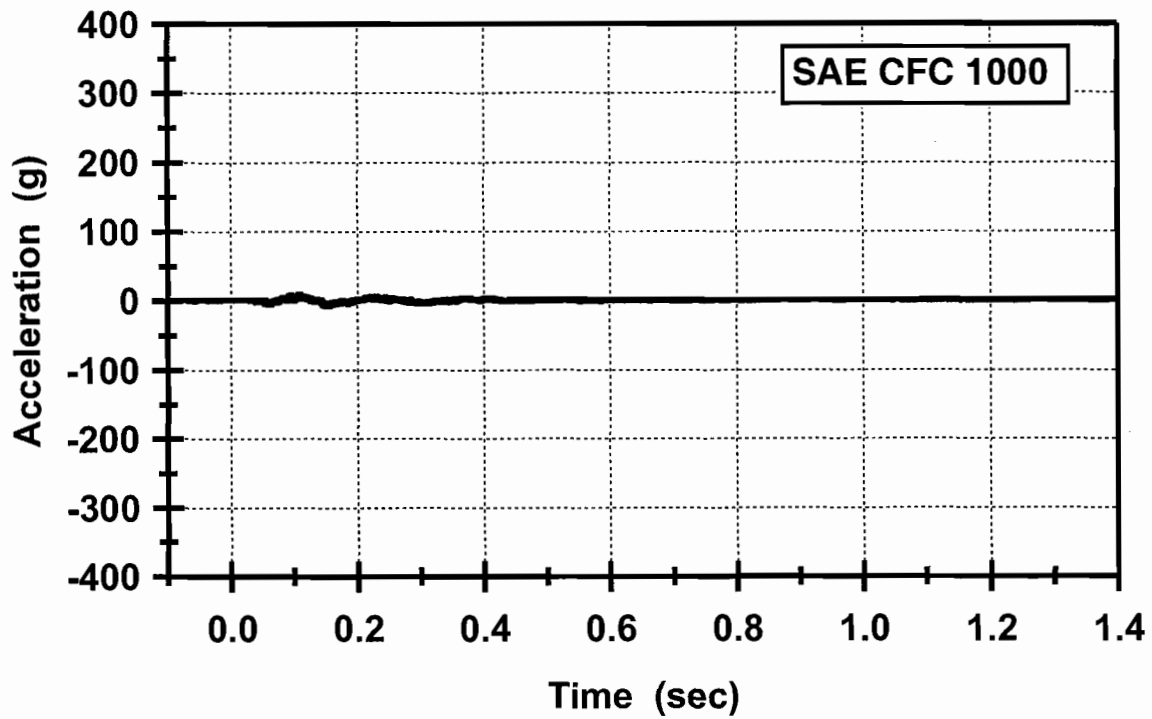


Figure 59. Accel., Trailing Car, RS, Position 3, Z-Axis

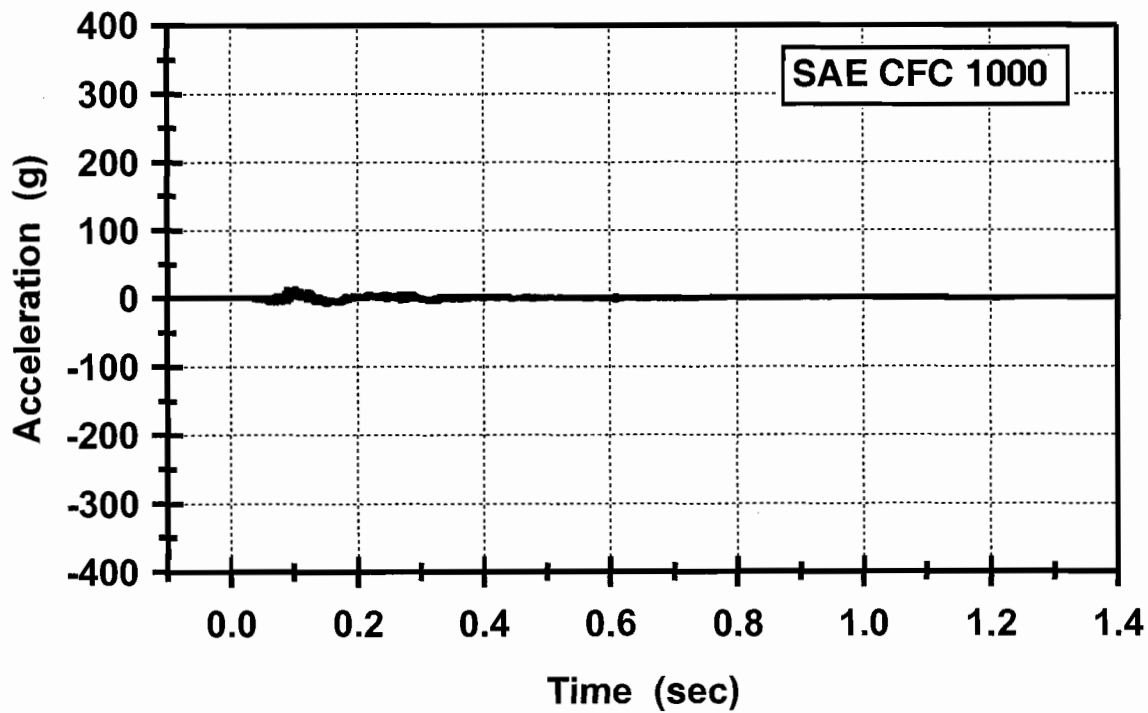


Figure 60. Accel., Trailing Car, LS, Position 3, Z-Axis

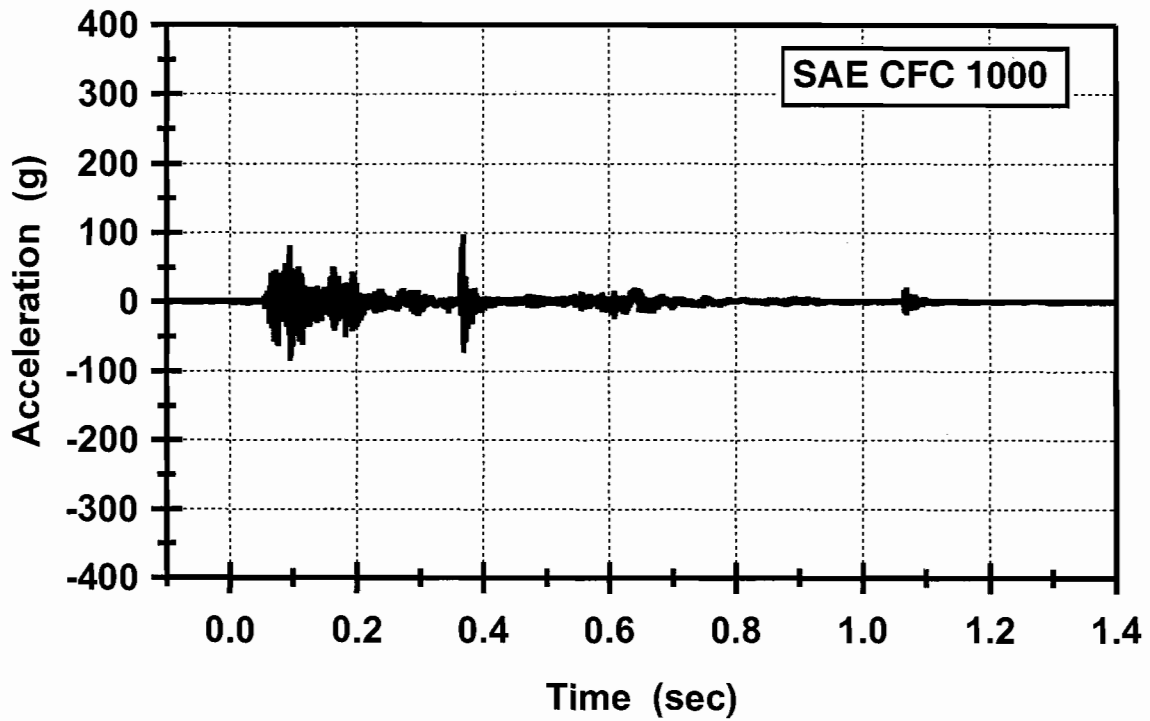


Figure 61. Accel., Trailing Car, A End Bogie, Z-Axis

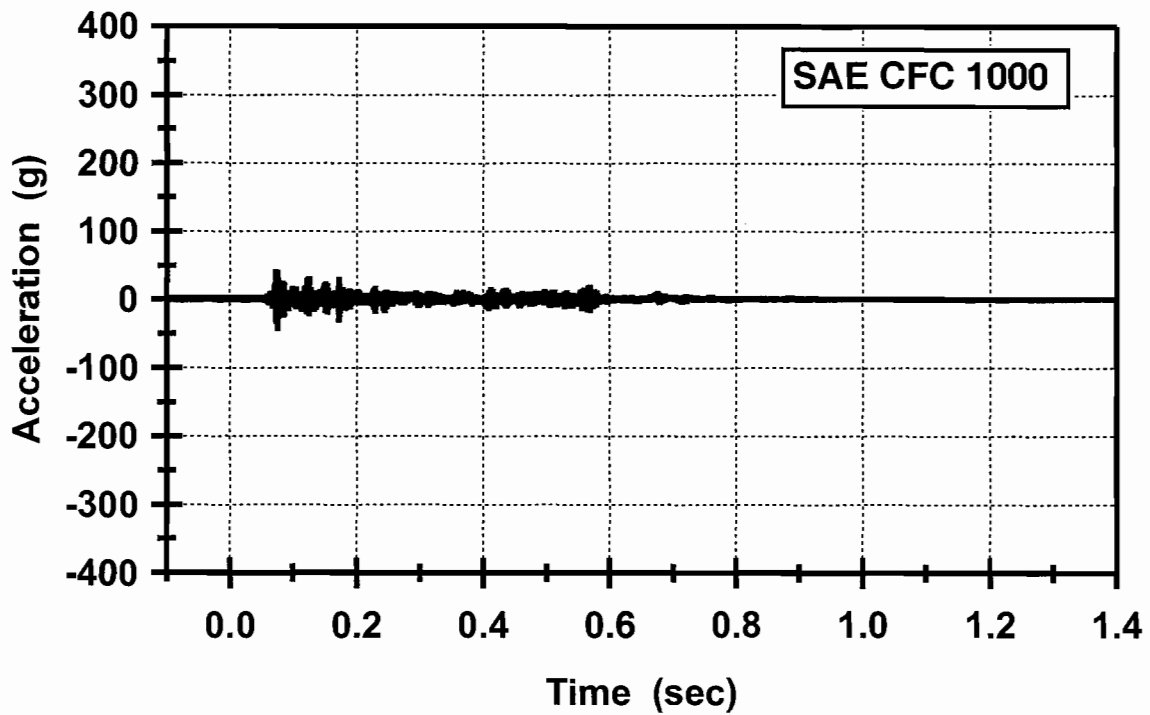


Figure 62. Accel., Trailing Car, B End Bogie, Z-Axis

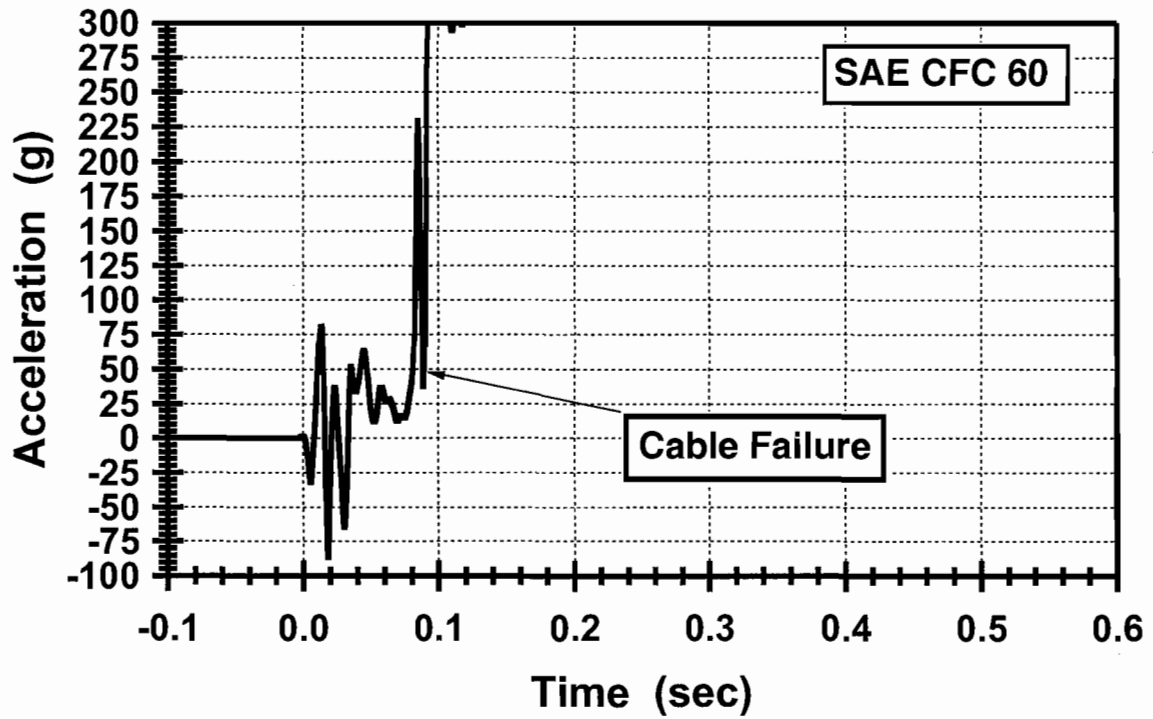


Figure 63. Accel., Lead Car, CS, Position 1, X-Axis

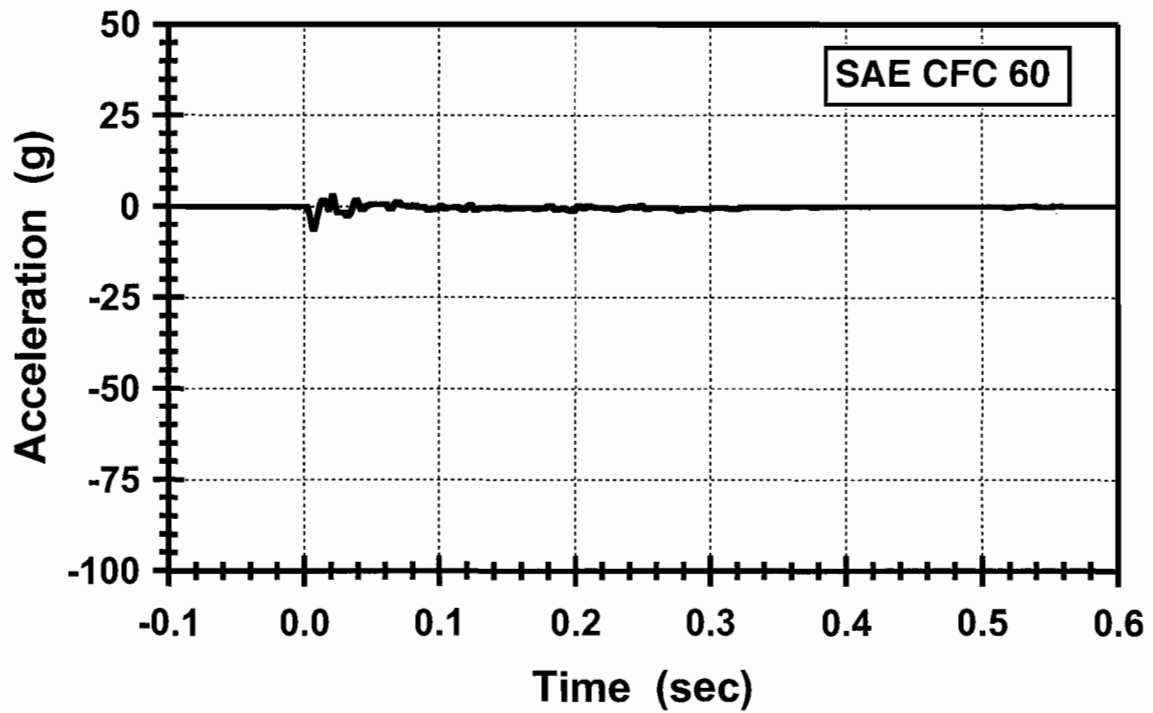


Figure 64. Accel., Lead Car, CS, Position 2, X-Axis

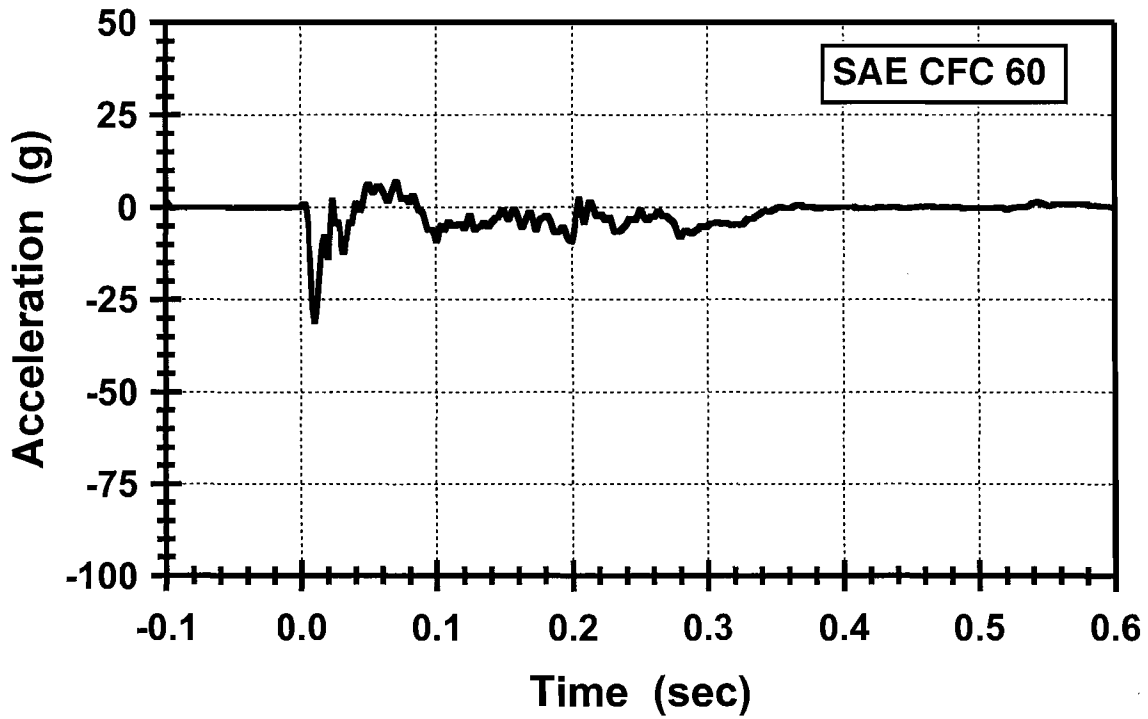


Figure 65. Accel., Lead Car, CS, Position 3, X-Axis

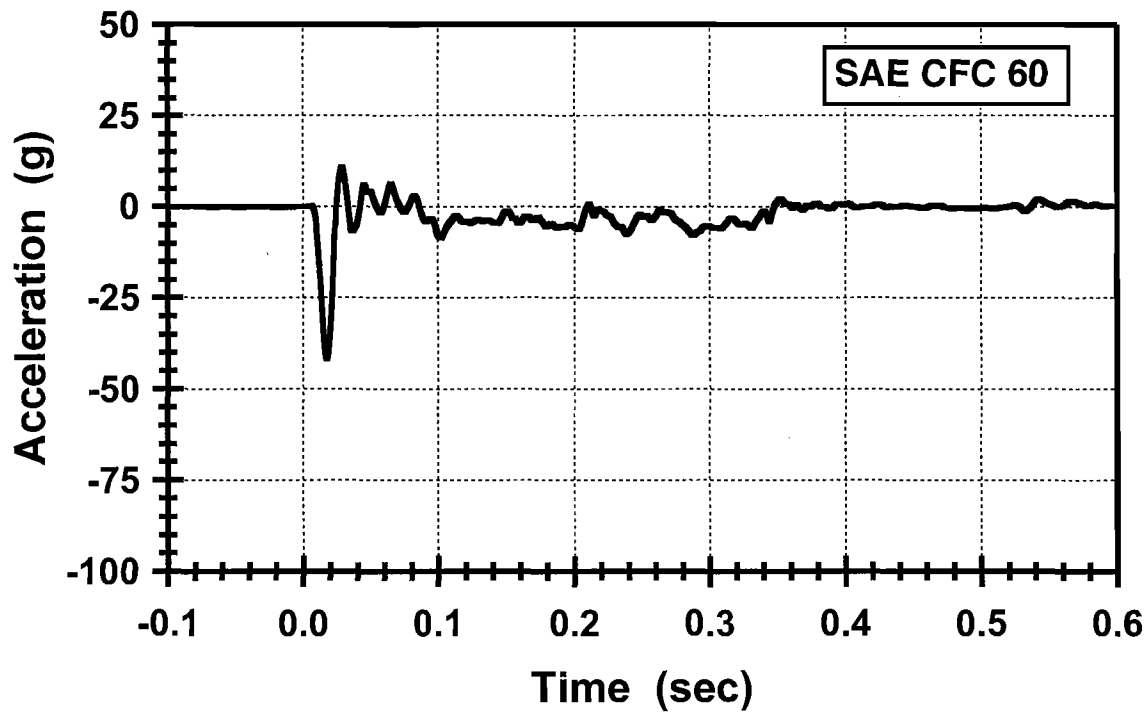


Figure 66. Accel., Lead Car, CS, Position 4, X-Axis

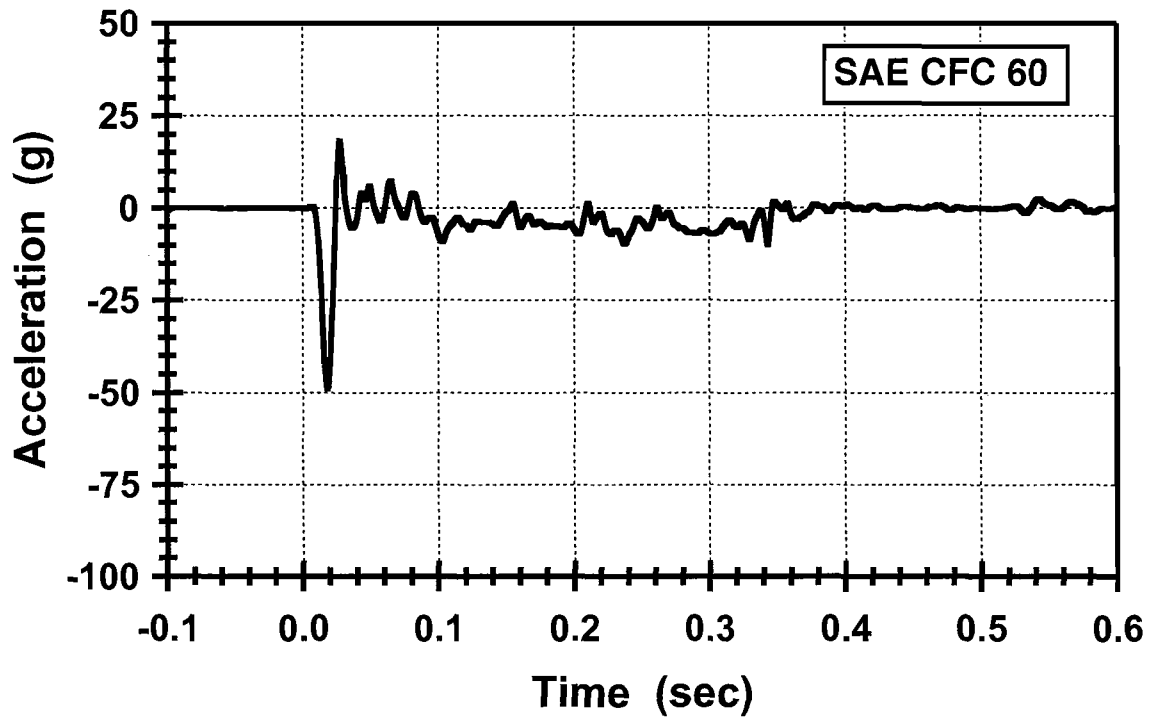


Figure 67. Accel., Lead Car, CS, Position 5, X-Axis

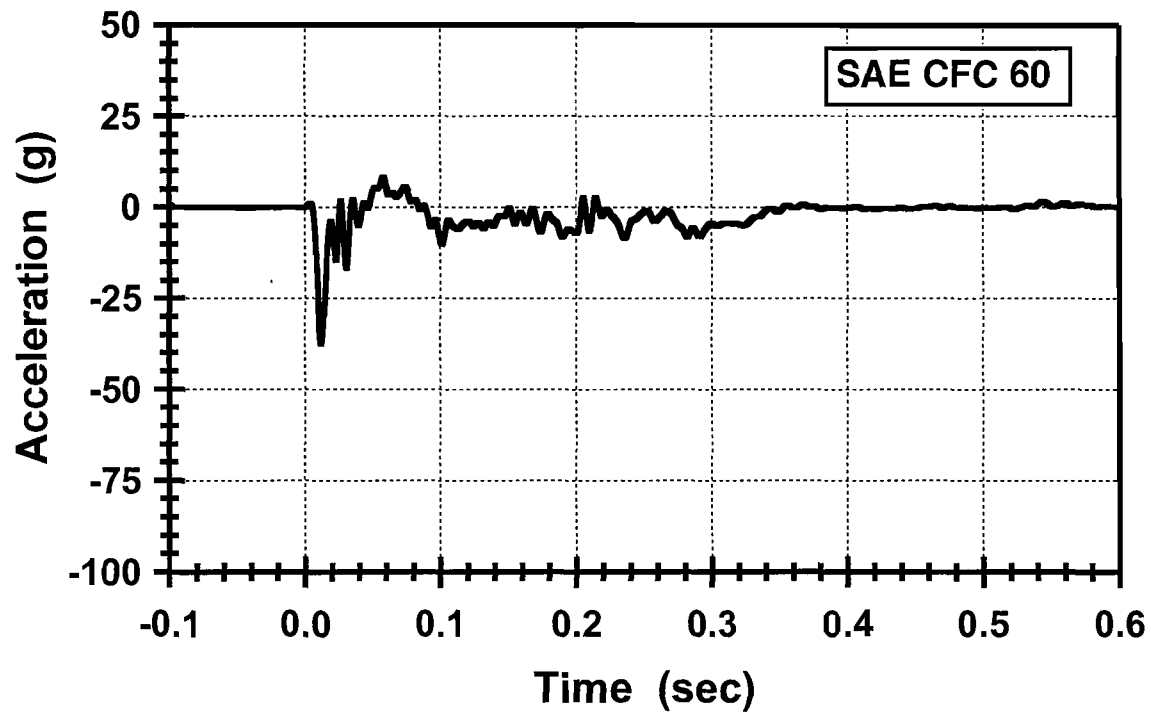


Figure 68. Accel., Lead Car, RS, Position 3, X-Axis

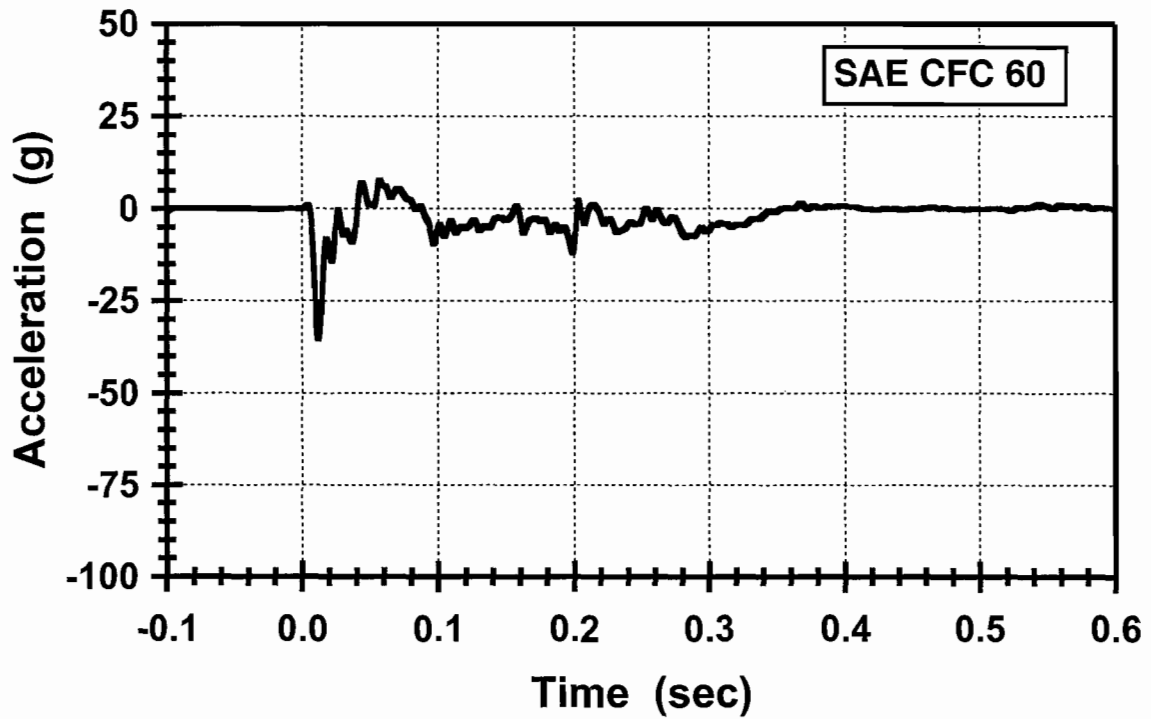


Figure 69. Accel., Lead Car, LS, Position 3, X-Axis

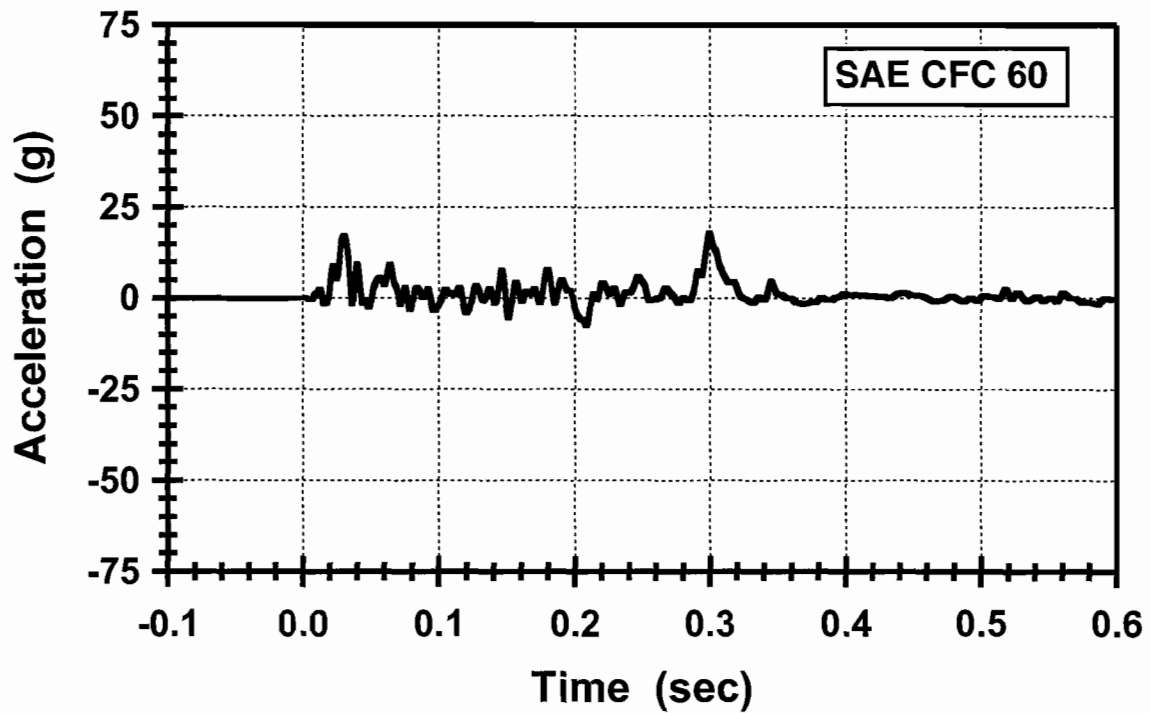


Figure 70. Accel., Lead Car, CS, Position 2, Y-Axis

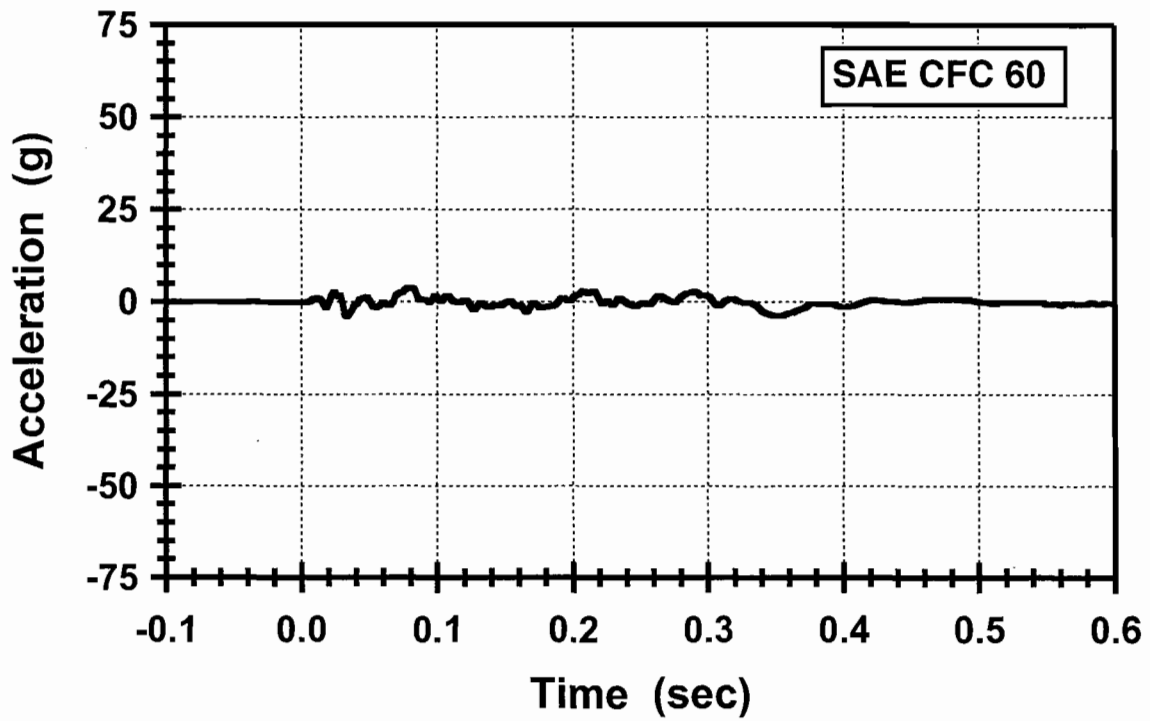


Figure 71. Accel., Lead Car, CS, Position 3, Y-Axis

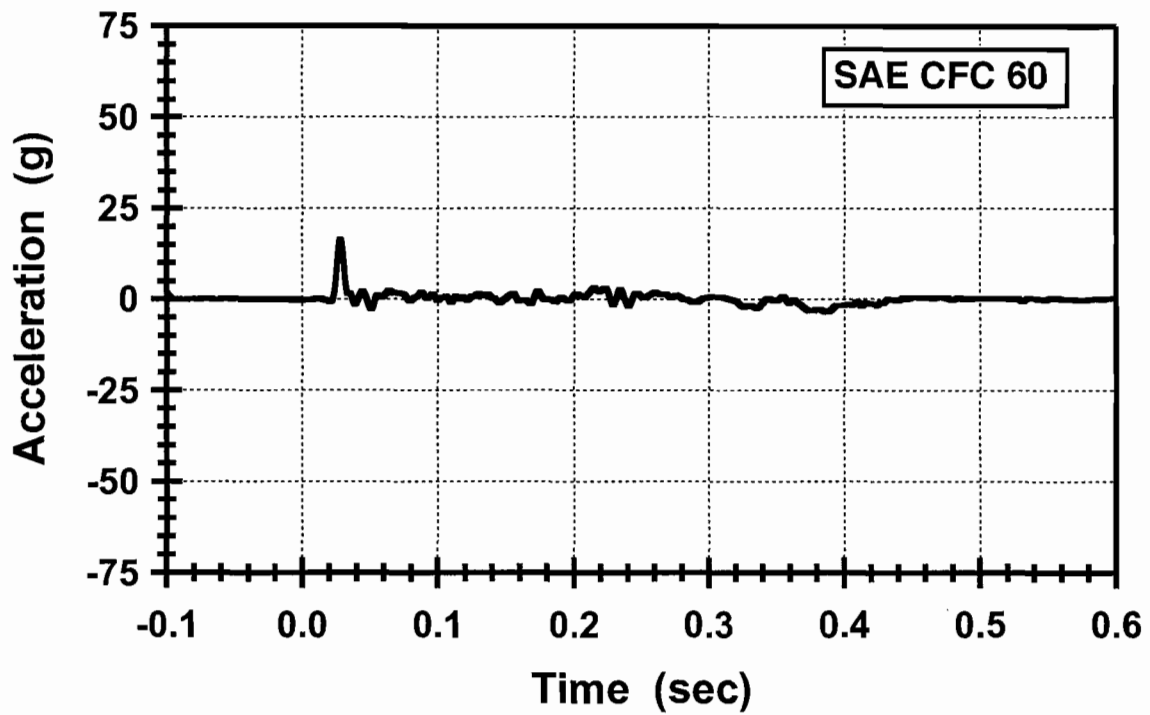


Figure 72. Accel., Lead Car, CS, Position 4, Y-Axis

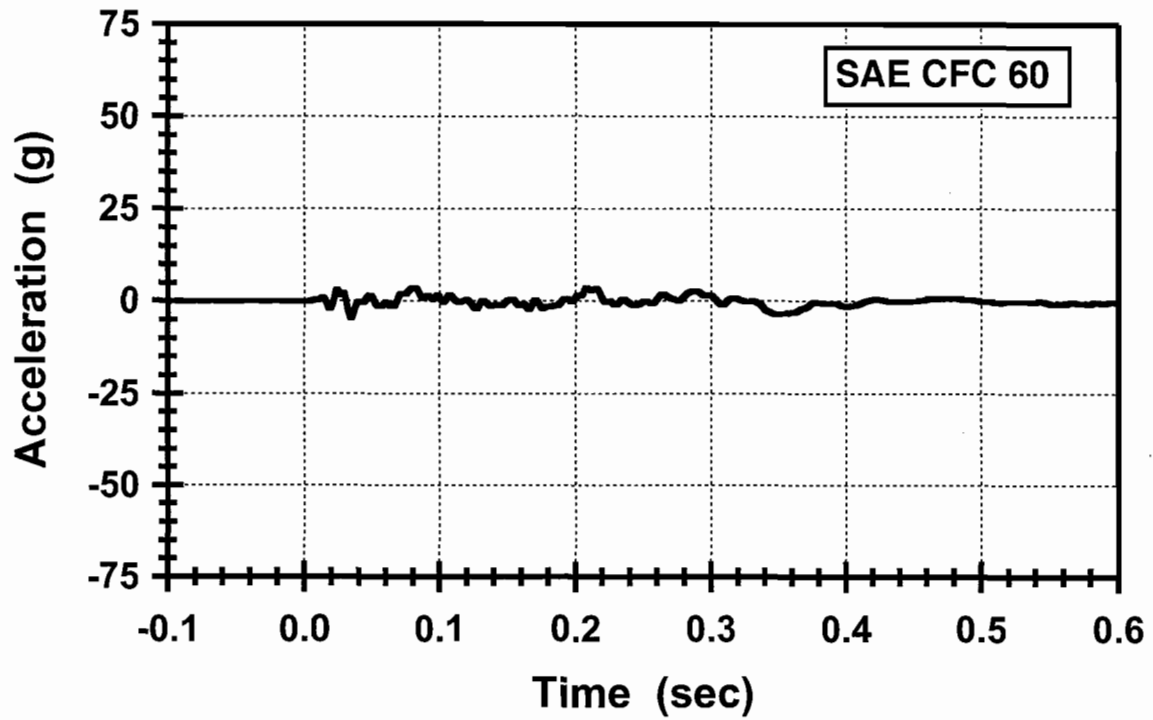


Figure 73. Accel., Lead Car, RS, Position 3, Y-Axis

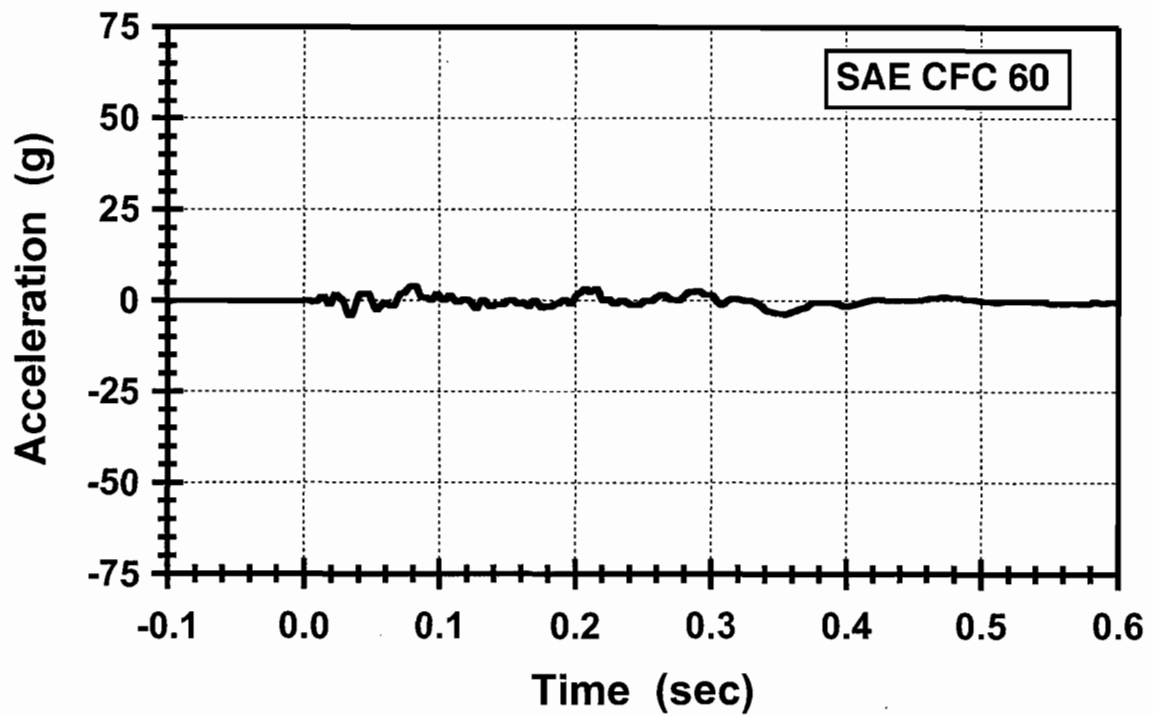


Figure 74. Accel., Lead Car, LS, Position 3, Y-Axis

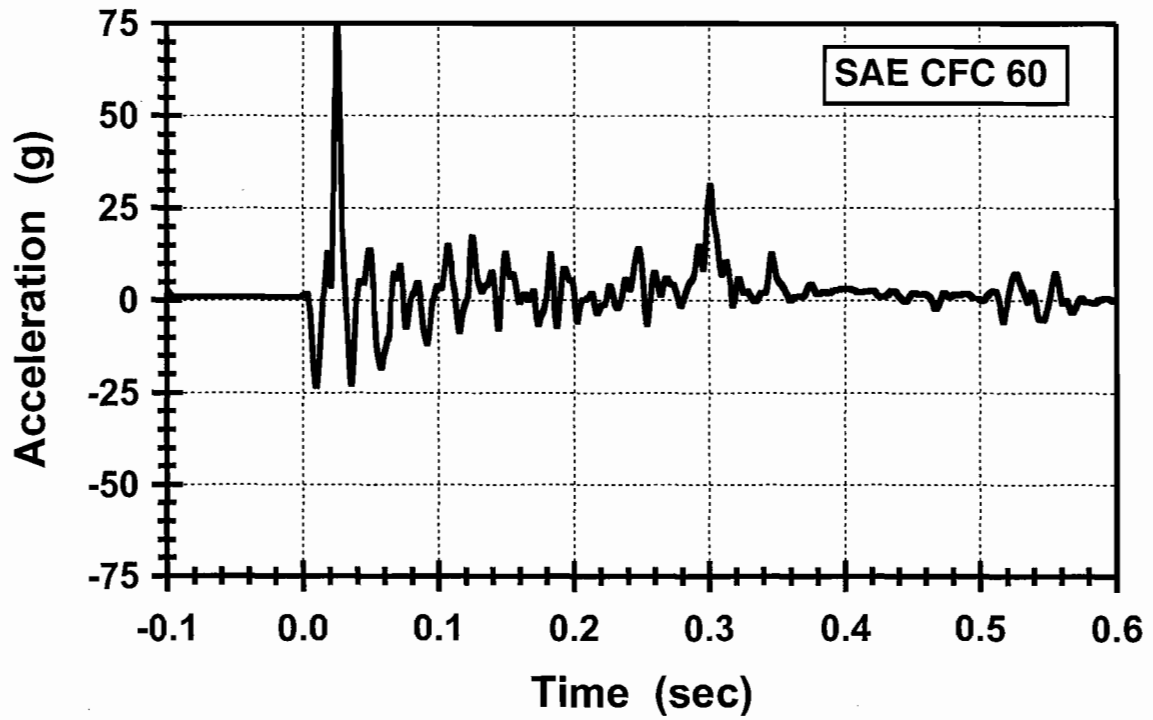


Figure 75. Accel., Lead Car, CS, Position 2, Z-Axis

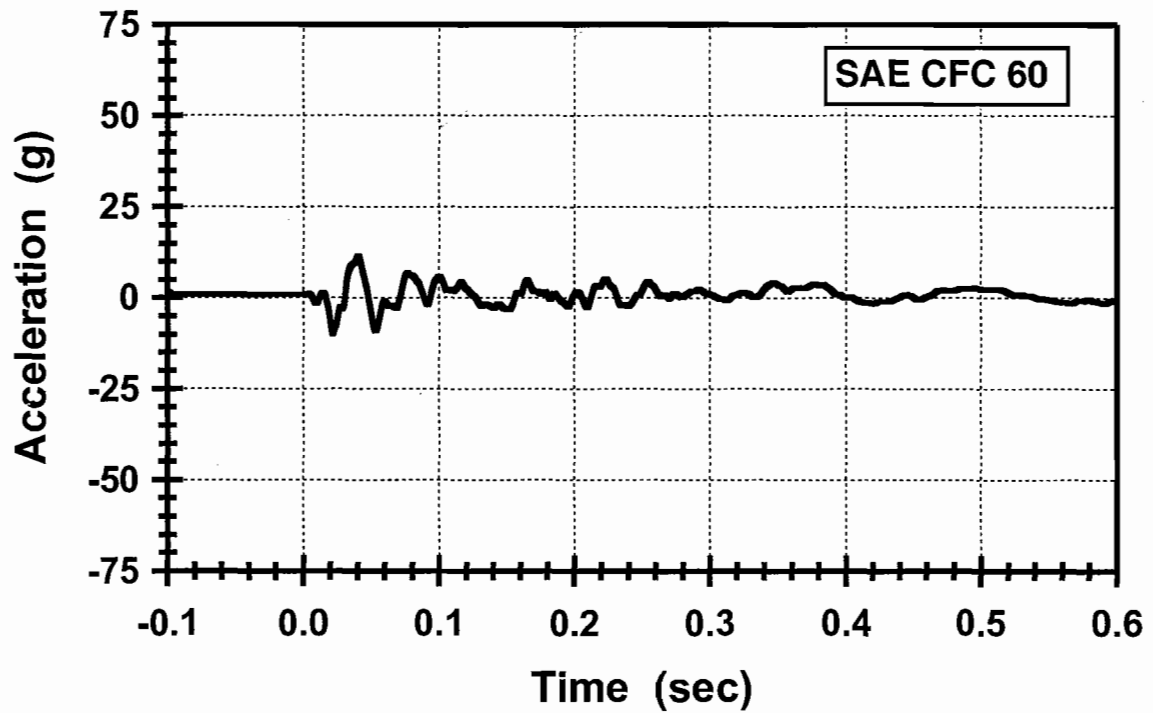


Figure 76. Accel., Lead Car, CS, Position 3, Z-Axis

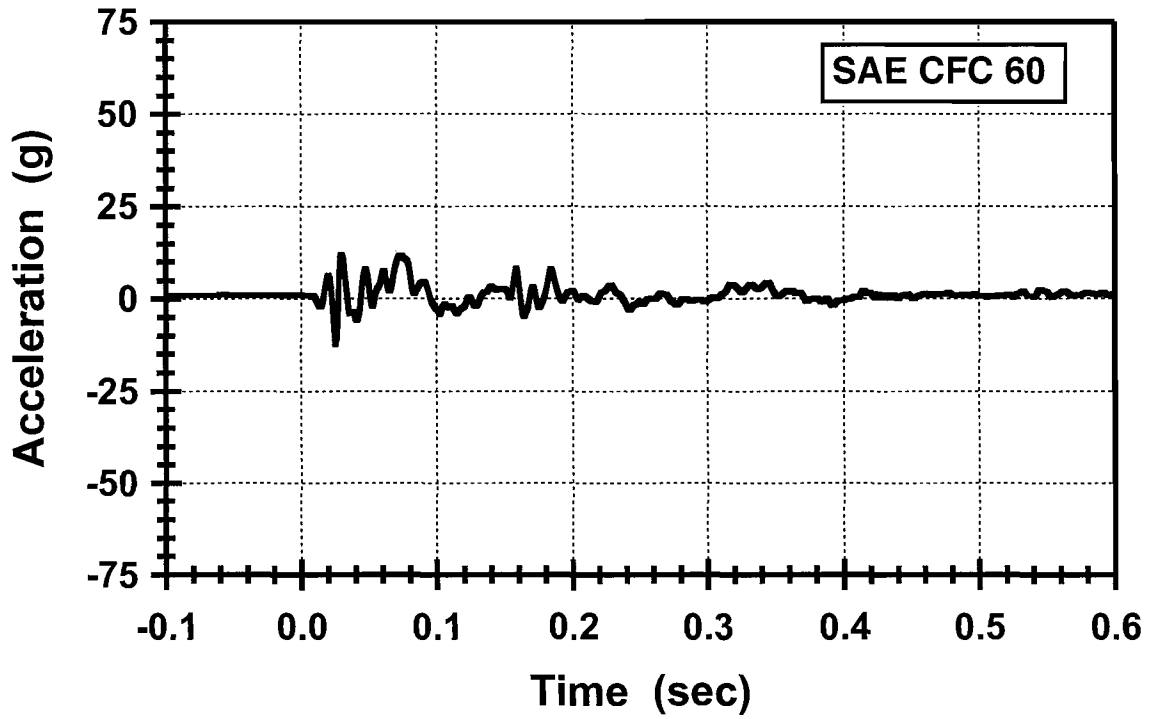


Figure 77. Accel., Lead Car, CS, Position 4, Z-Axis

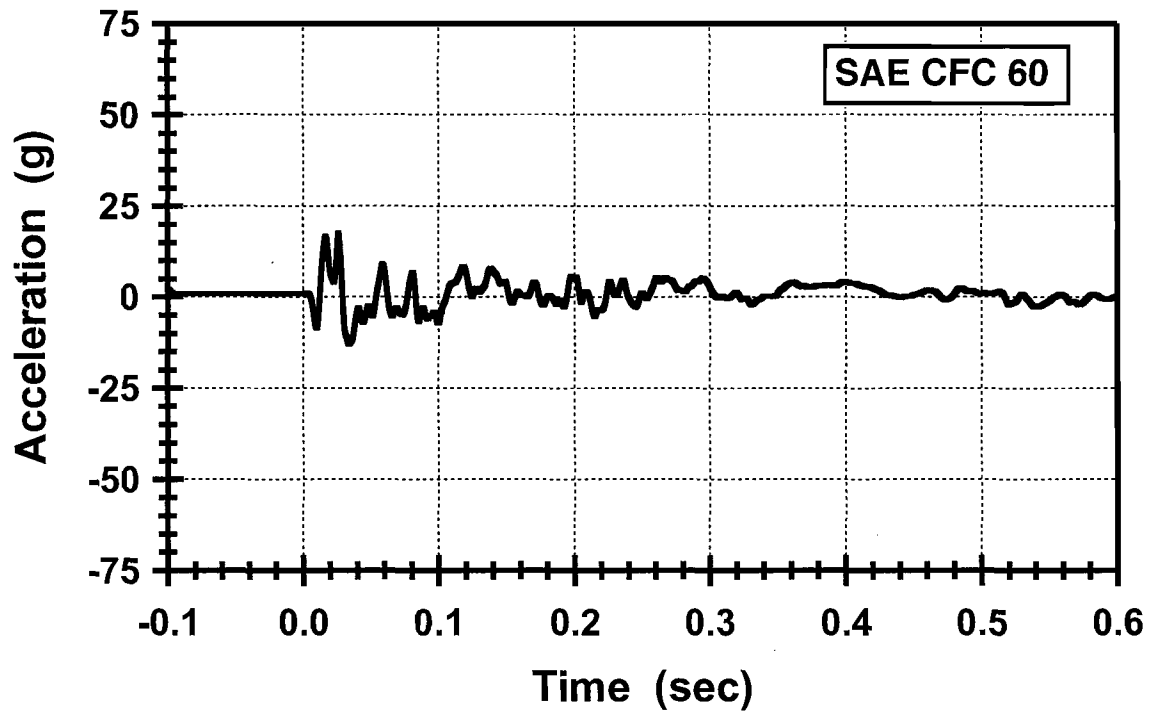


Figure 78. Accel., Lead Car, RS, Position 1, Z-Axis

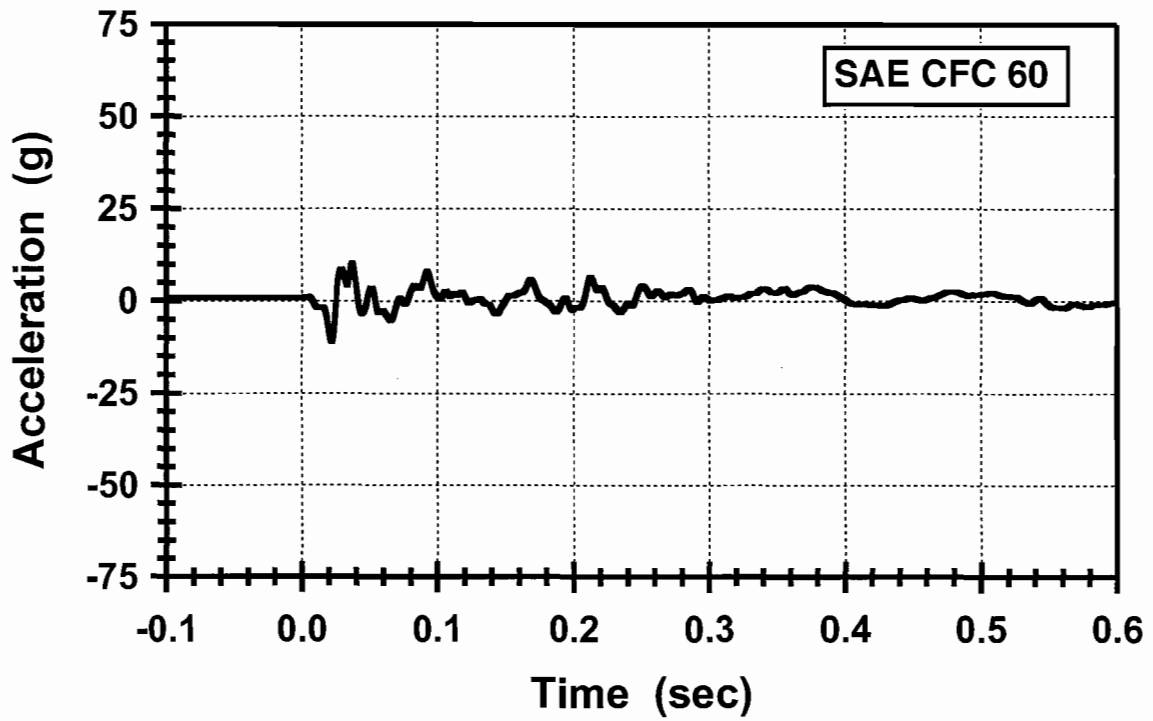


Figure 79. Accel., Lead Car, RS, Position 3, Z-Axis

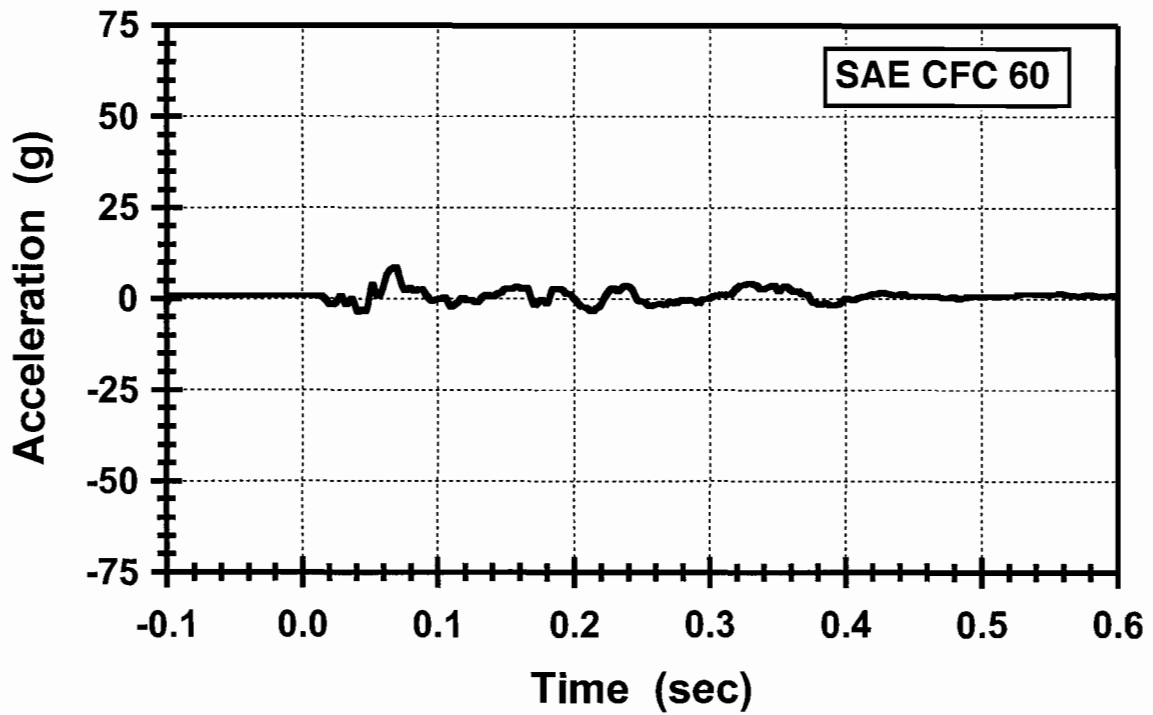


Figure 80. Accel., Lead Car, RS, Position 5, Z-Axis

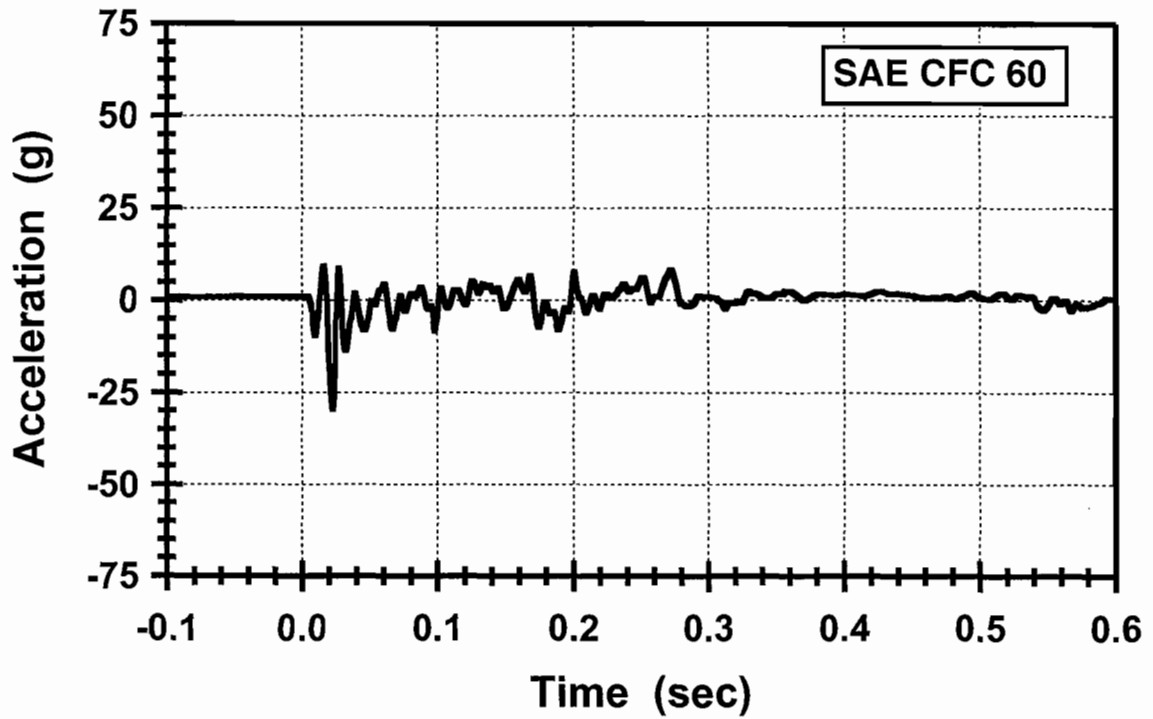


Figure 81. Accel., Lead Car, LS, Position 1, Z-Axis

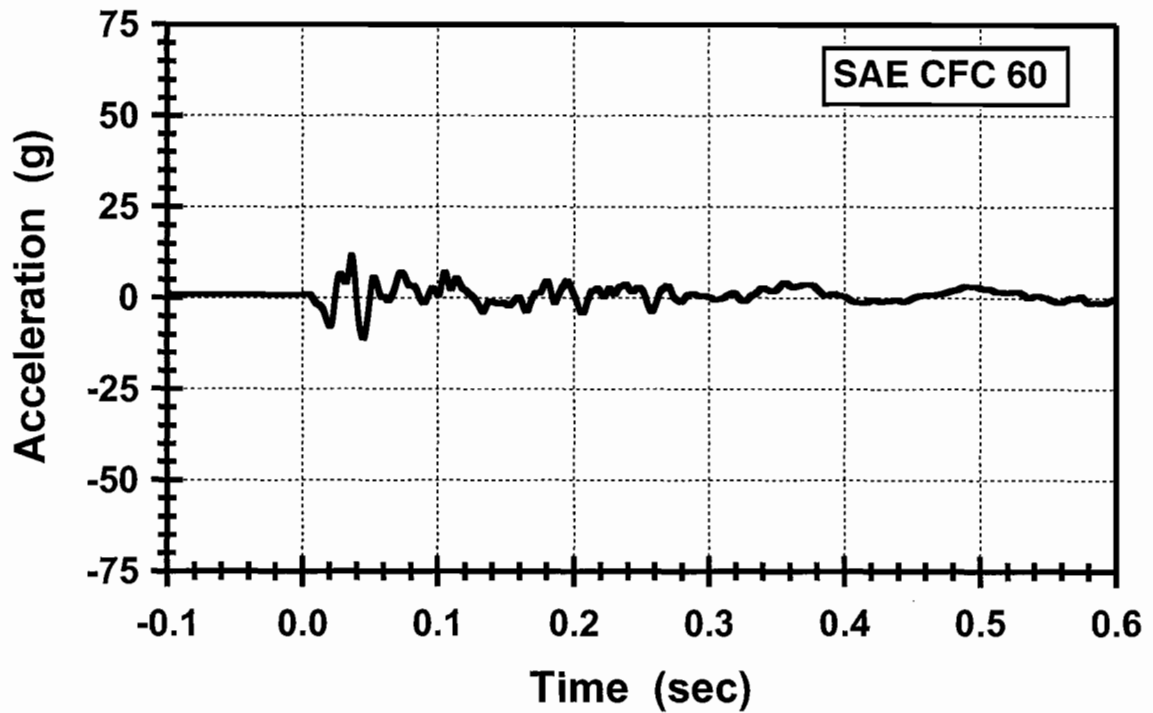


Figure 82. Accel., Lead Car, LS, Position 3, Z-Axis

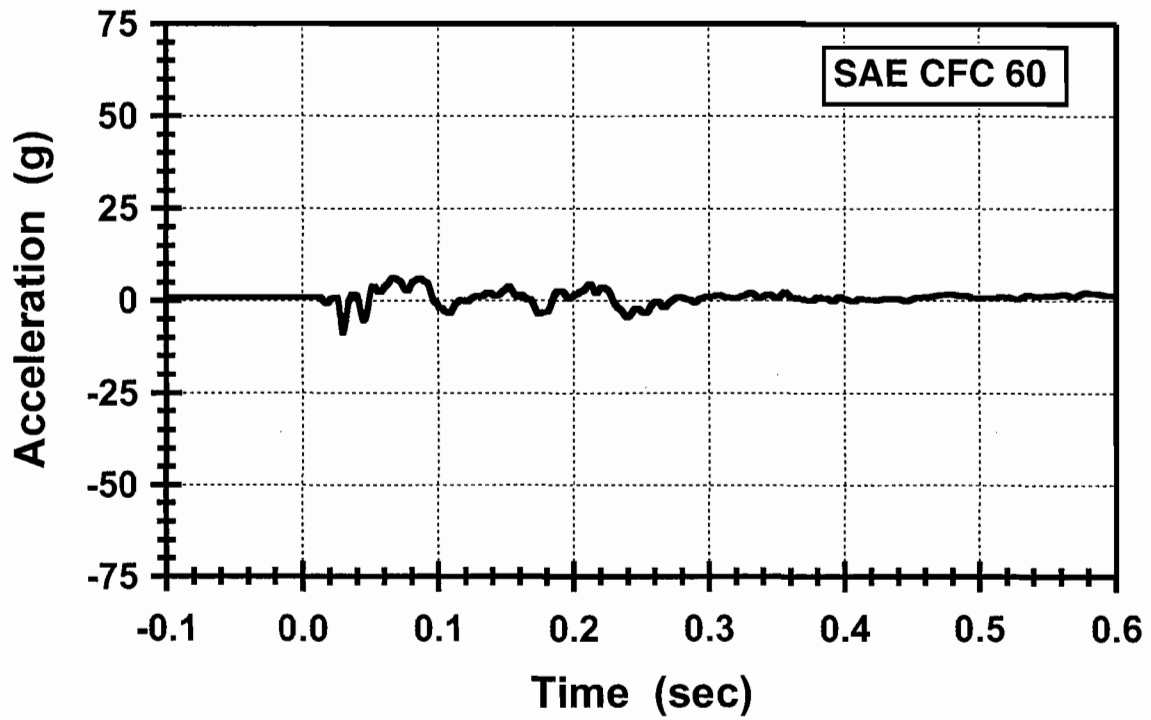


Figure 83. Accel., Lead Car, LS, Position 5, Z-Axis

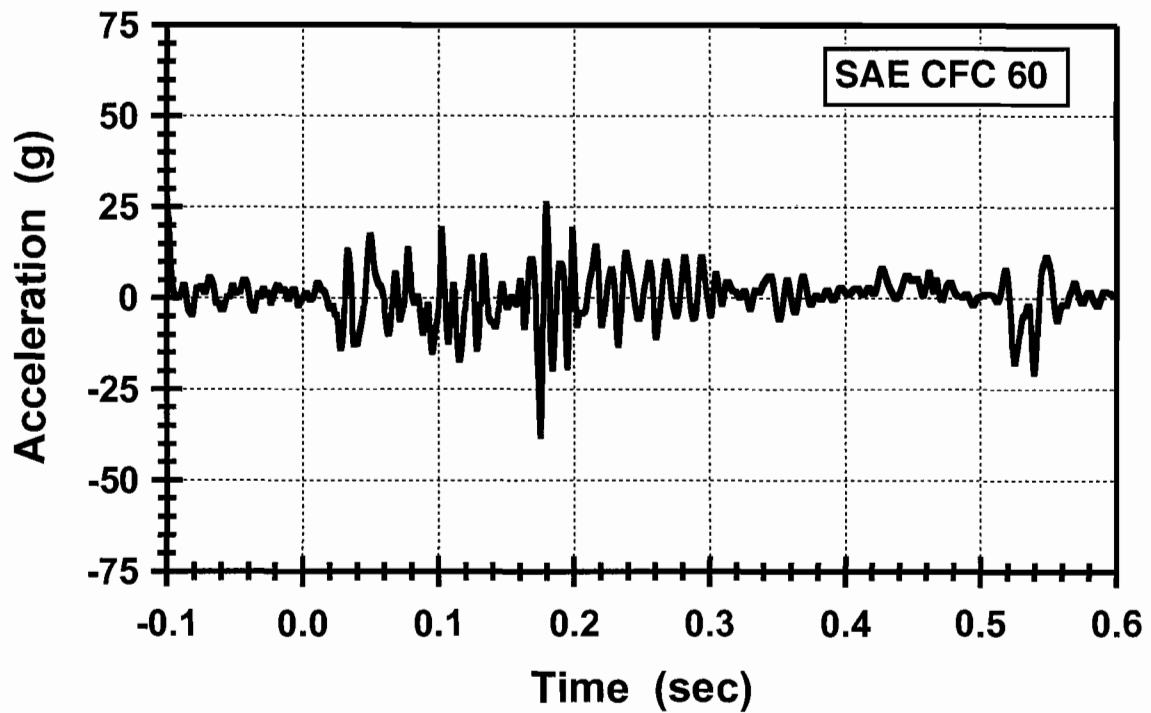


Figure 84. Accel., Lead Car, A End Bogie, Z-Axis

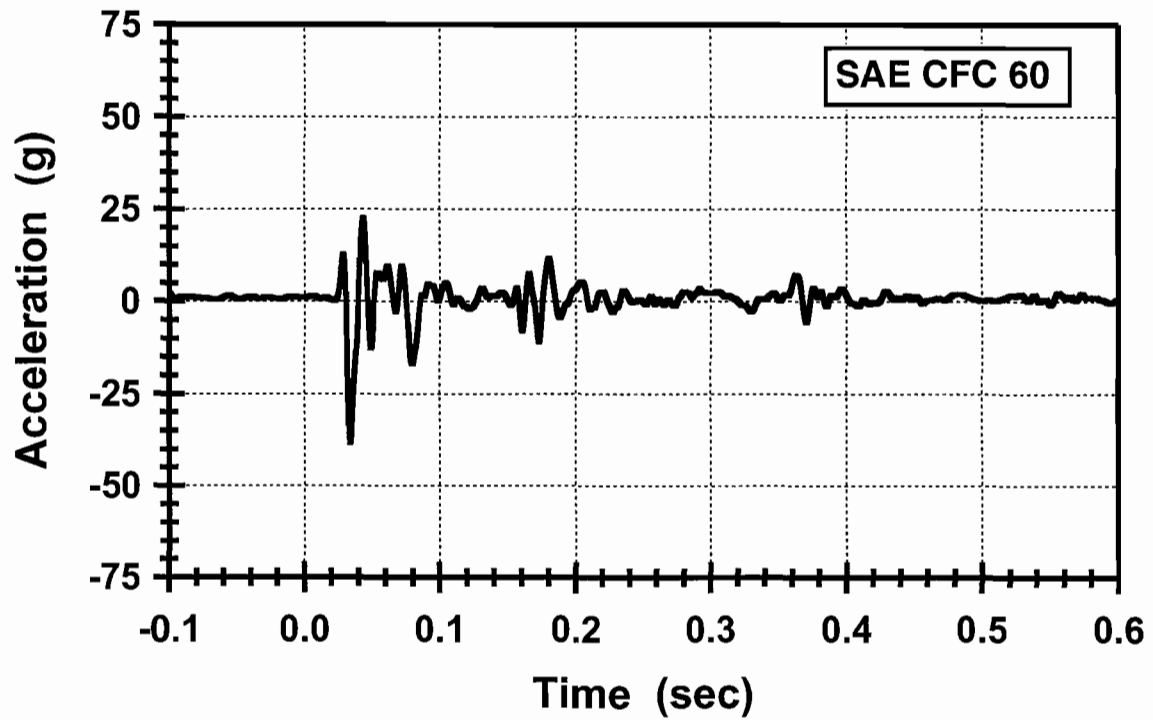


Figure 85. Accel., Lead Car, B End Bogie, Z-Axis

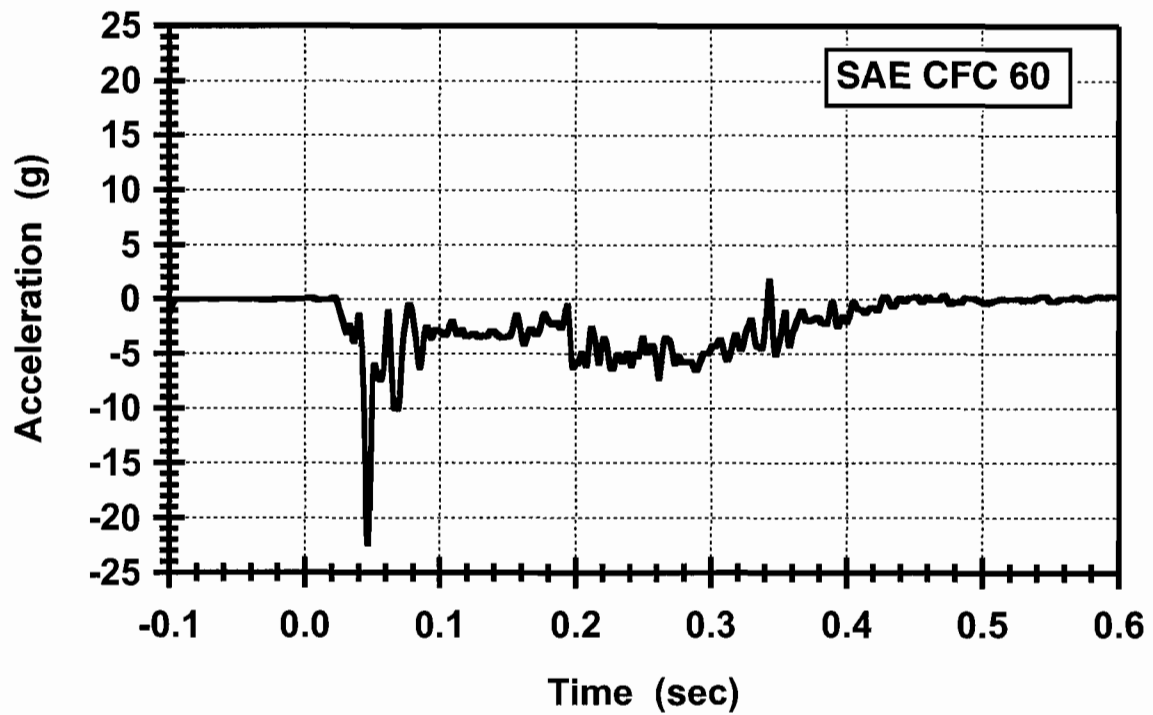


Figure 86. Accel., Trailing Car, CS, Position 1, X-Axis

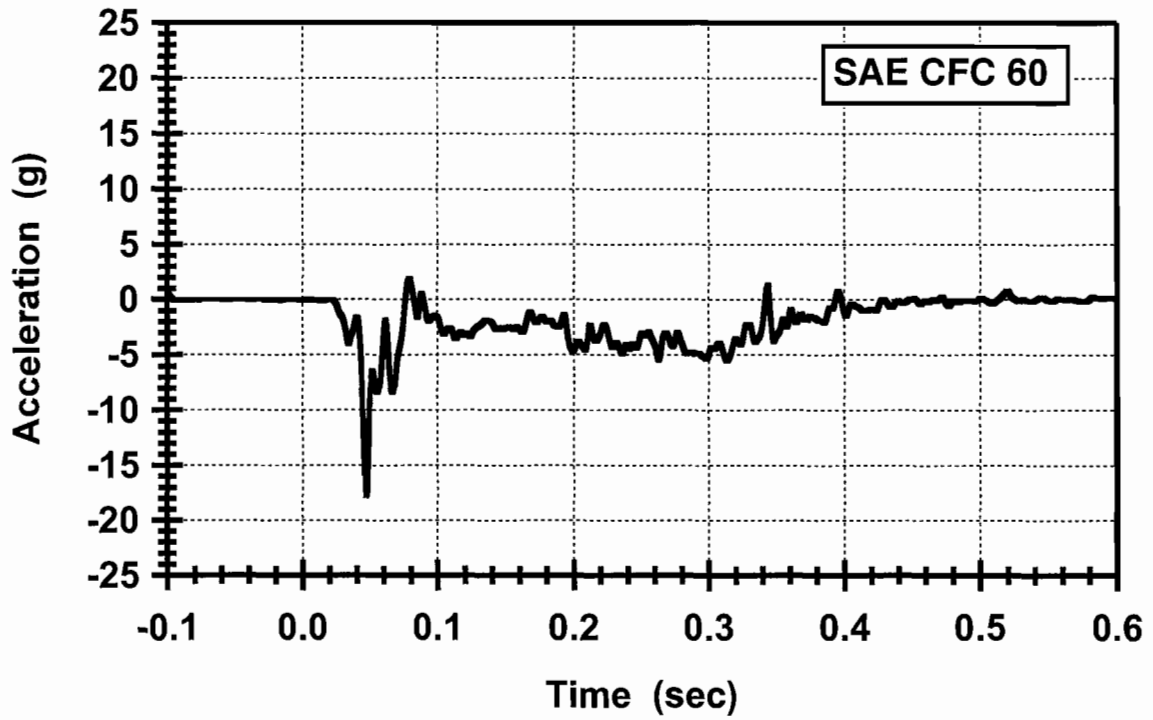


Figure 87. Accel., Trailing Car, CS, Position 2, X-Axis

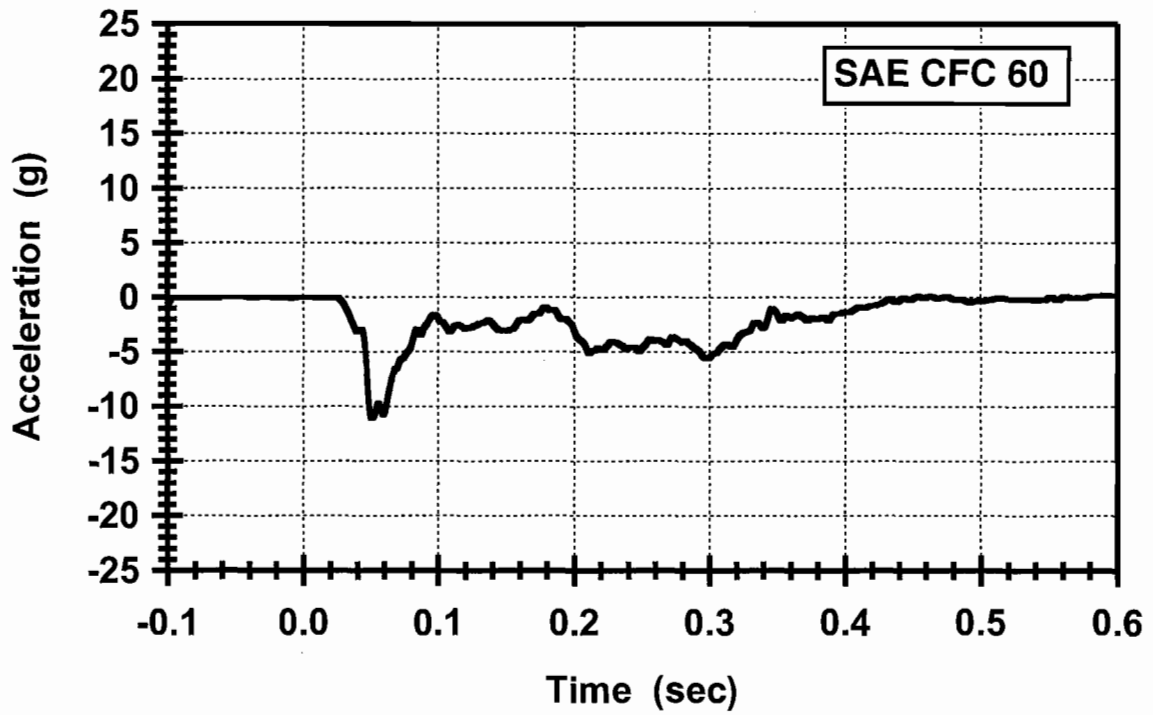


Figure 88. Accel., Trailing Car, CS, Position 3, X-Axis

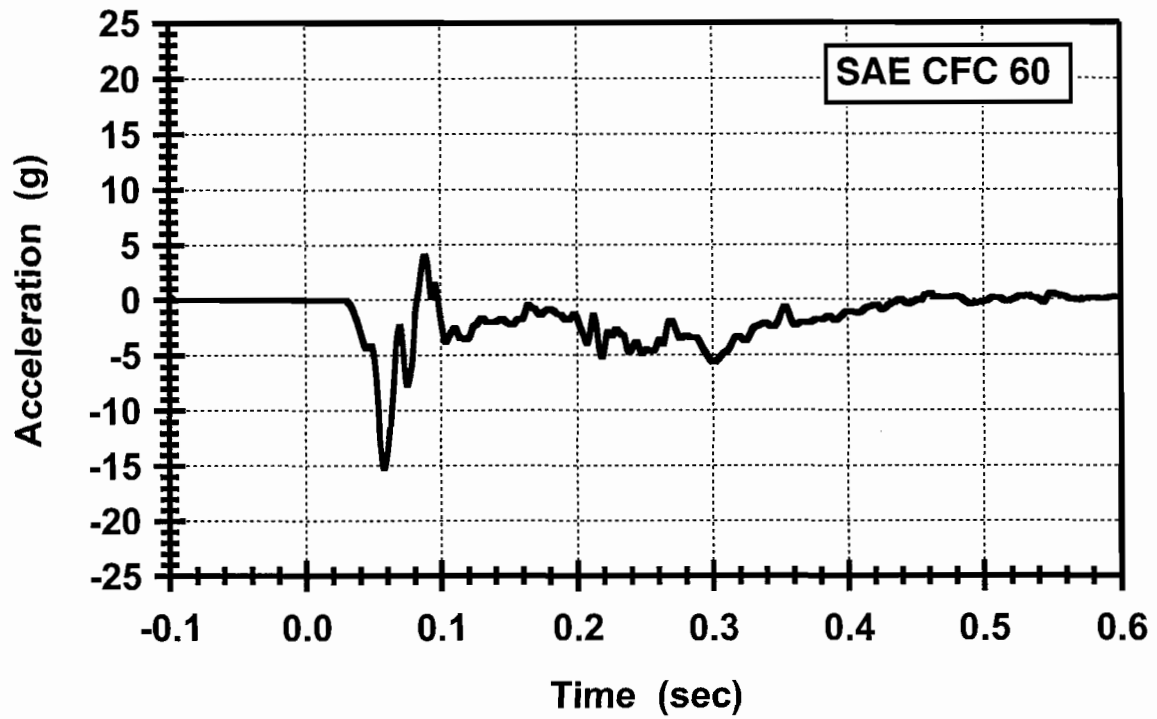


Figure 89. Accel., Trailing Car, CS, Position 4, X-Axis

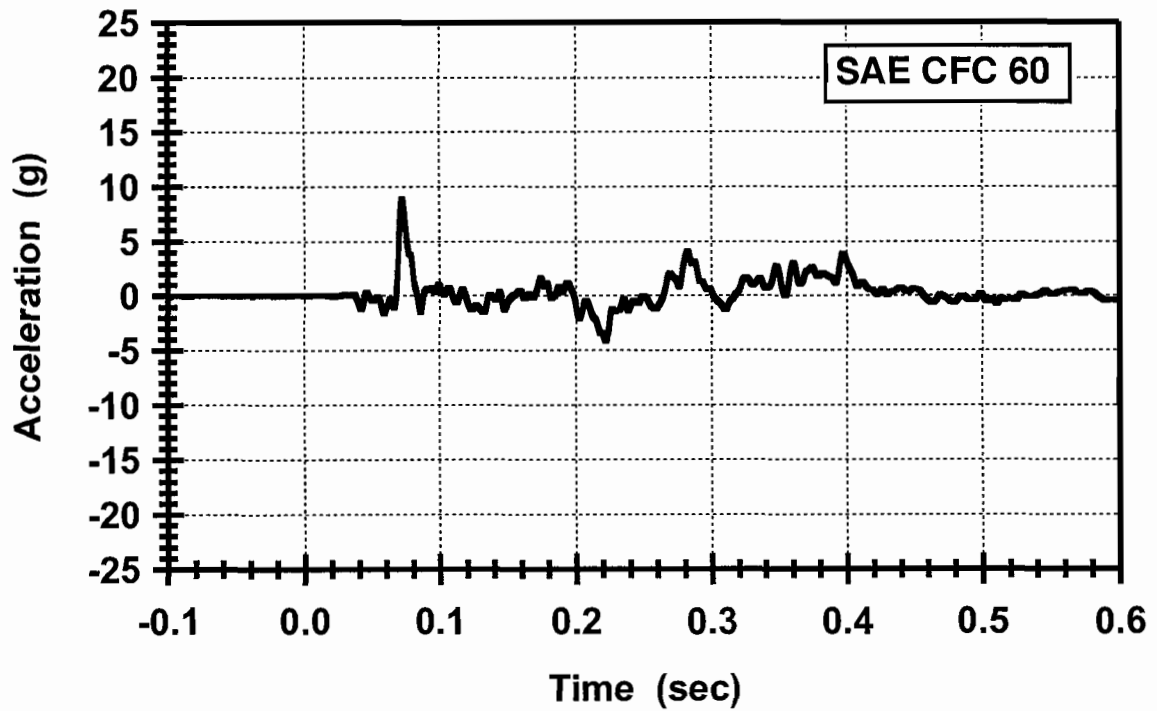


Figure 90. Accel., Trailing Car, CS, Position 2, Y-Axis

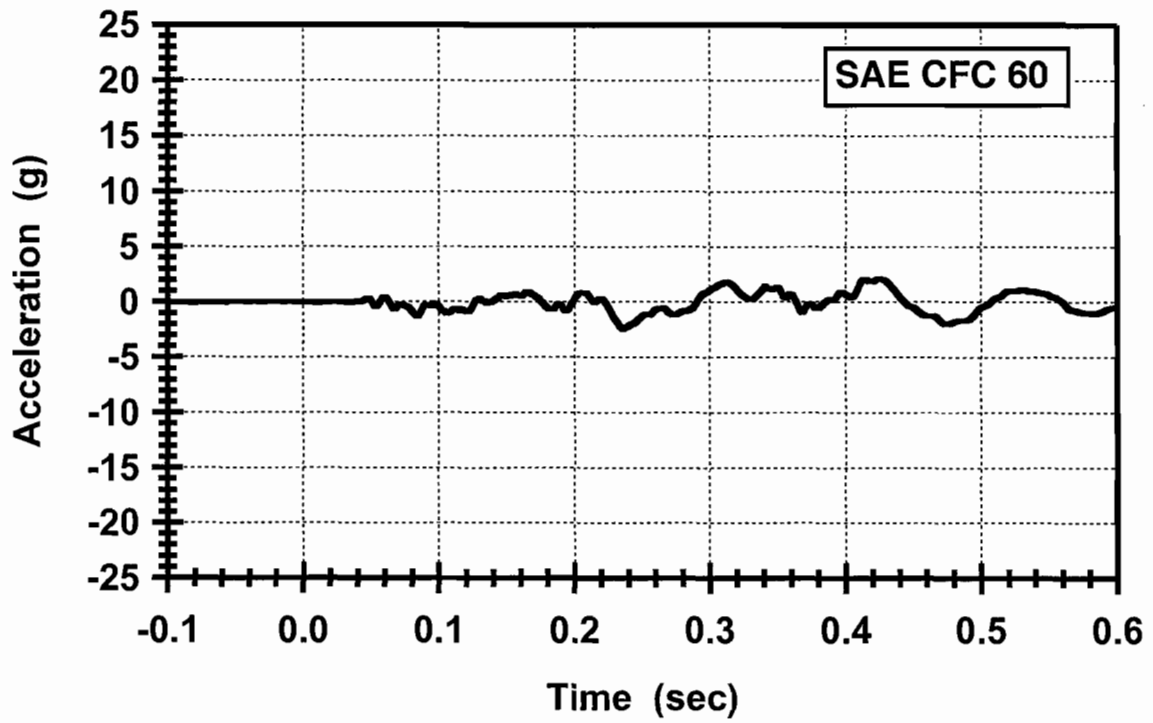


Figure 91. Accel., Trailing Car, CS, Position 3, Y-Axis

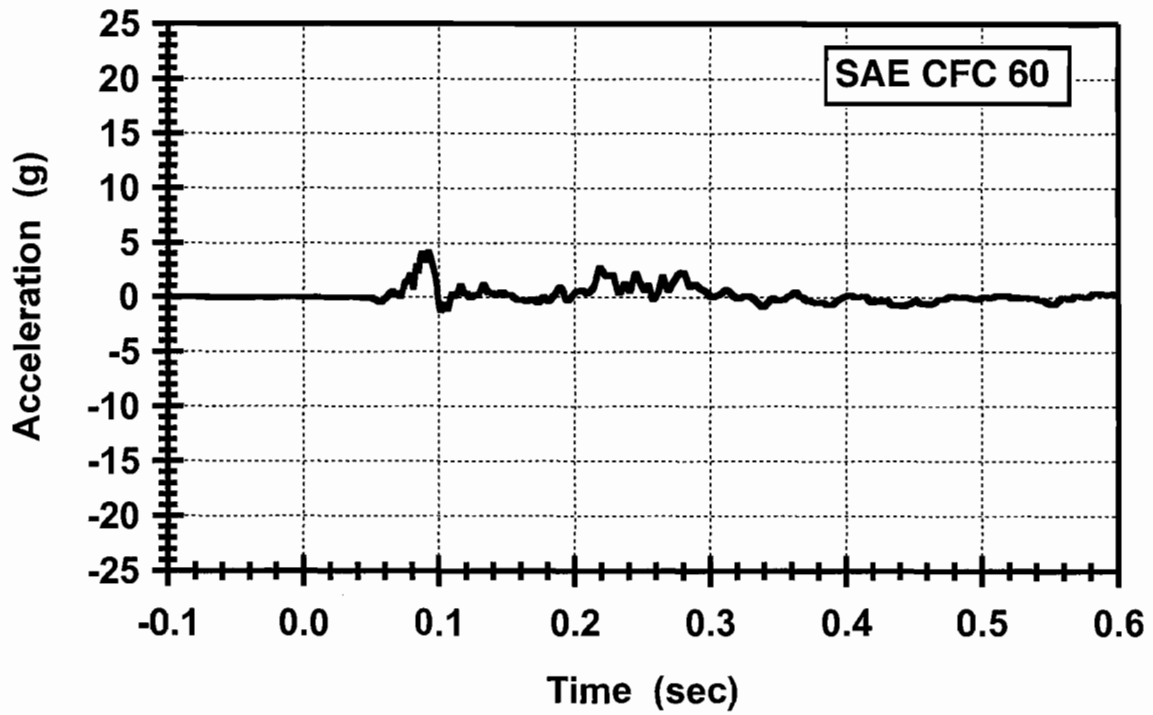


Figure 92. Accel., Trailing Car, CS, Position 4, Y-Axis

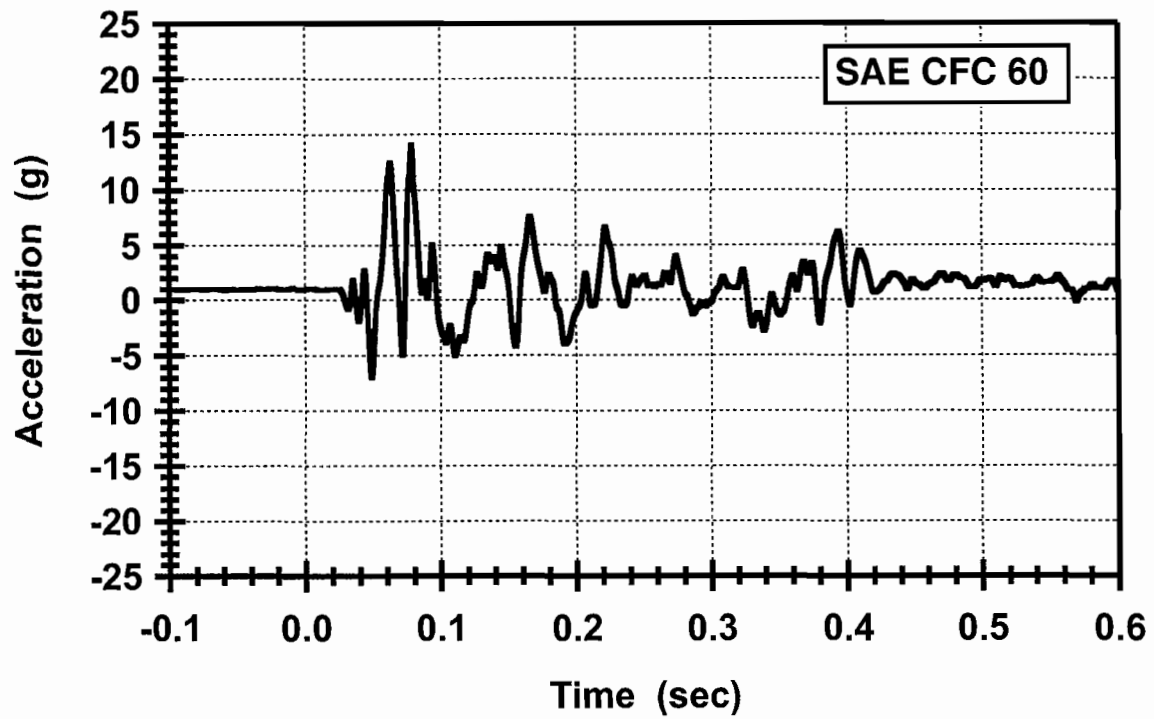


Figure 93. Accel., Trailing Car, CS, Position 2, Z-Axis

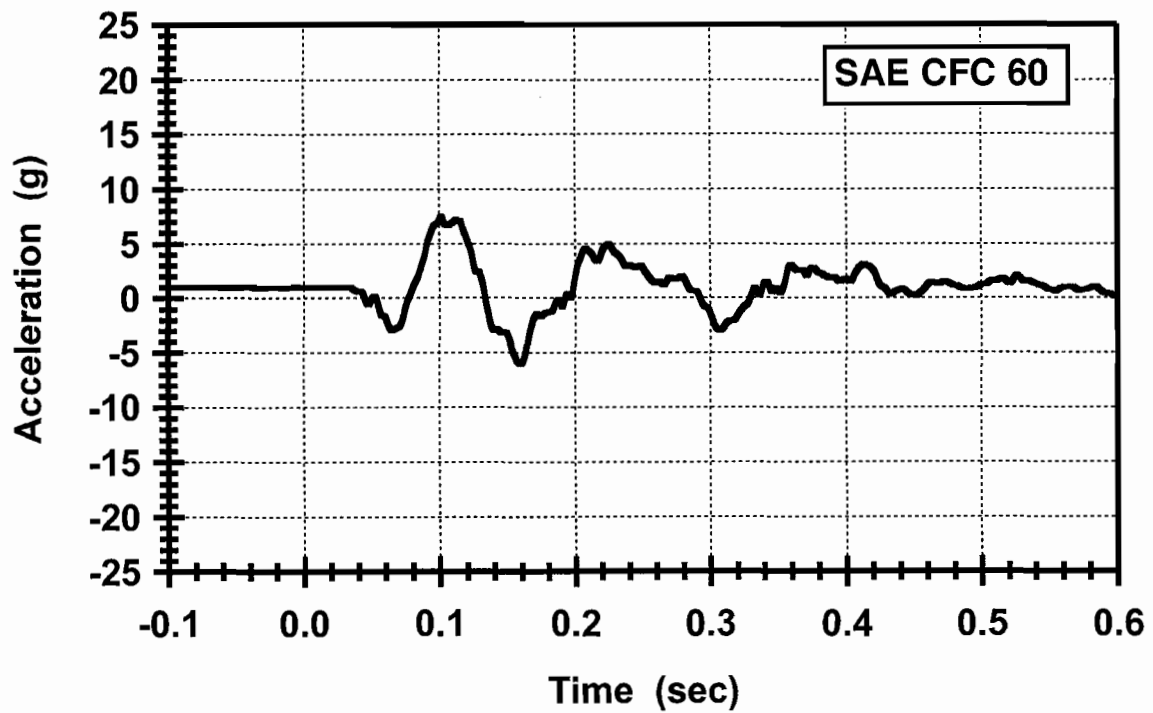


Figure 94. Accel., Trailing Car, CS, Position 3, Z-Axis

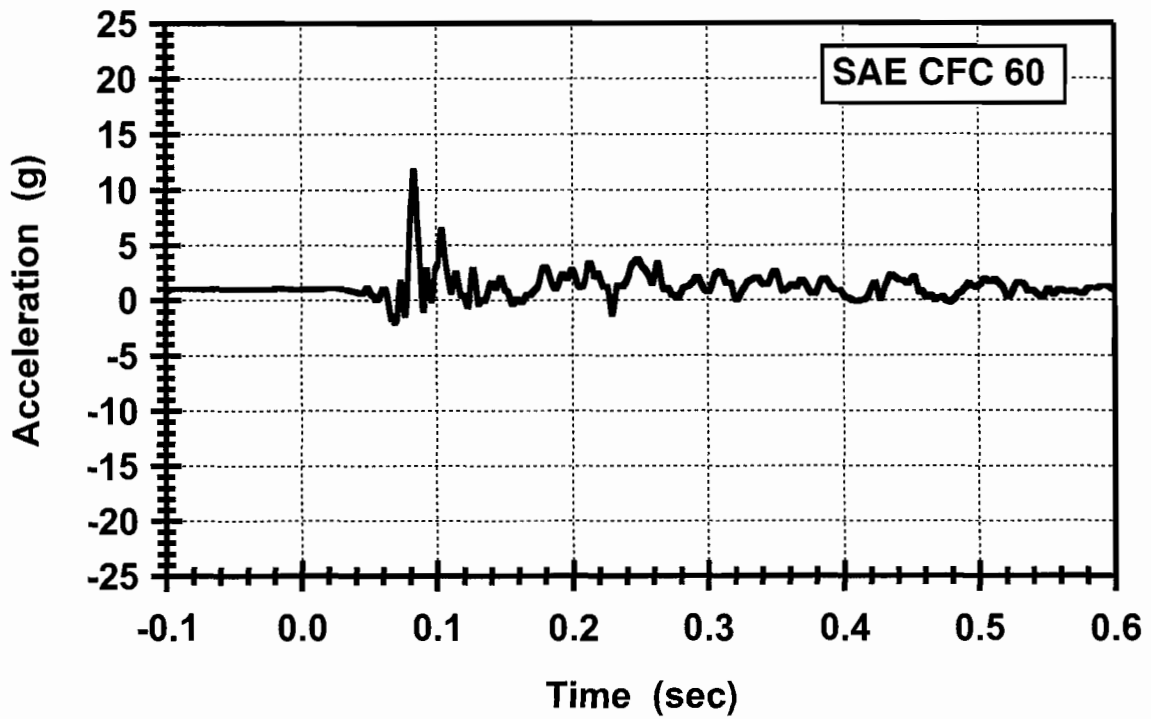


Figure 95. Accel., Trailing Car, CS, Position 4, Z-Axis

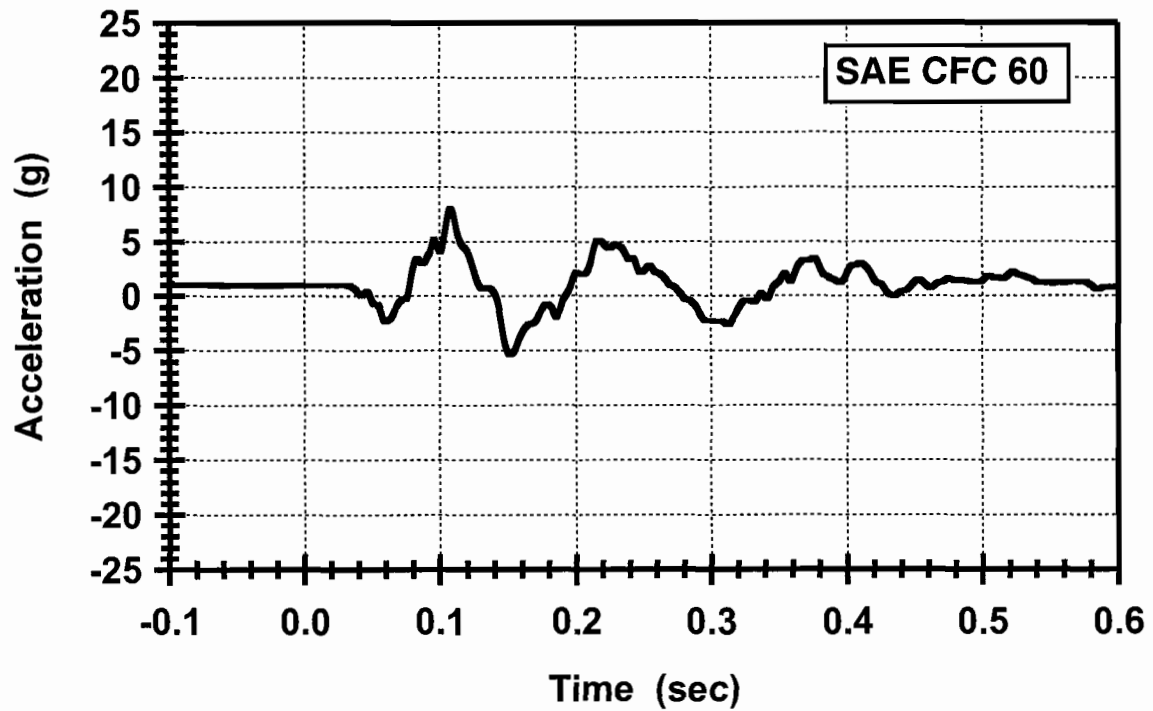


Figure 96. Accel., Trailing Car, RS, Position 3, Z-Axis

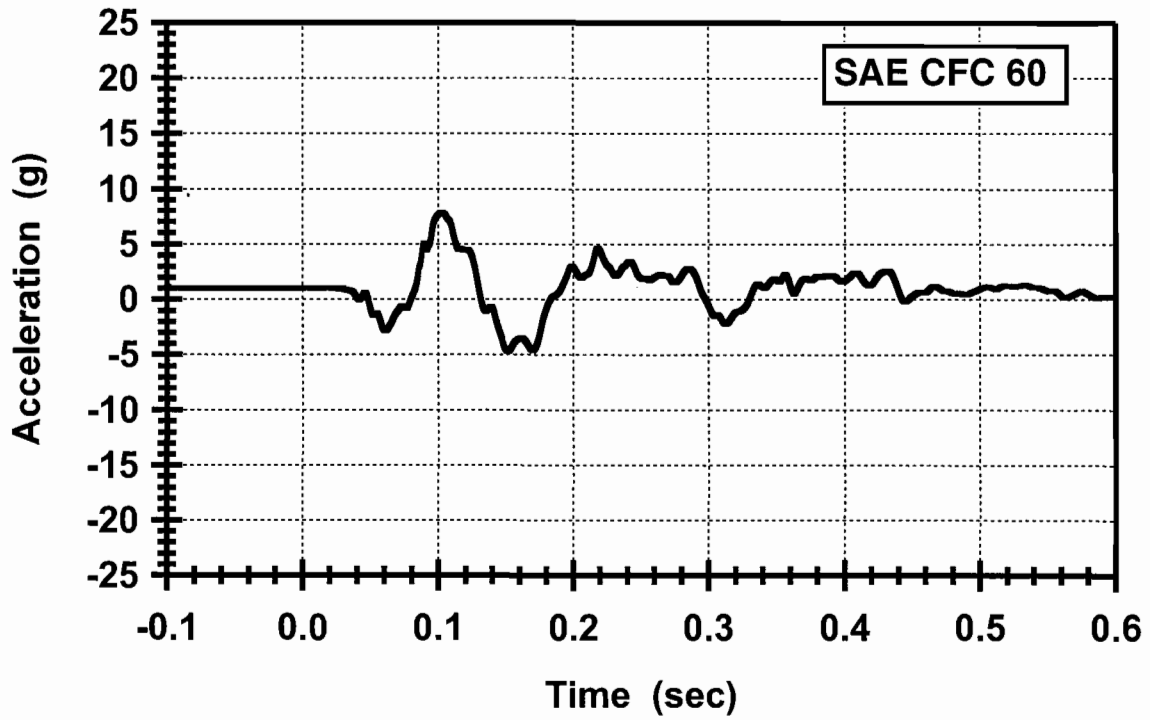


Figure 97. Accel., Trailing Car, LS, Position 3, Z-Axis

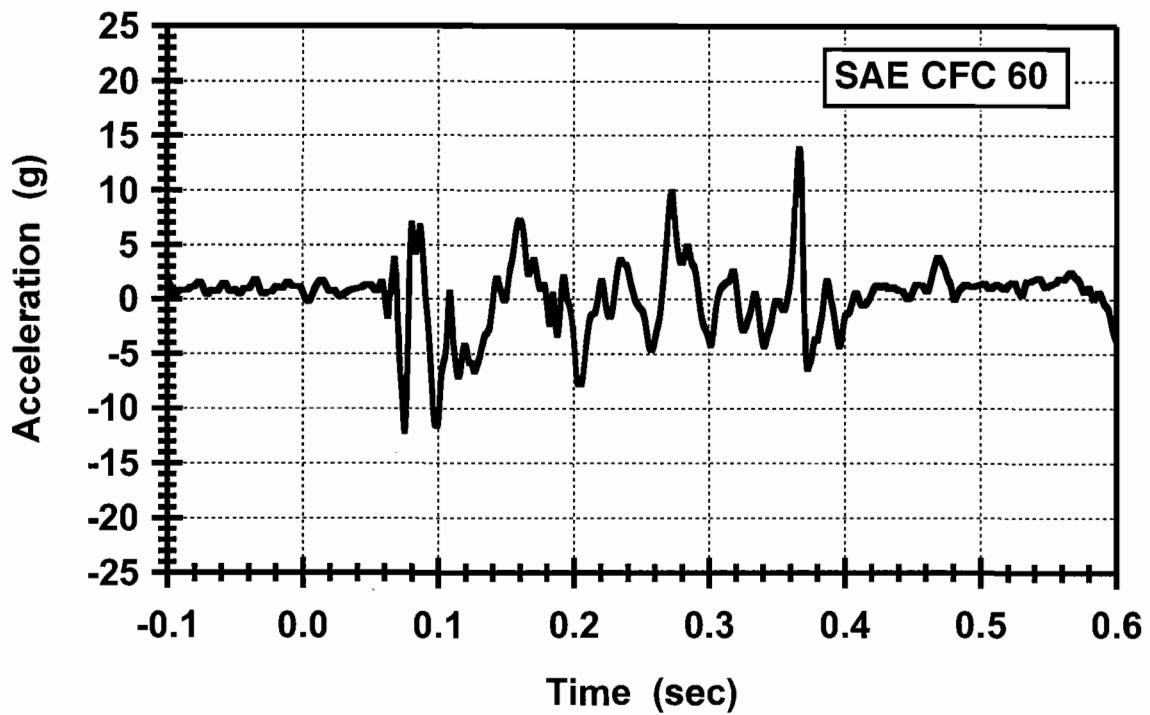


Figure 98. Accel., Trailing Car, A End Bogie, Z-Axis

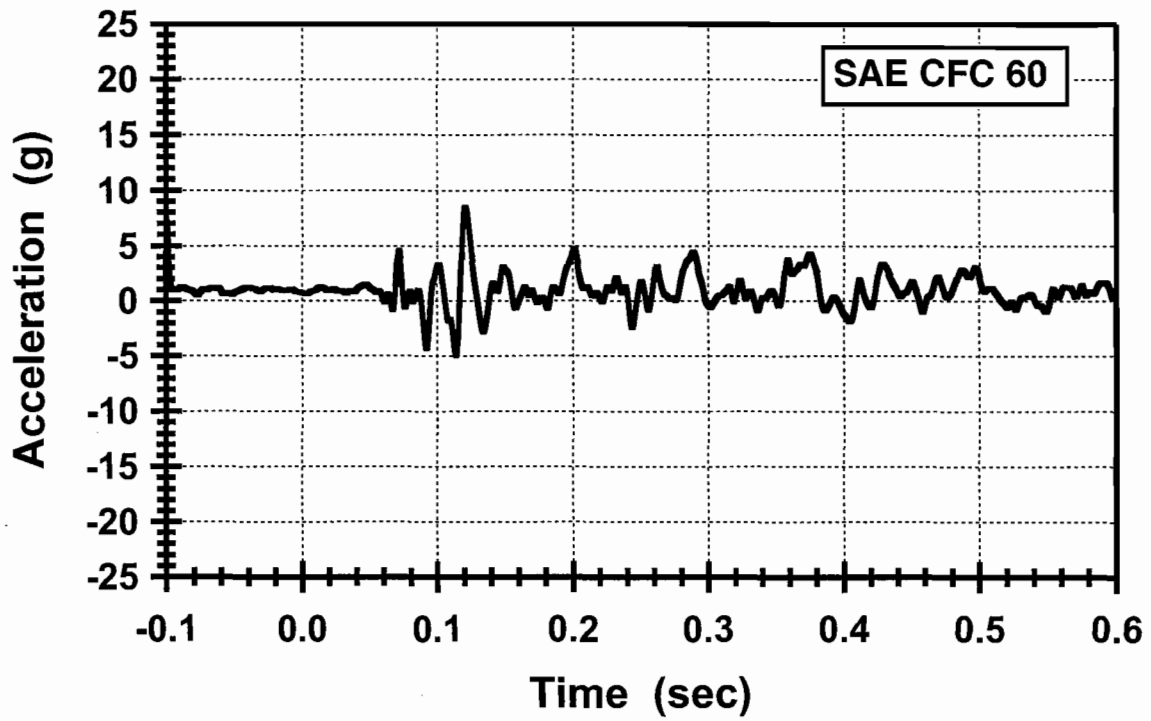


Figure 99. Accel., Trailing Car, B-End Bogie, Z-Axis

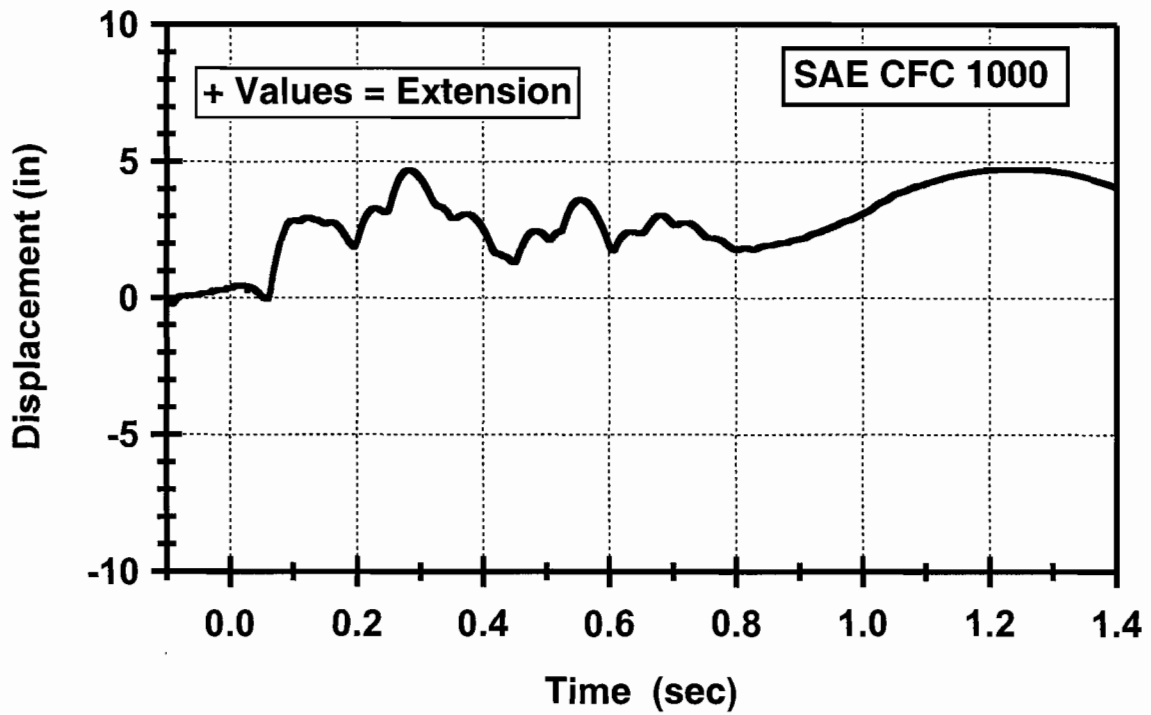


Figure 100. Disp., Lead Car, A-End, Right Side, Sec. Susp. String-Pot

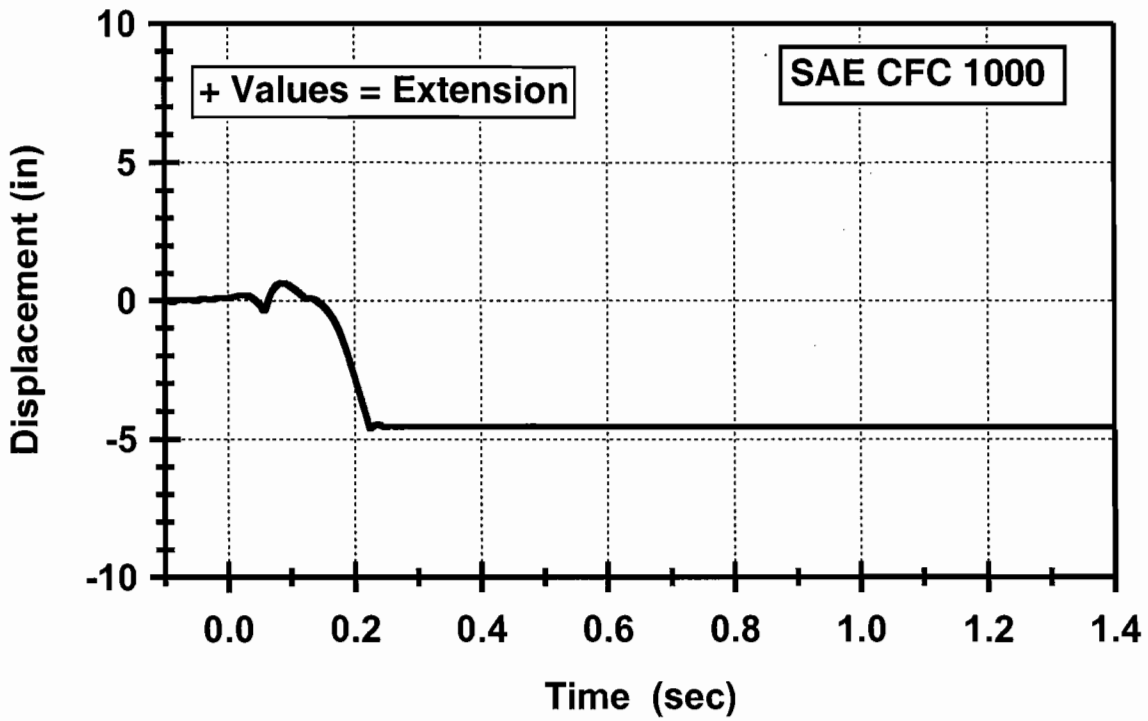


Figure 101. Disp., Lead Car, A-End, Left Side, Sec. Susp. String-Pot

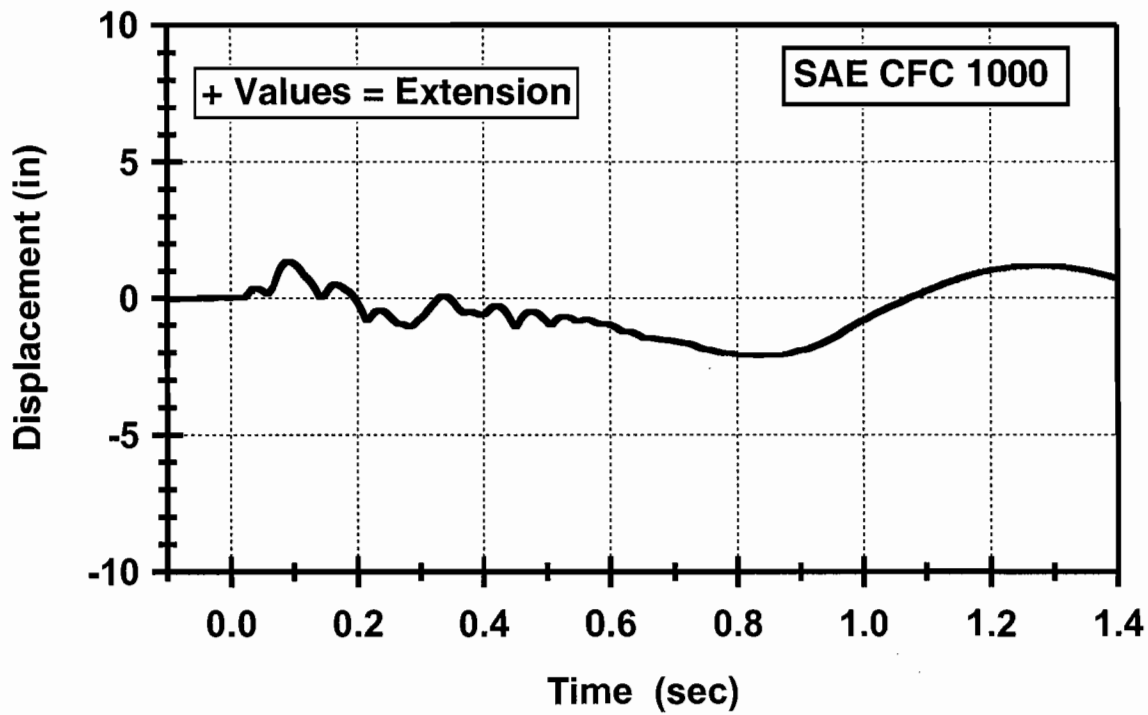


Figure 102. Disp., Lead Car, B-End, Right Side, Sec. Susp. String-Pot

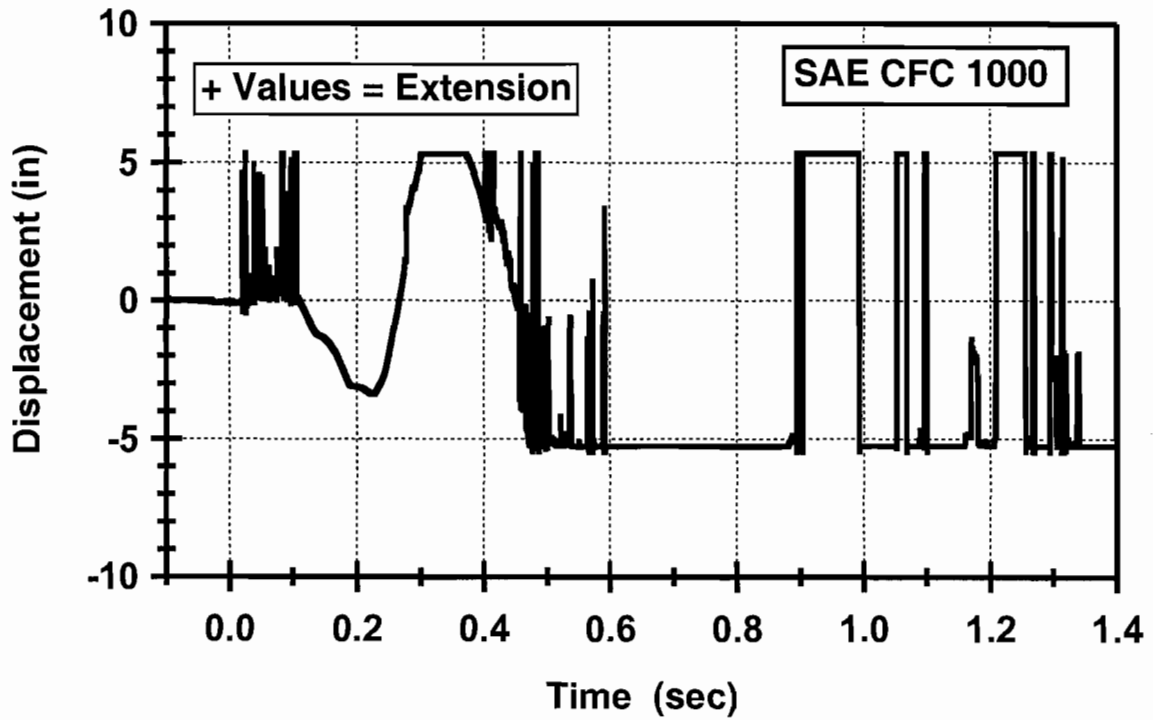


Figure 103. Disp., Lead Car, B-End, Left Side, Sec. Susp. String-Pot

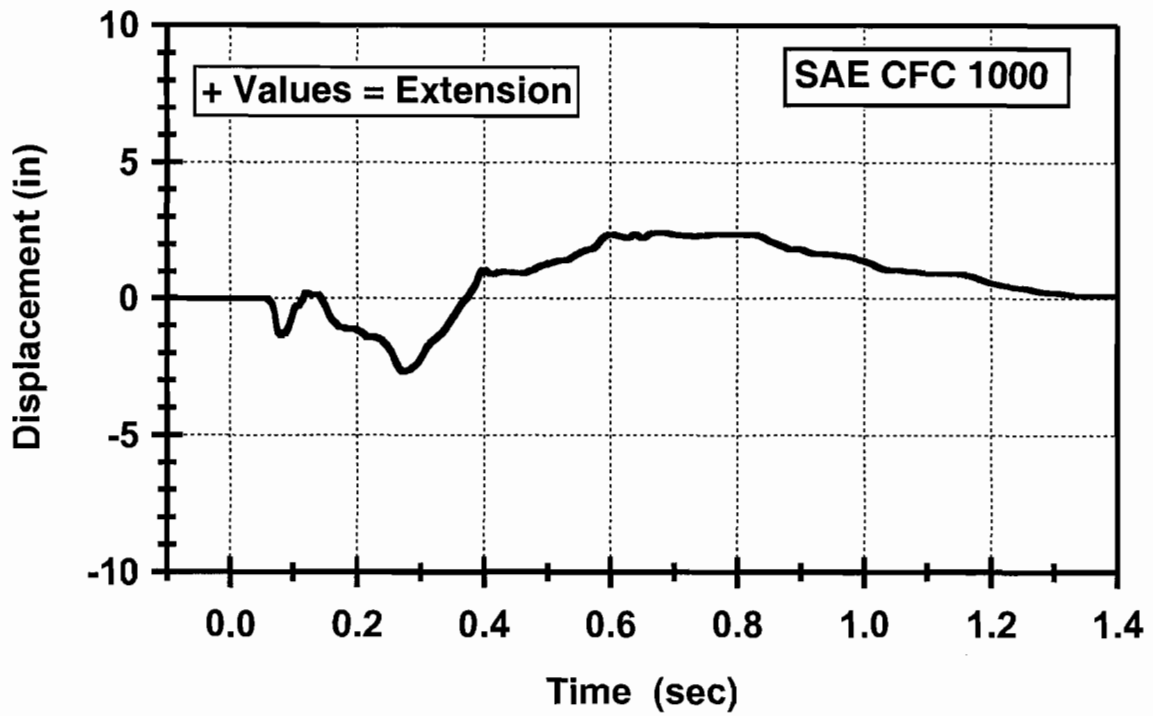


Figure 104. Disp., Trailing Car, A-End, Right Side, Sec. Susp. String-Pot

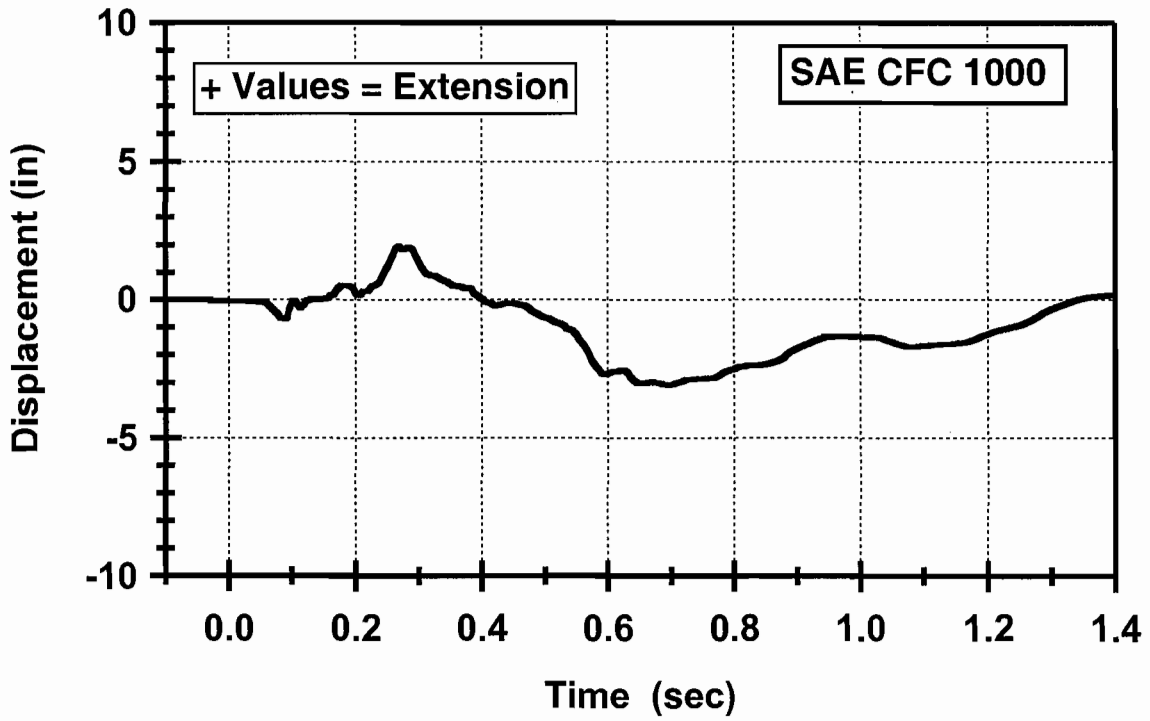


Figure 105. Disp., Trailing Car, A-End, Left Side, Sec. Susp. String-Pot

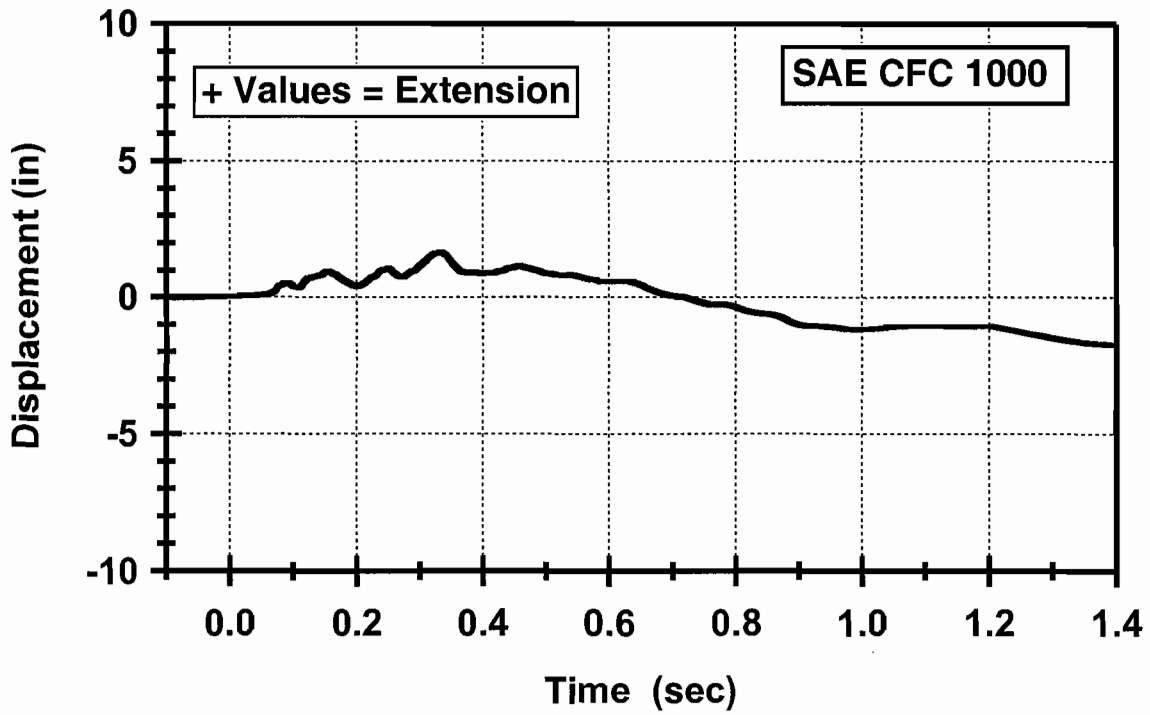


Figure 106. Disp., Trailing Car, B-End, Right Side, Sec. Susp. String-Pot

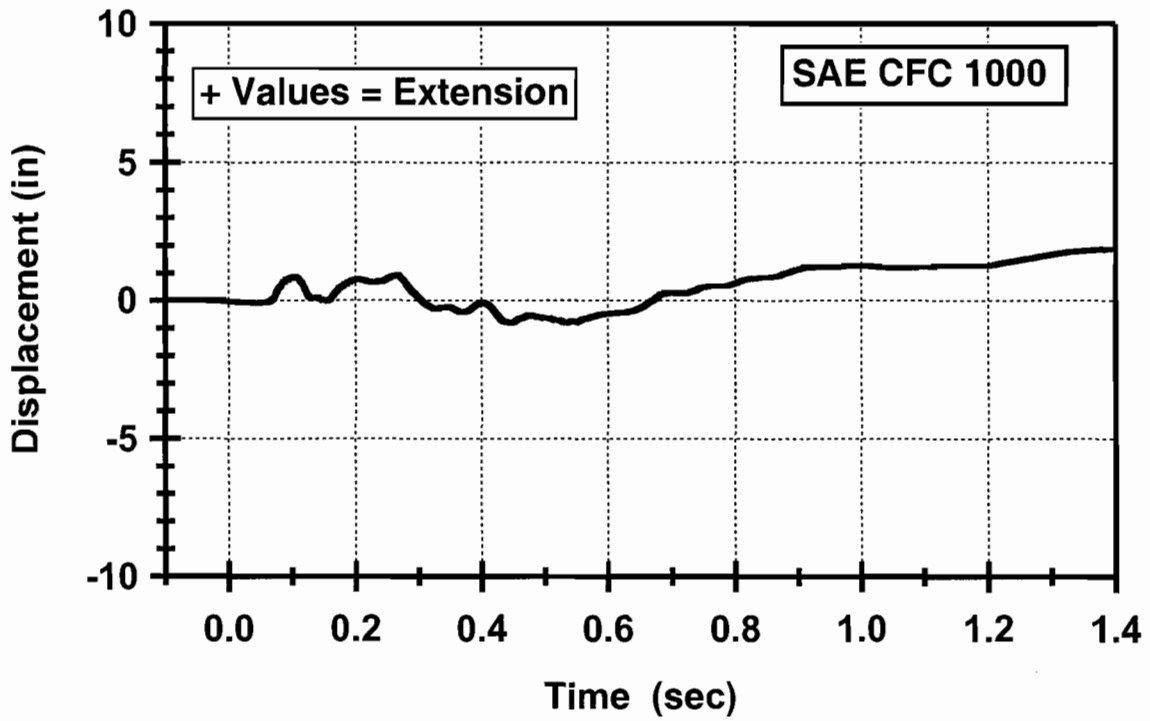


Figure 107. Disp., Trailing Car, B-End, Left Side, Sec. Susp. String-Pot

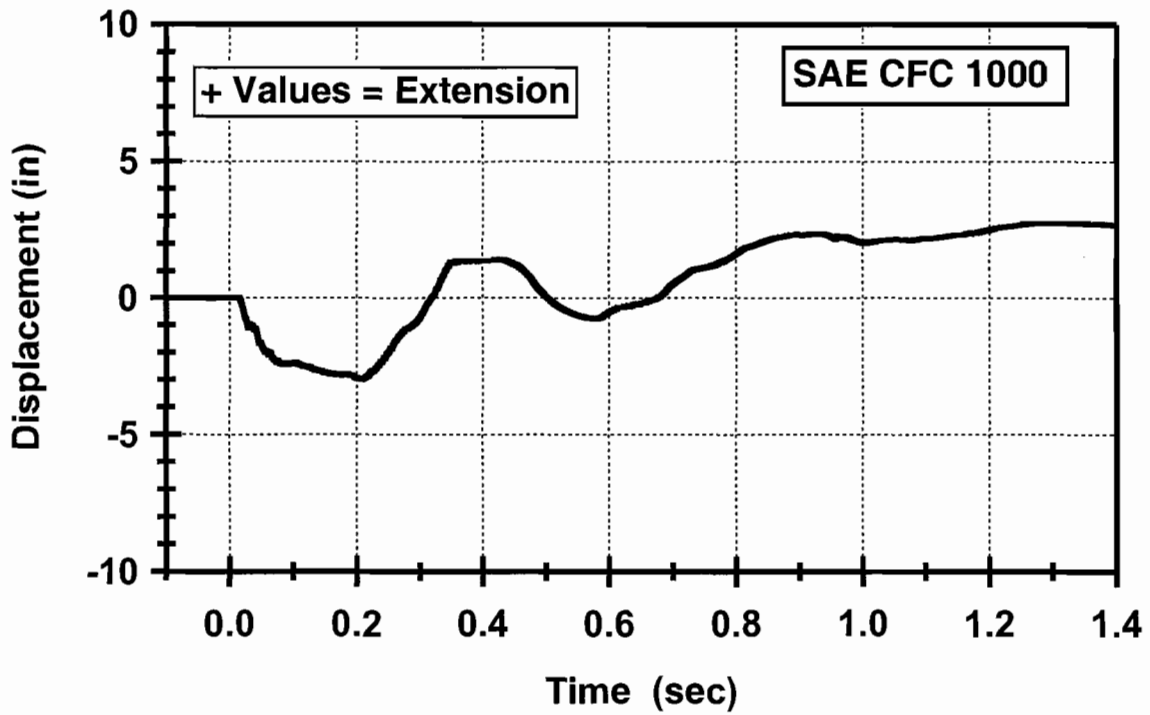


Figure 108. Disp., Lead Car to B-End Coupler, X-Axis String-Pot

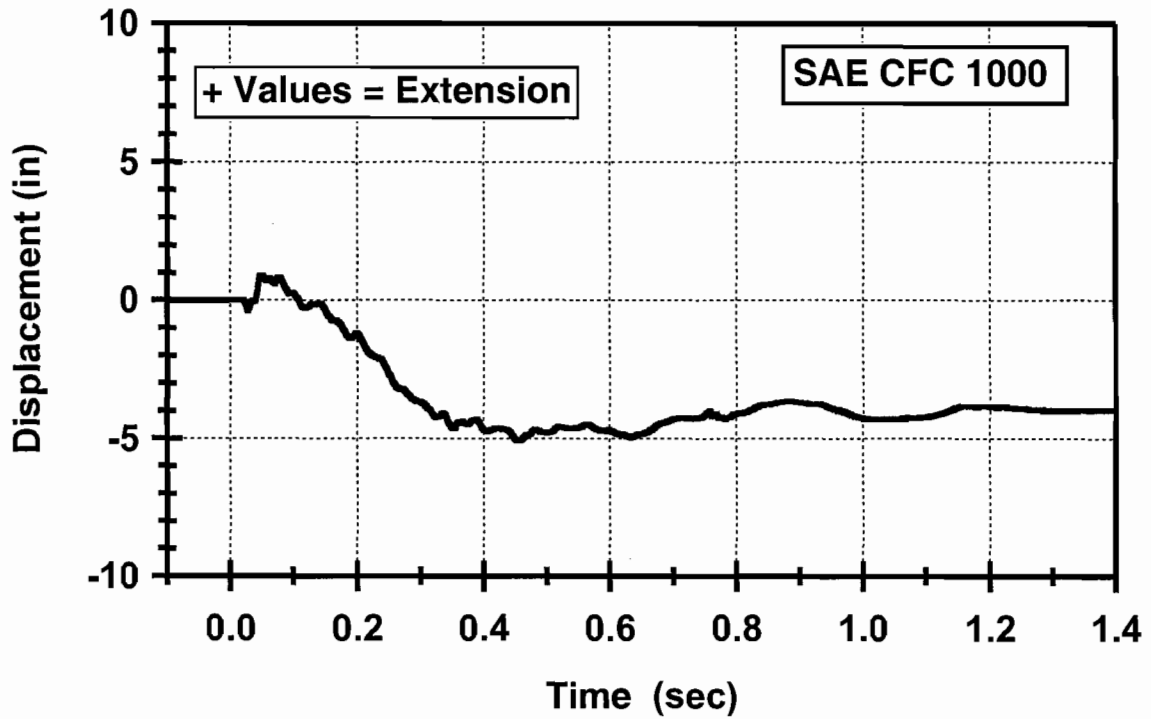


Figure 109. Disp., Lead Car to B-End Coupler, Y-Axis String-Pot

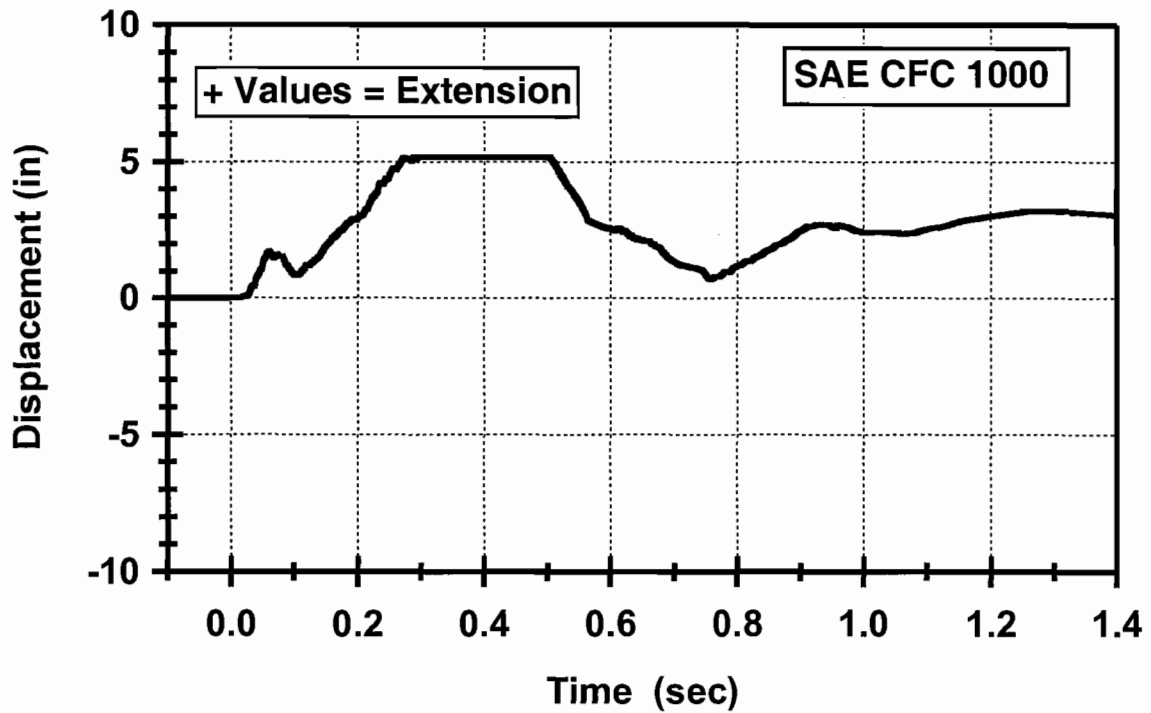


Figure 110. Disp., Lead Car to B-End Coupler, Z-Axis String-Pot

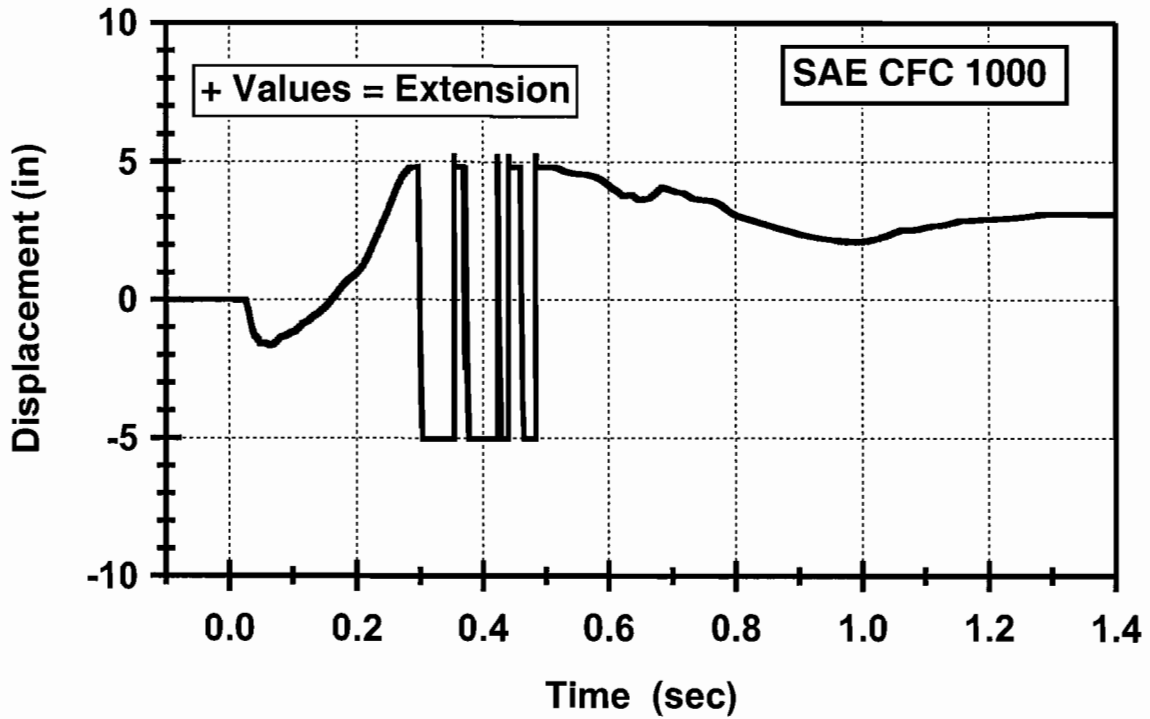


Figure 111. Disp., Trailing Car to A-End Coupler, X-Axis String-Pot

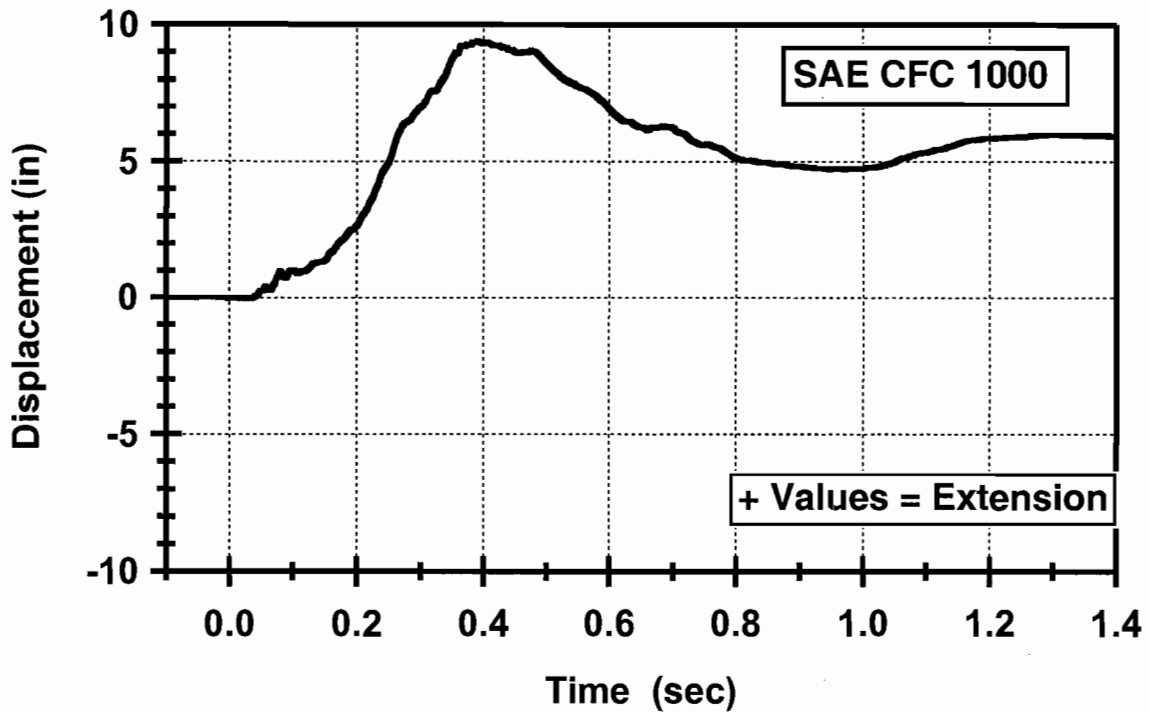


Figure 112. Disp., Trailing Car to A-End Coupler, Y-Axis String-Pot

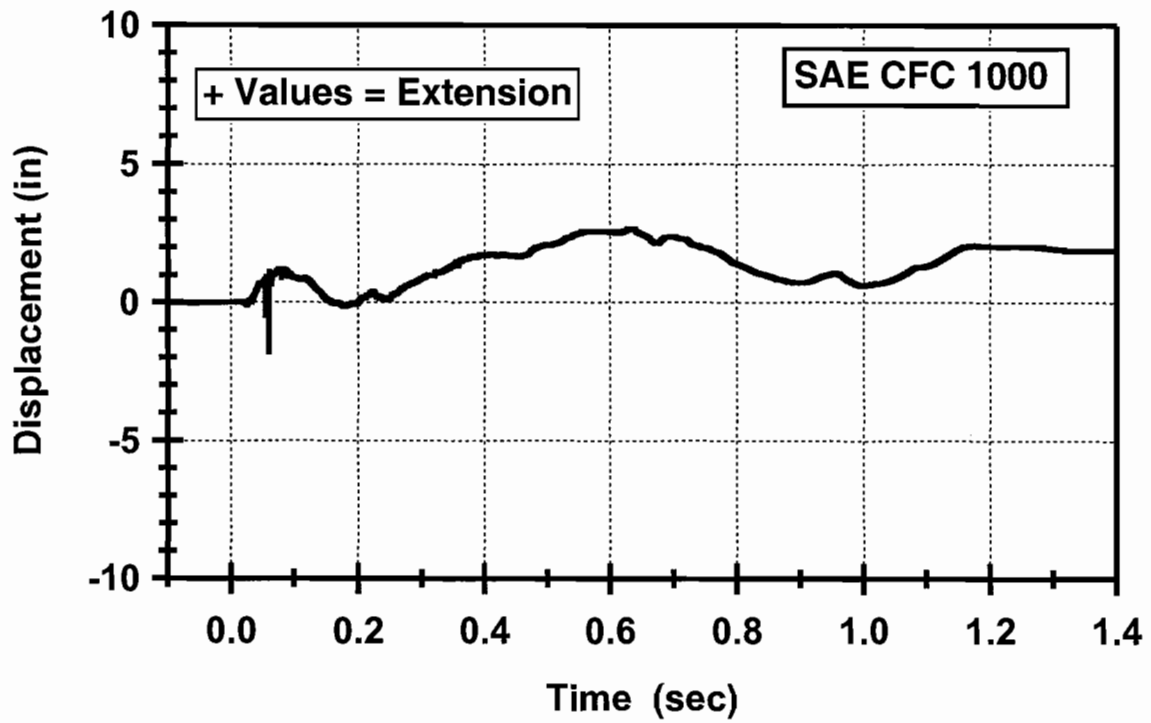


Figure 113. Trailing Car to A-End Coupler, Z-Axis String-Pot

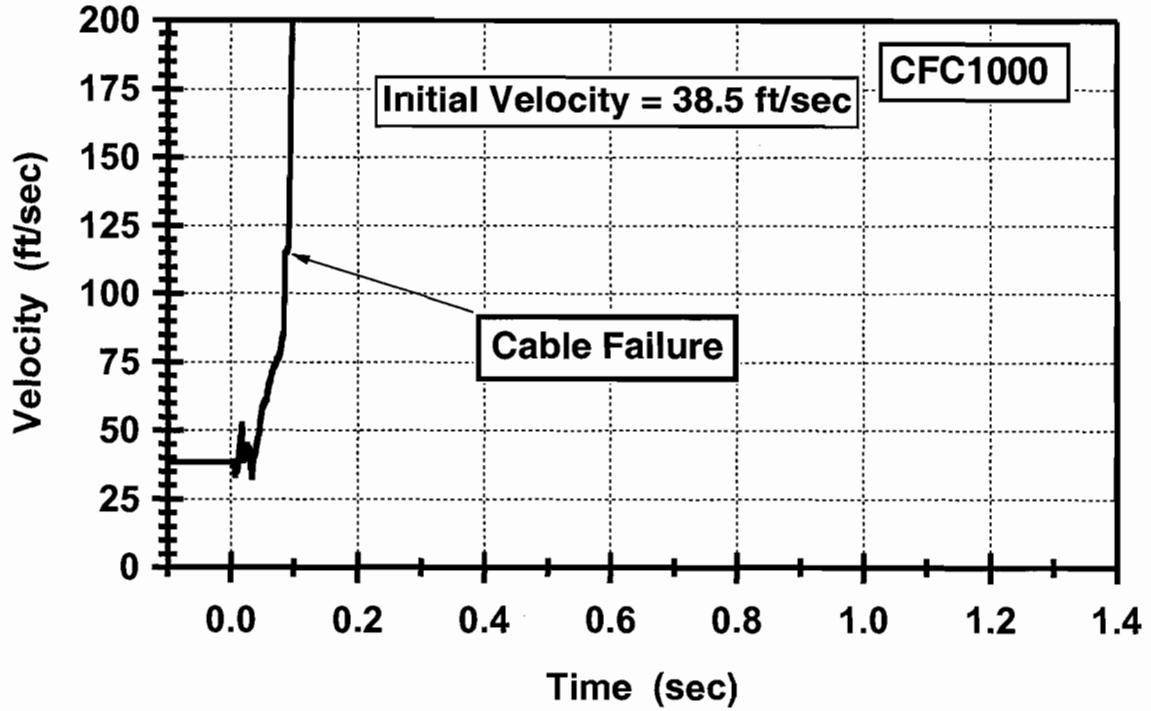


Figure 114. Lead Car, CS Position 1, X-Axis Accel. Integrated

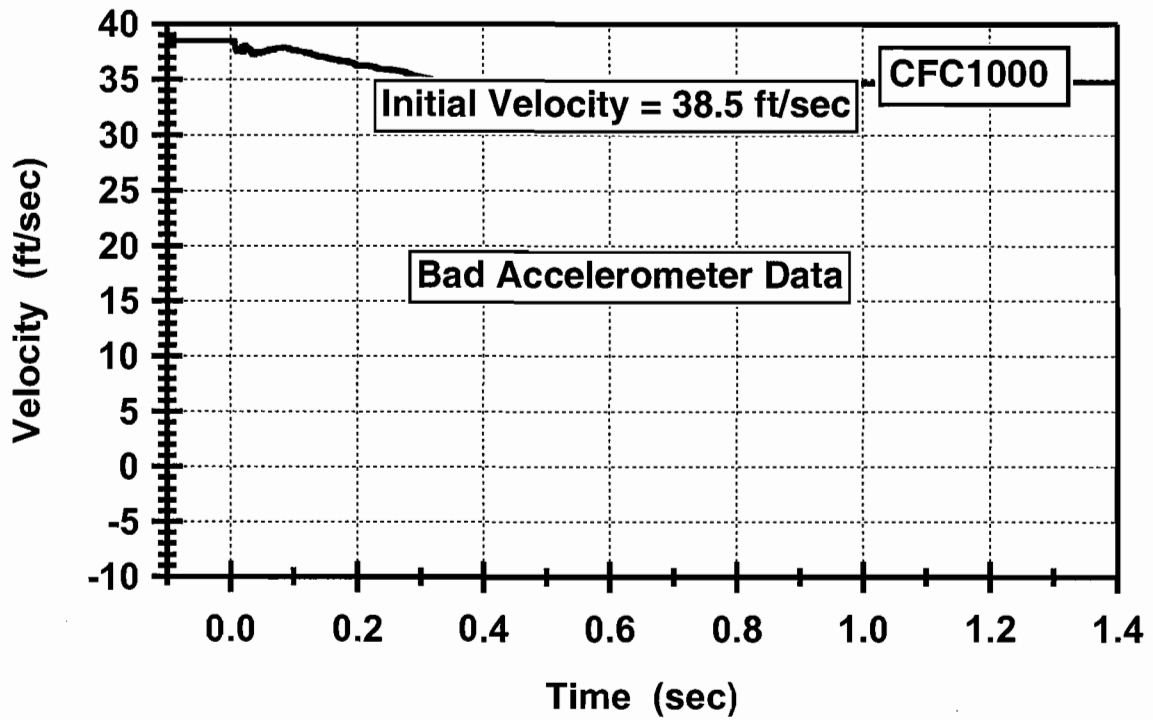


Figure 115. Lead Car, CS Position 2, X-Axis Accel. Integrated

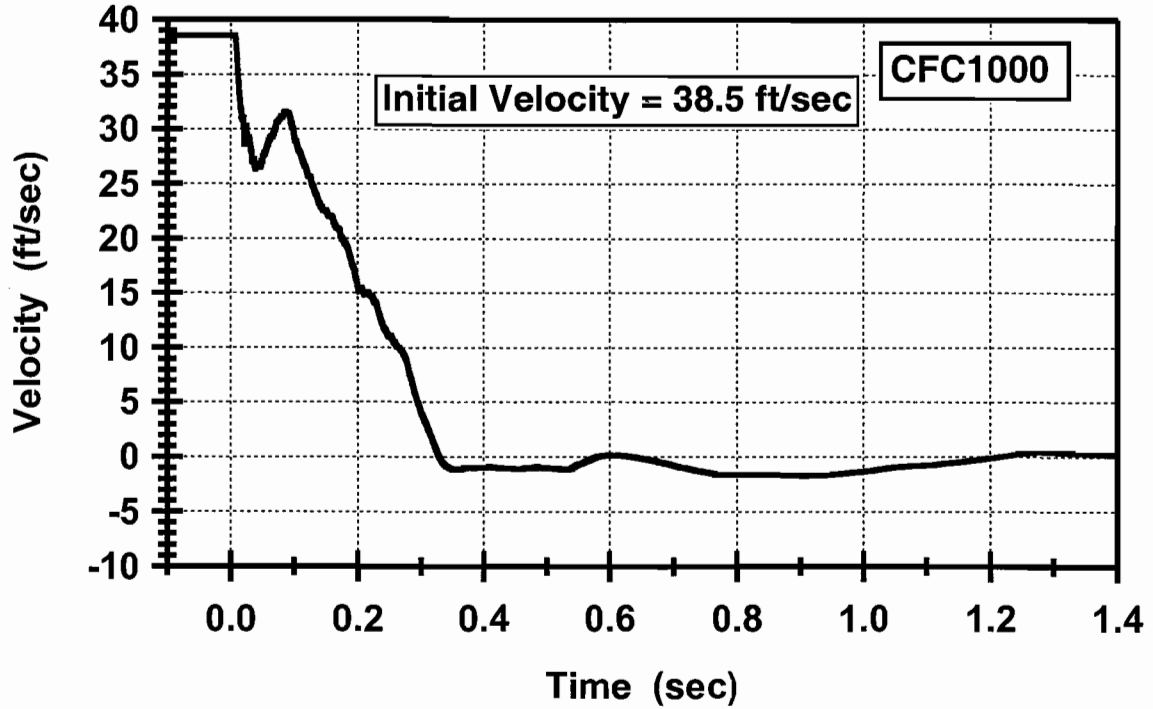


Figure 116. Lead Car, CS Position 3, X-Axis Accel. Integrated

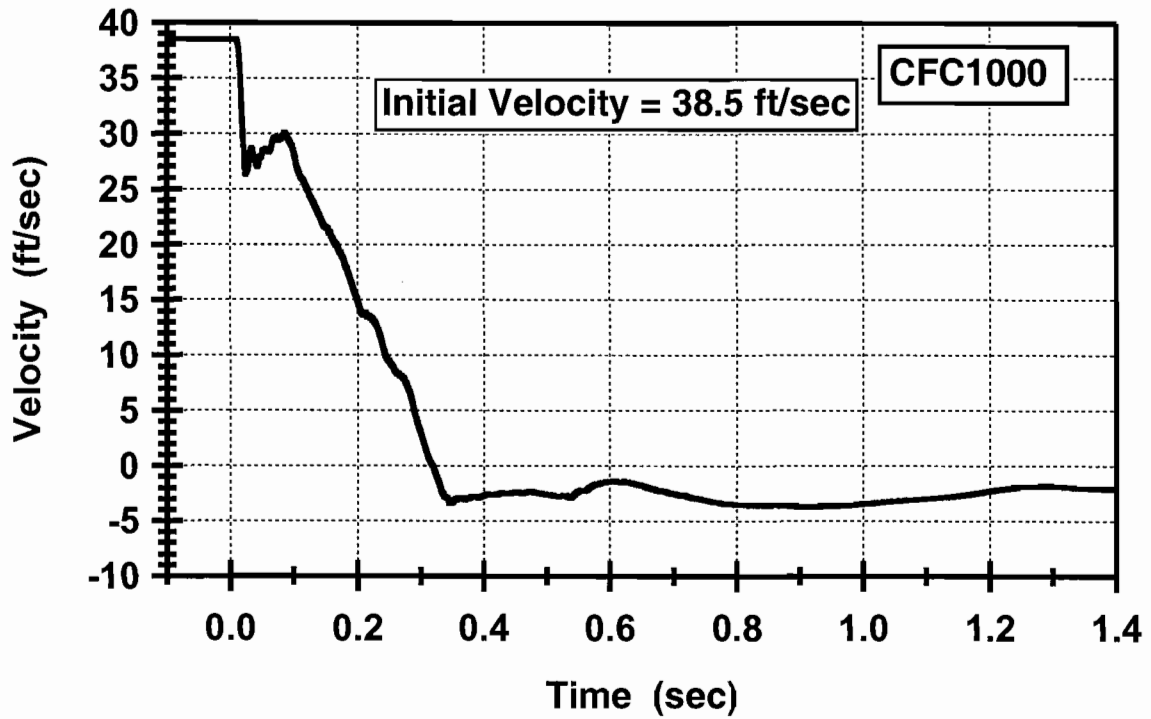


Figure 117. Lead Car, CS Position 4, X-Axis Accel. Integrated

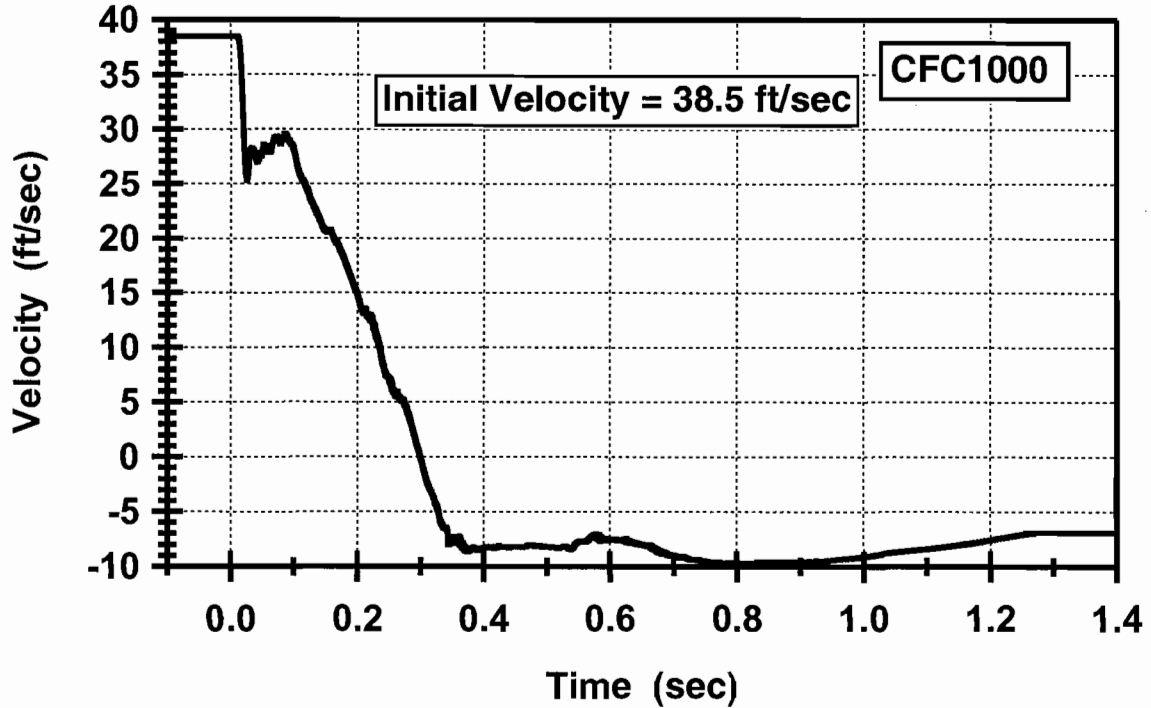


Figure 118. Lead Car, CS Position 5, X-Axis Accel. Integrated

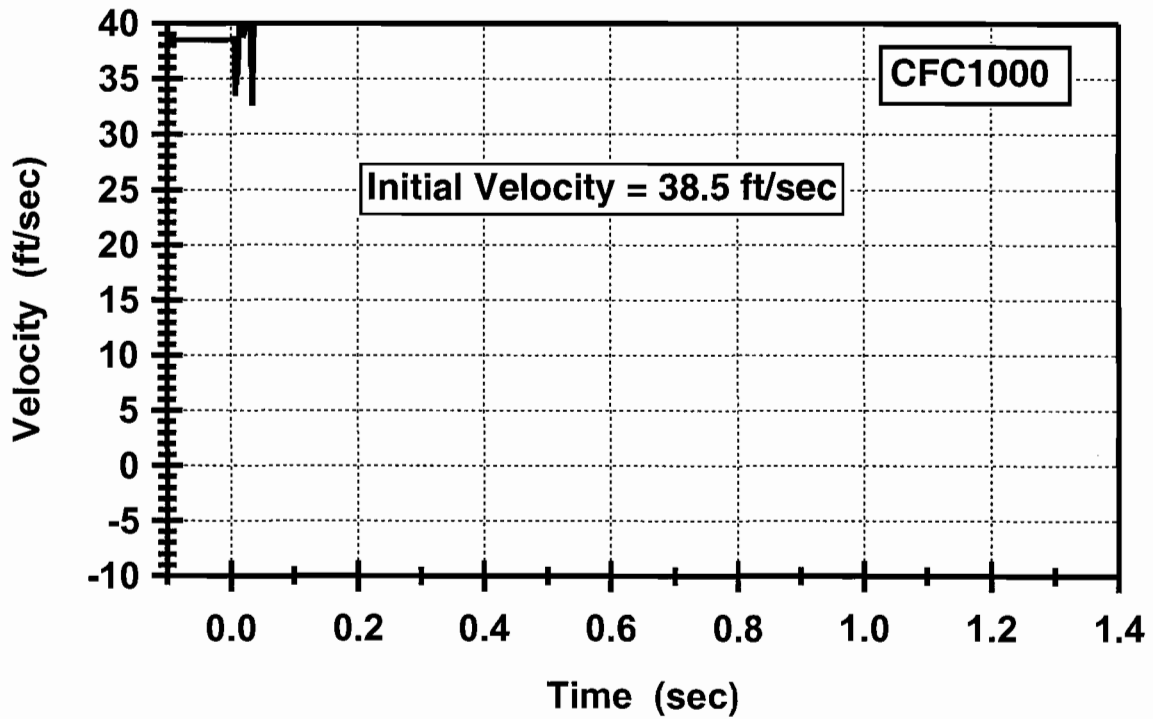


Figure 119. Trailing Car, CS Position 1, X-Axis Accel. Integrated

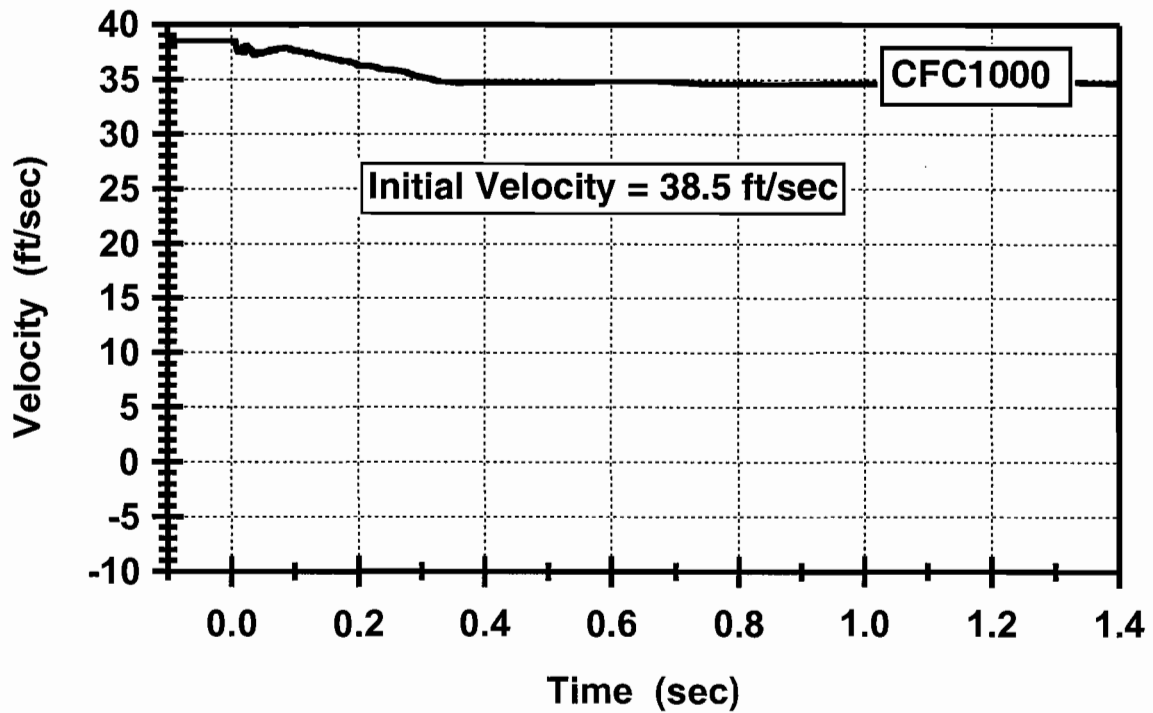


Figure 120. Trailing Car, CS Position 2, X-Axis Accel. Integrated

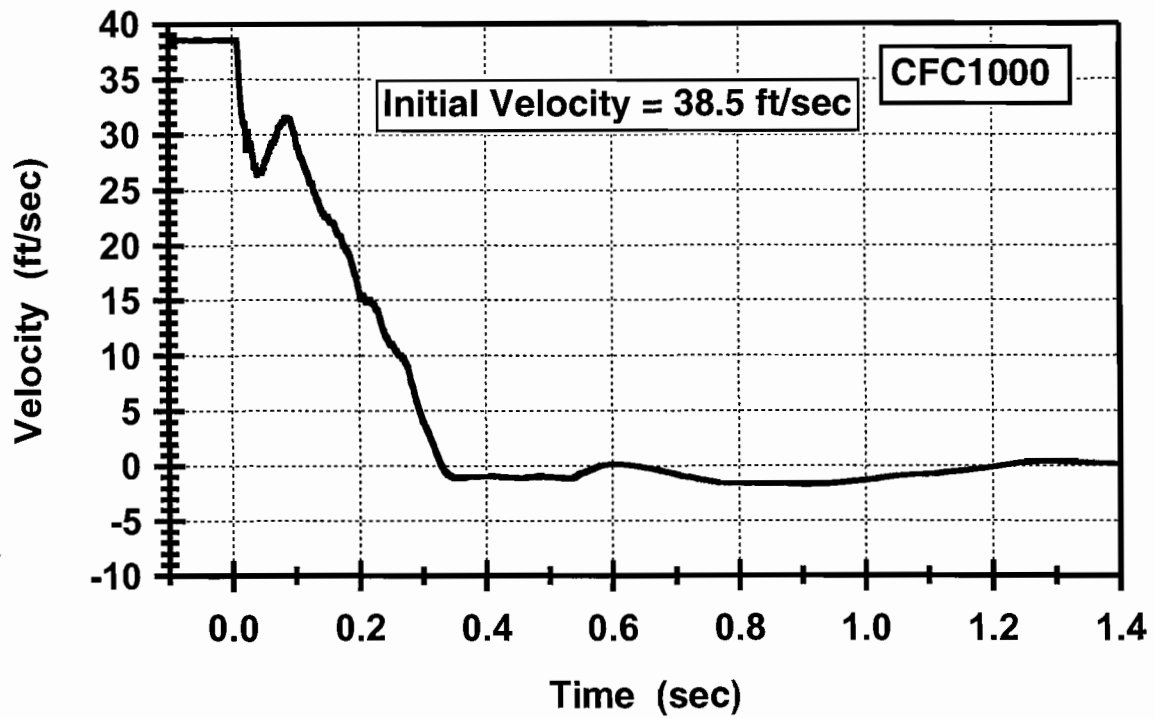


Figure 121. Trailing Car, CS Position 3, X-Axis Accel. Integrated

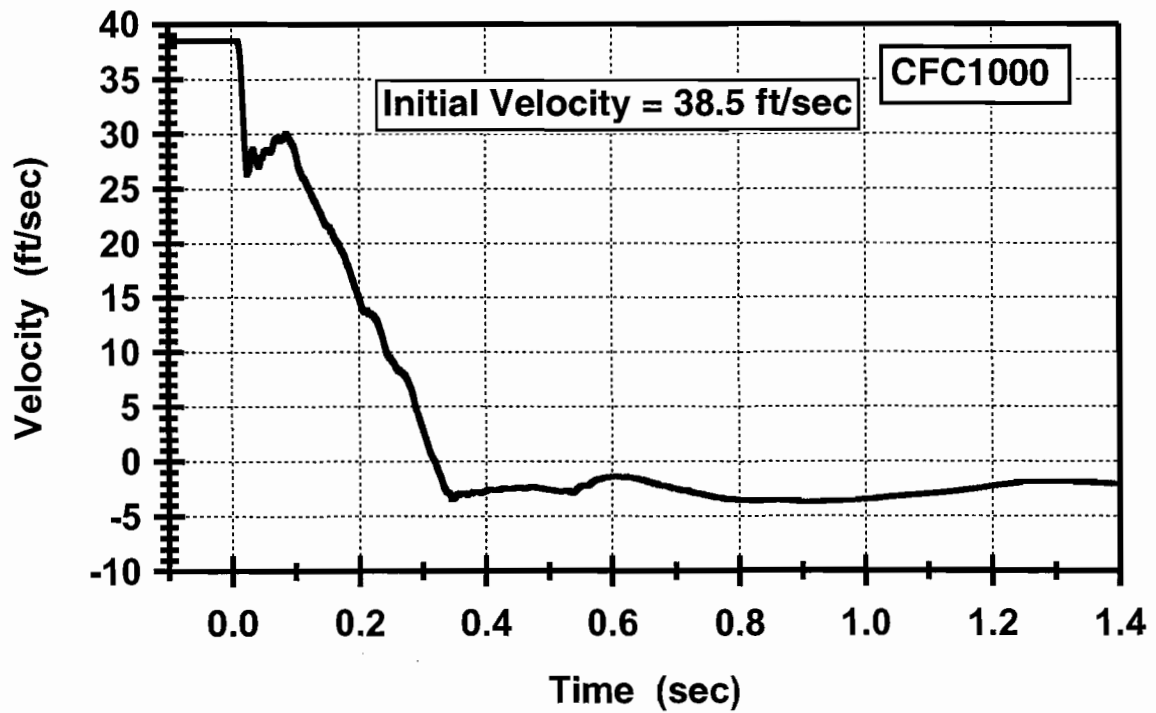


Figure 122. Trailing Car, CS Position 4, X-Axis Accel. Integrated

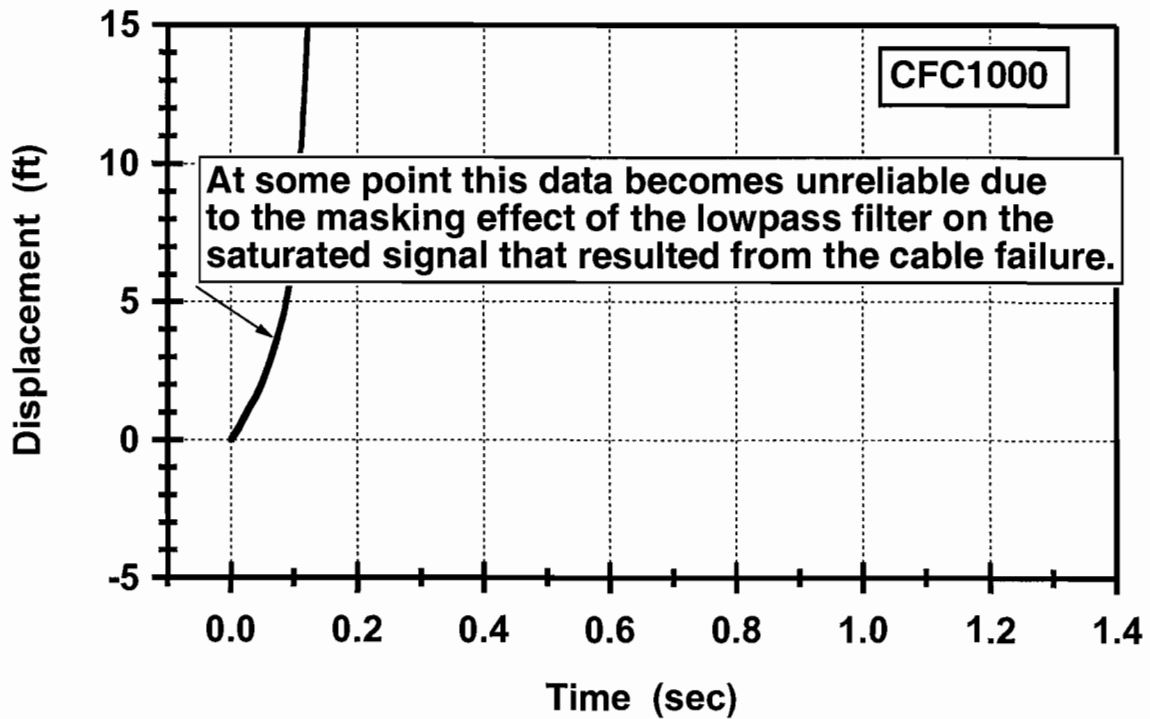


Figure 123. Lead Car, CS Position 1, X-Axis Accel. Double Integrated

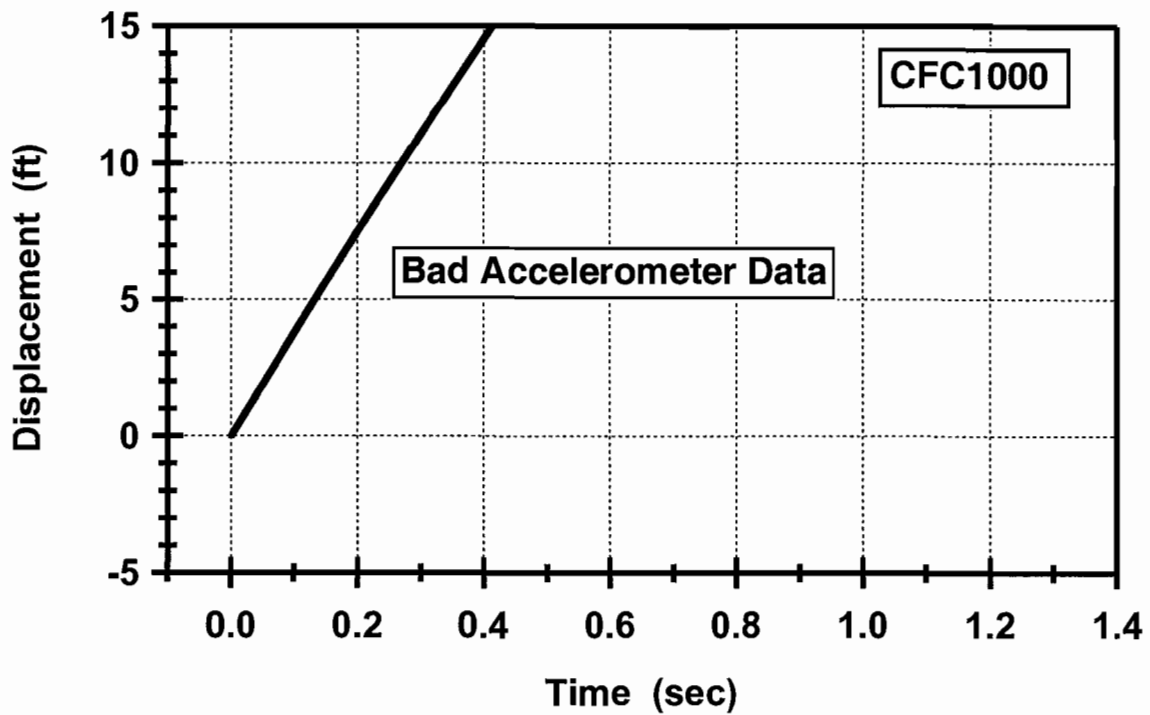


Figure 124. Lead Car, CS Position 2, X-Axis Accel. Double Integrated

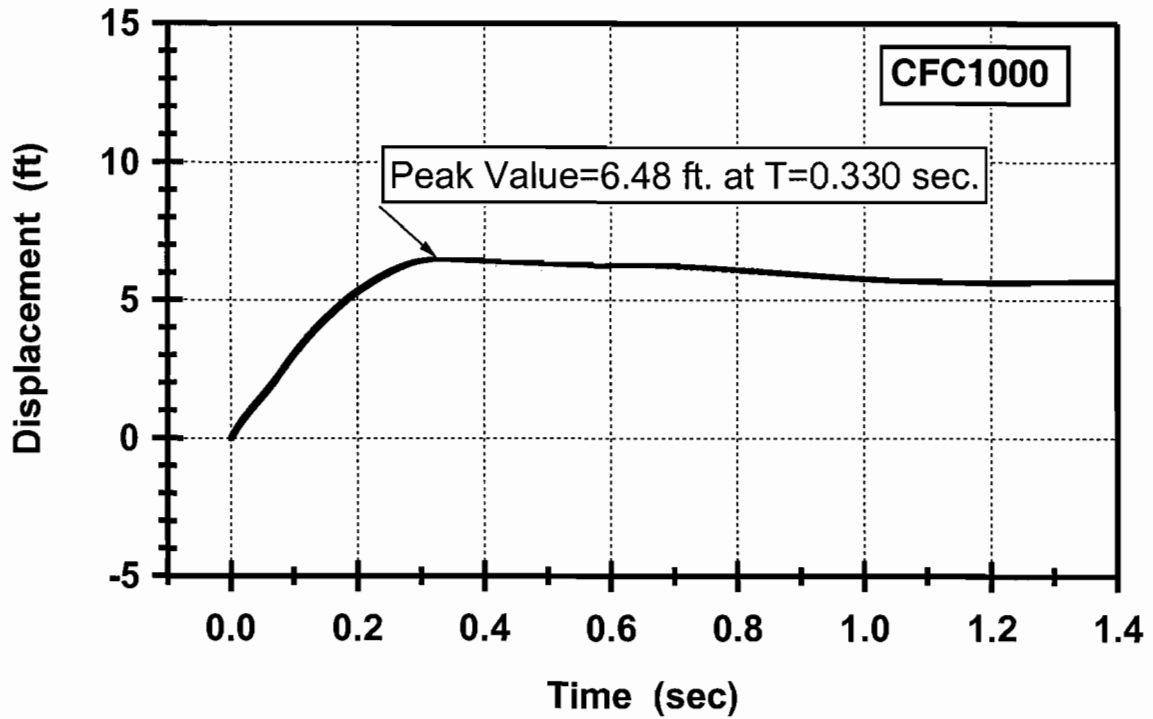


Figure 125. Lead Car, CS Position 3, X-Axis Accel. Double Integrated

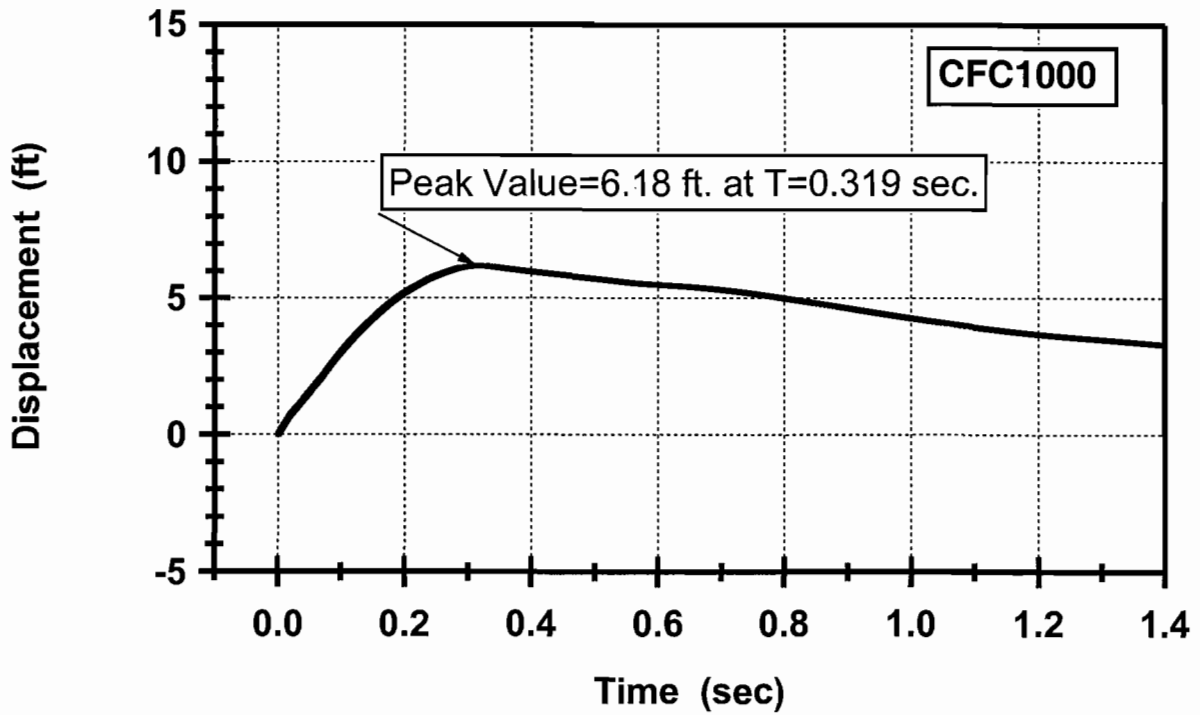


Figure 126. Lead Car, CS Position 4, X-Axis Accel. Double Integrated

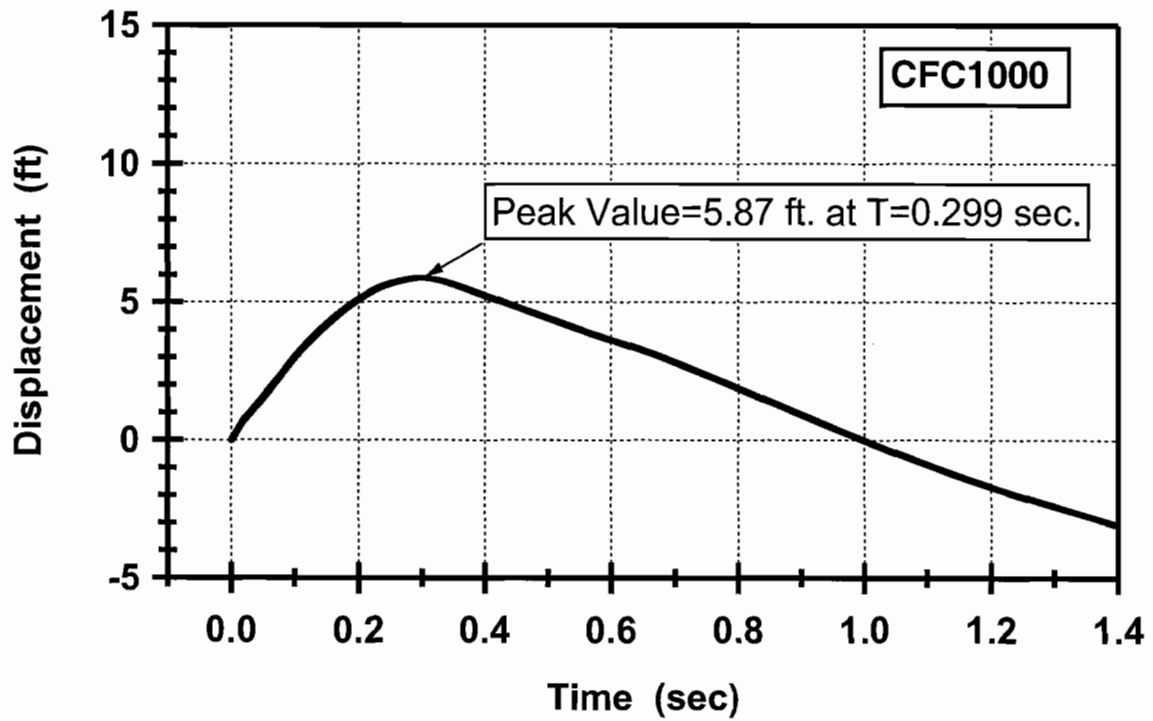


Figure 127. Lead Car, CS Position 5, X-Axis Accel. Double Integrated

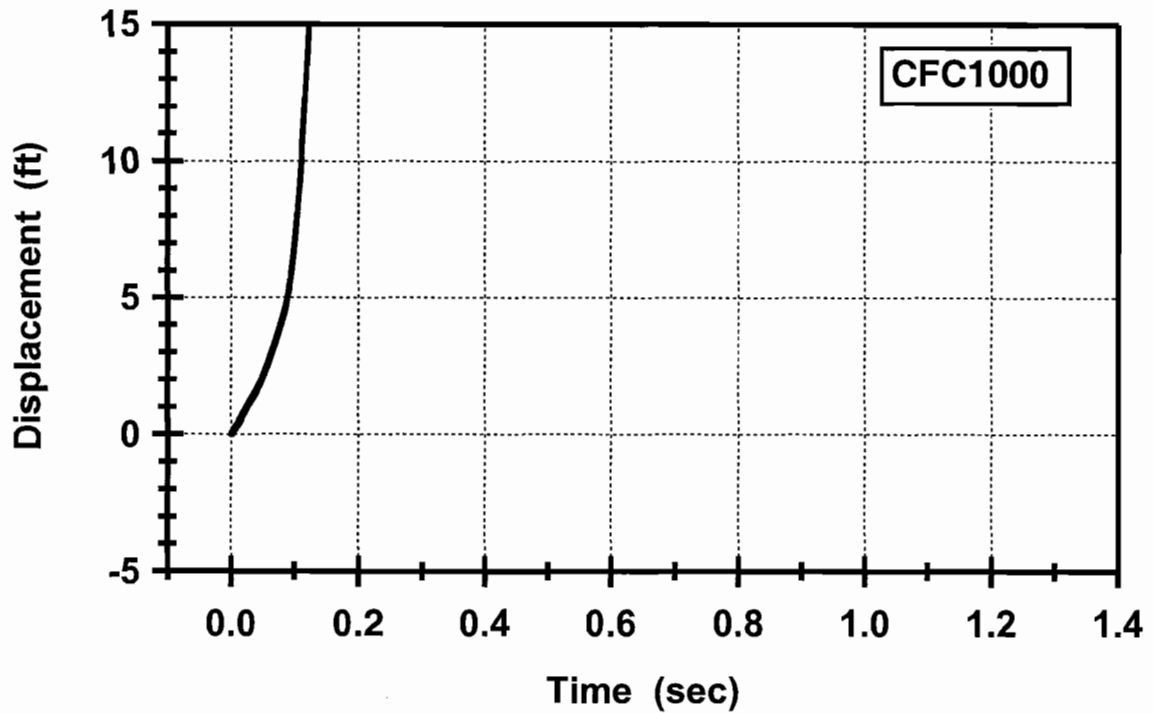


Figure 128. Trailing Car, CS Position 1, X-Axis Accel. Double Integrated

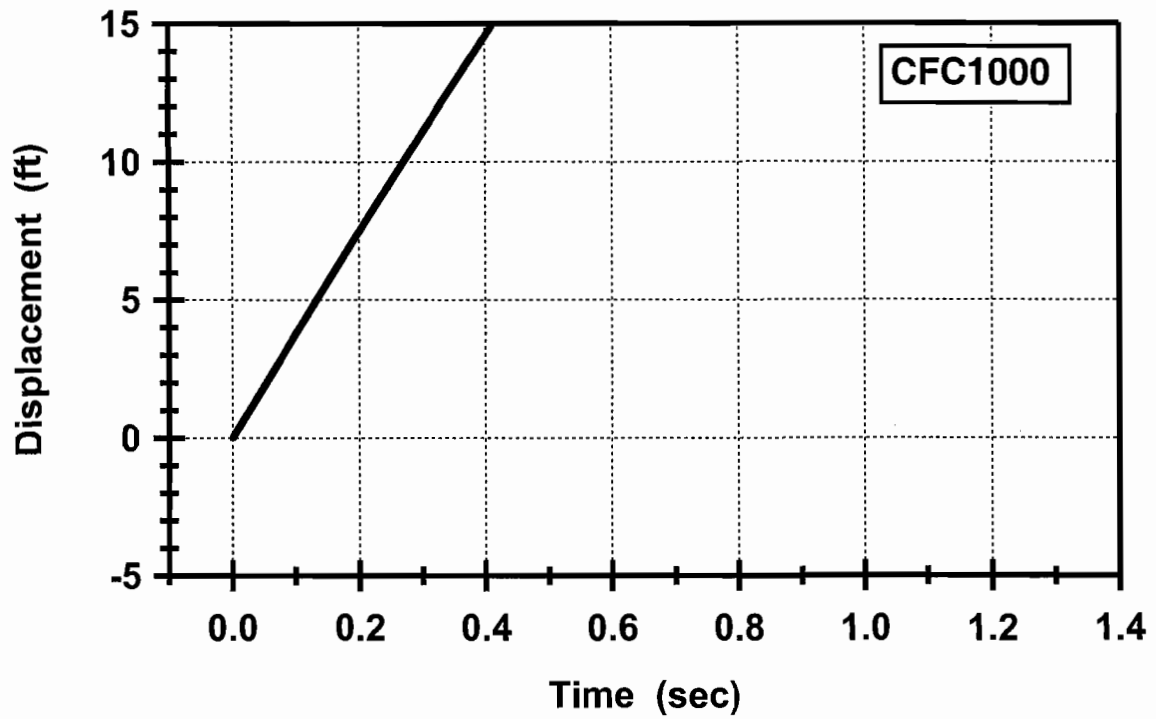


Figure 129. Trailing Car, CS Position 2, X-Axis Accel. Double Integrated

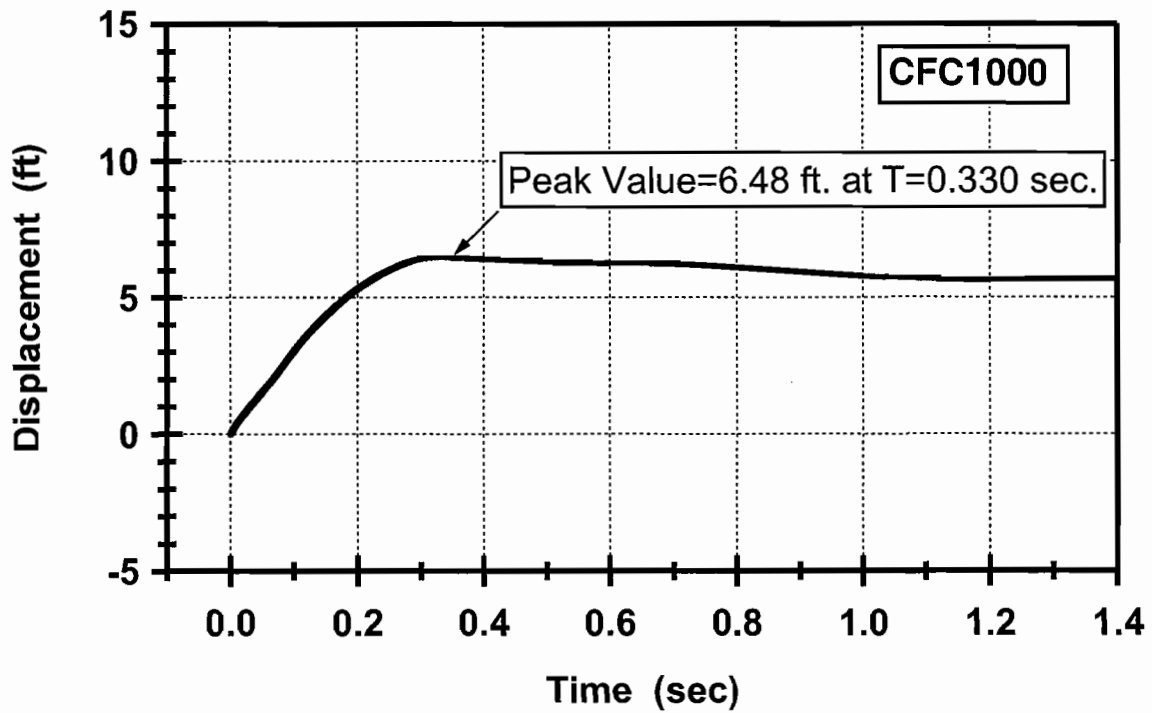


Figure 130. Trailing Car, CS Position 3, X-Axis Accel. Double Integrated

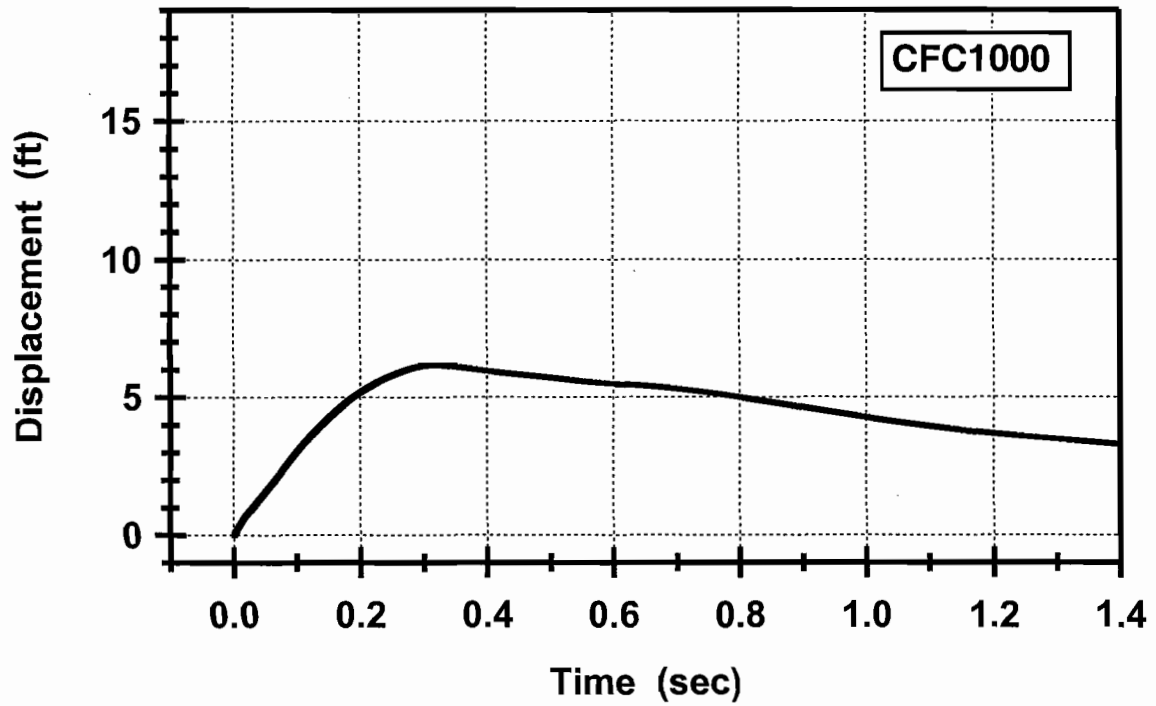


Figure 131. Trailing Car, CS Position 4, X-Axis Accel. Double Integrated

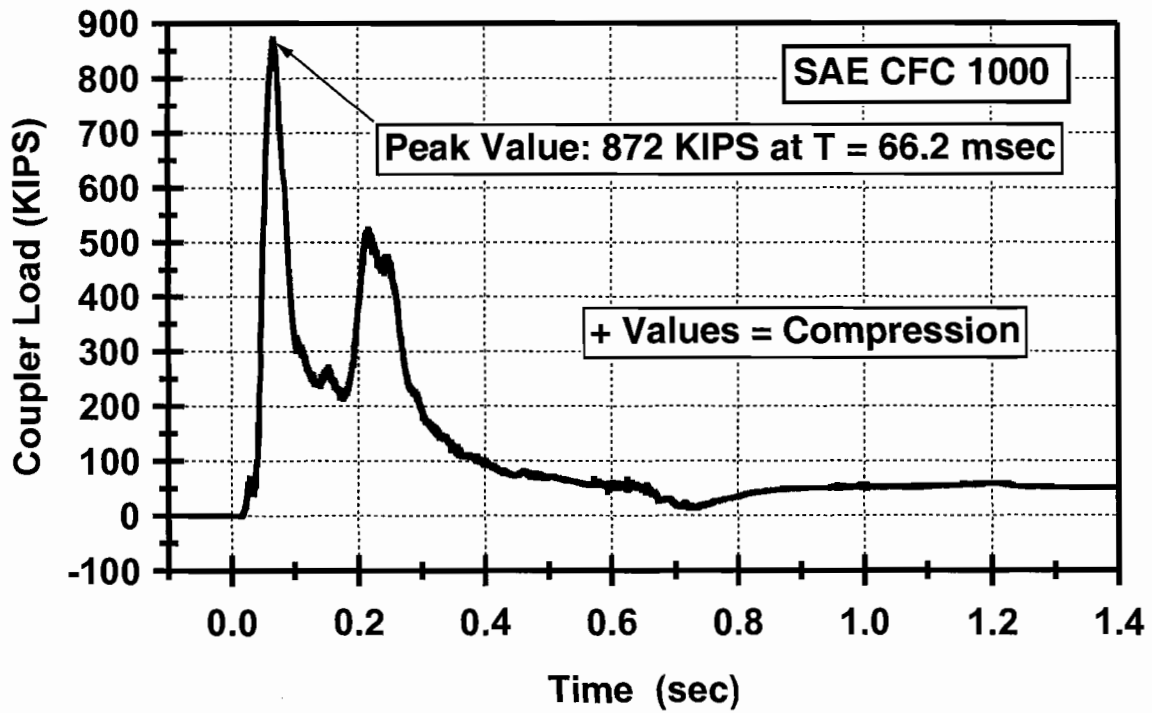


Figure 132. Coupler Load, Lead Car, B-End

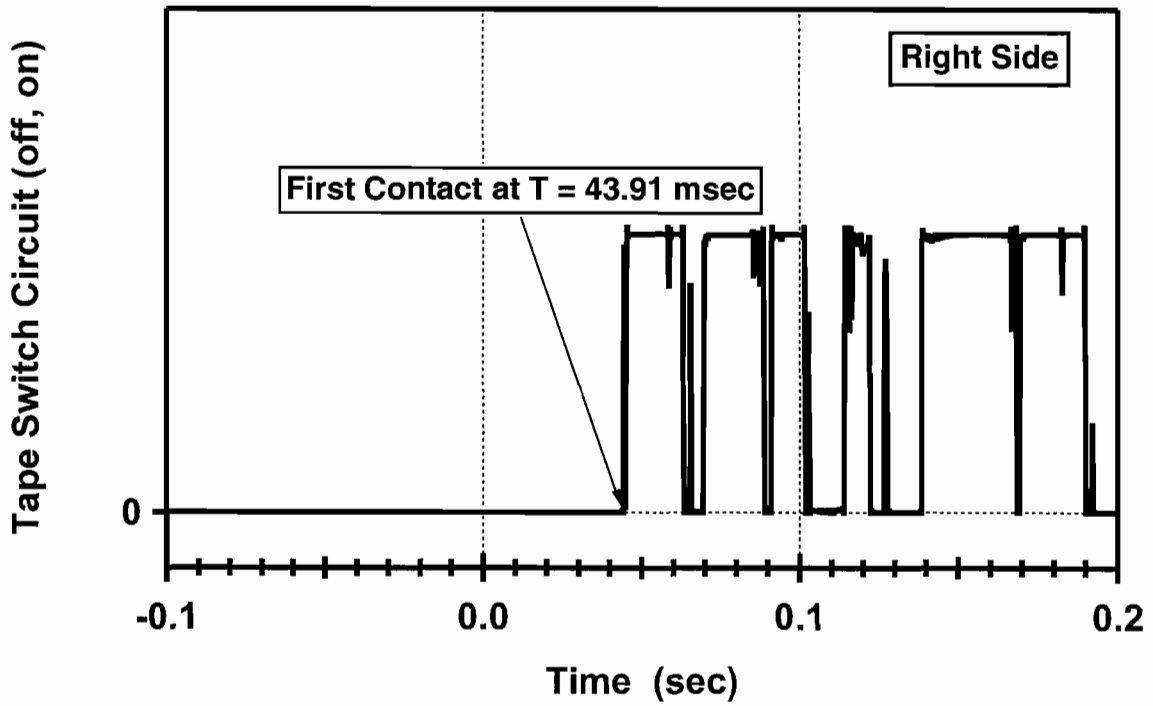


Figure 133. Lead Car, Right Vertical Column Tape Switch

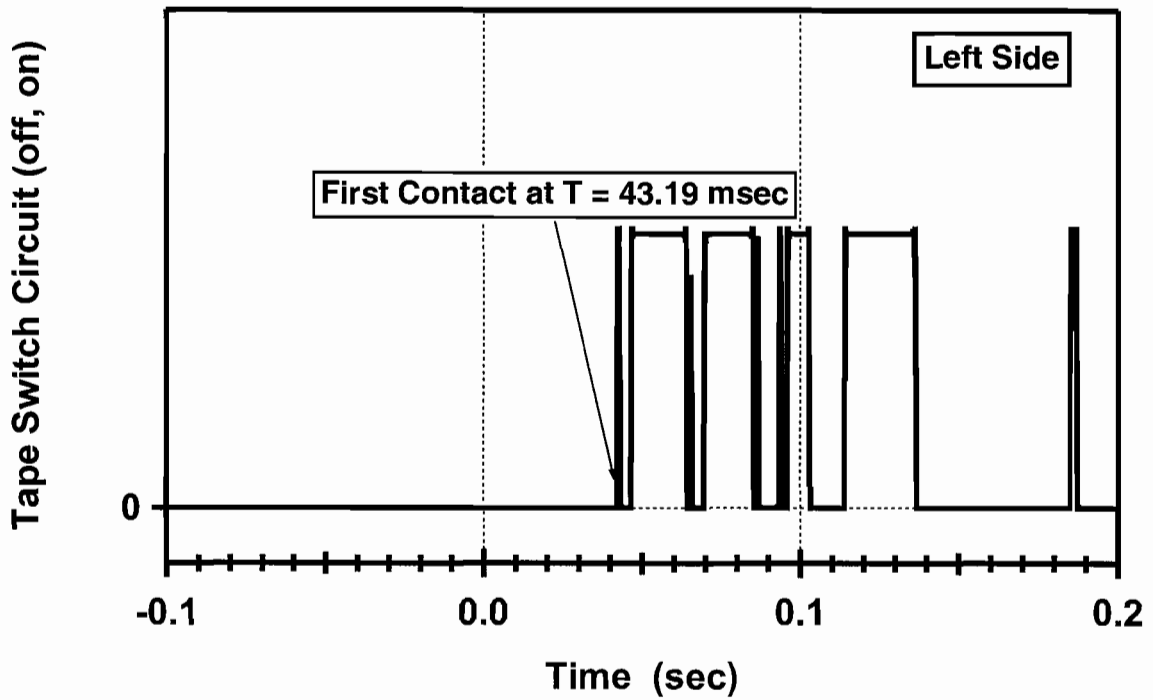


Figure 134. Lead Car, Left Vertical Column Tape Switch

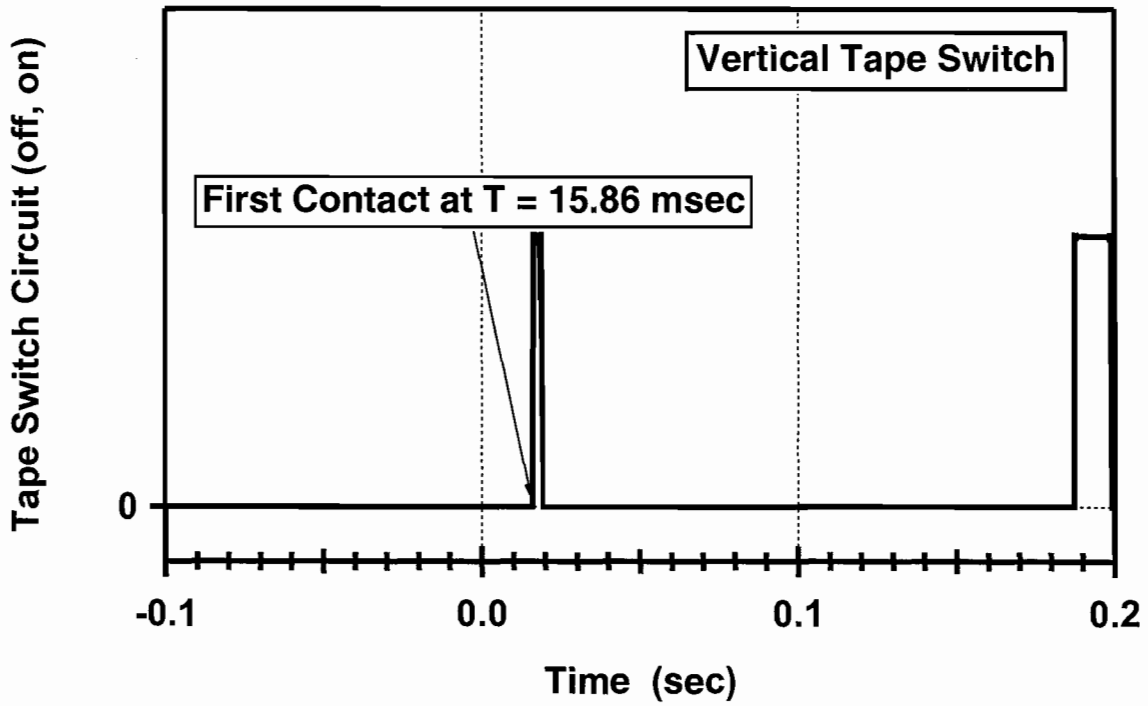


Figure 135. Lead Car, A-End, Coupler Pocket Vertical Tape Switch

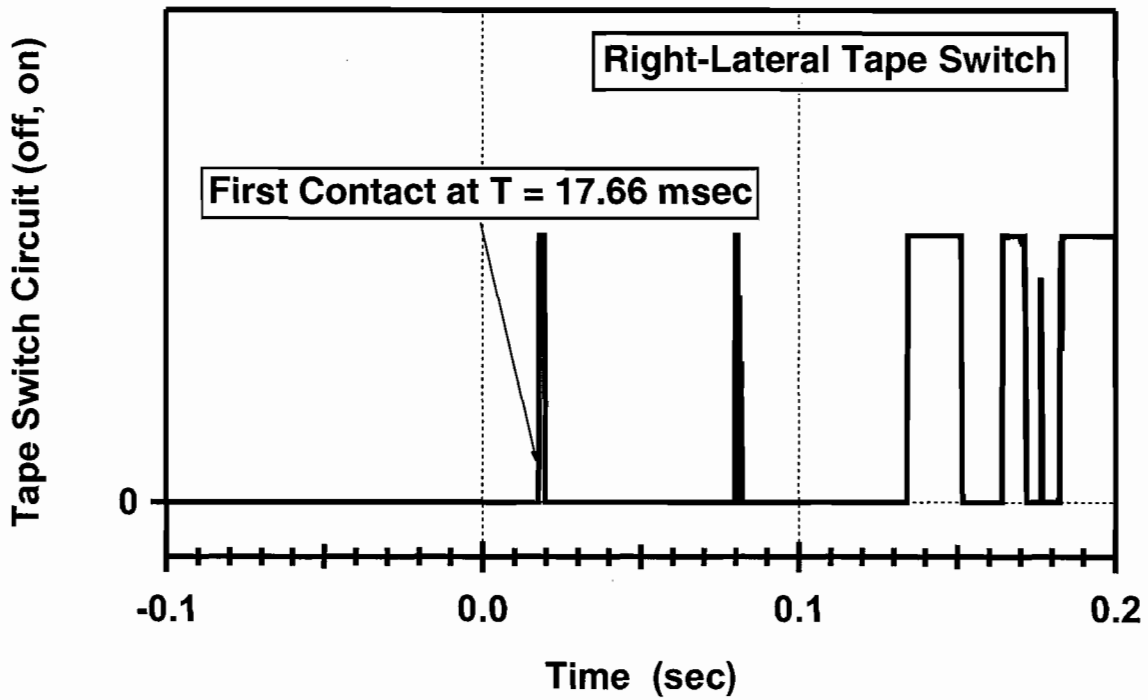


Figure 136. Lead Car, A-End, Coupler Pocket Right Lateral Tape Switch

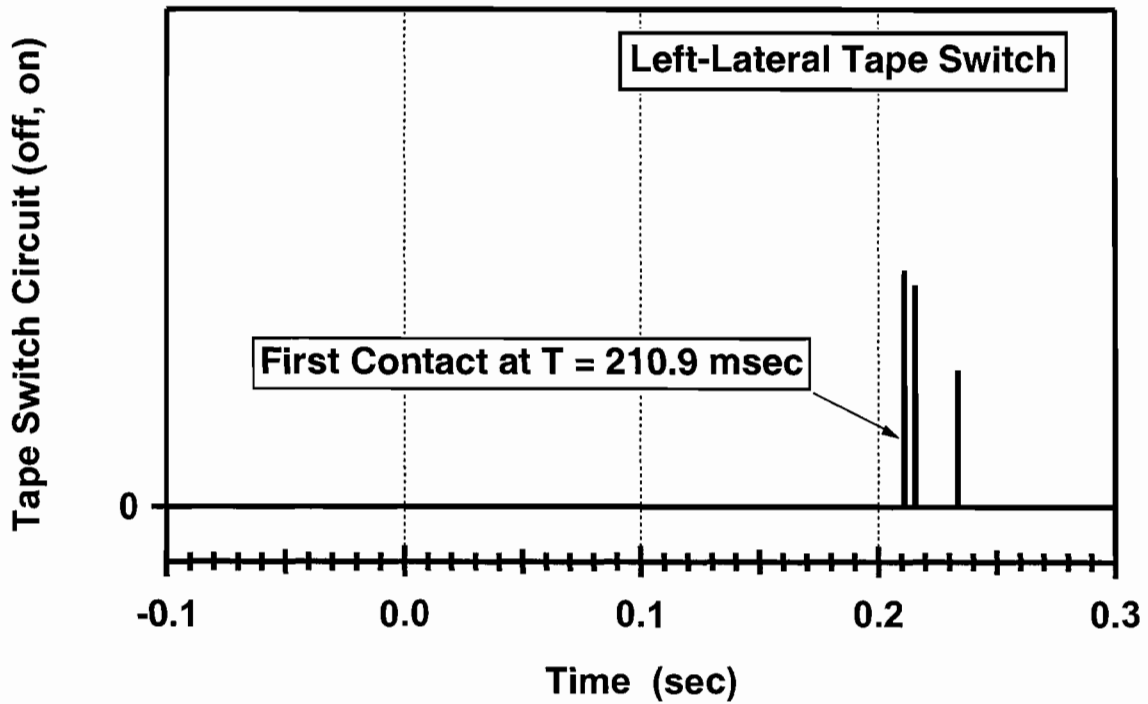


Figure 137. Lead Car, A-End, Coupler Pocket Left Lateral Tape Switch

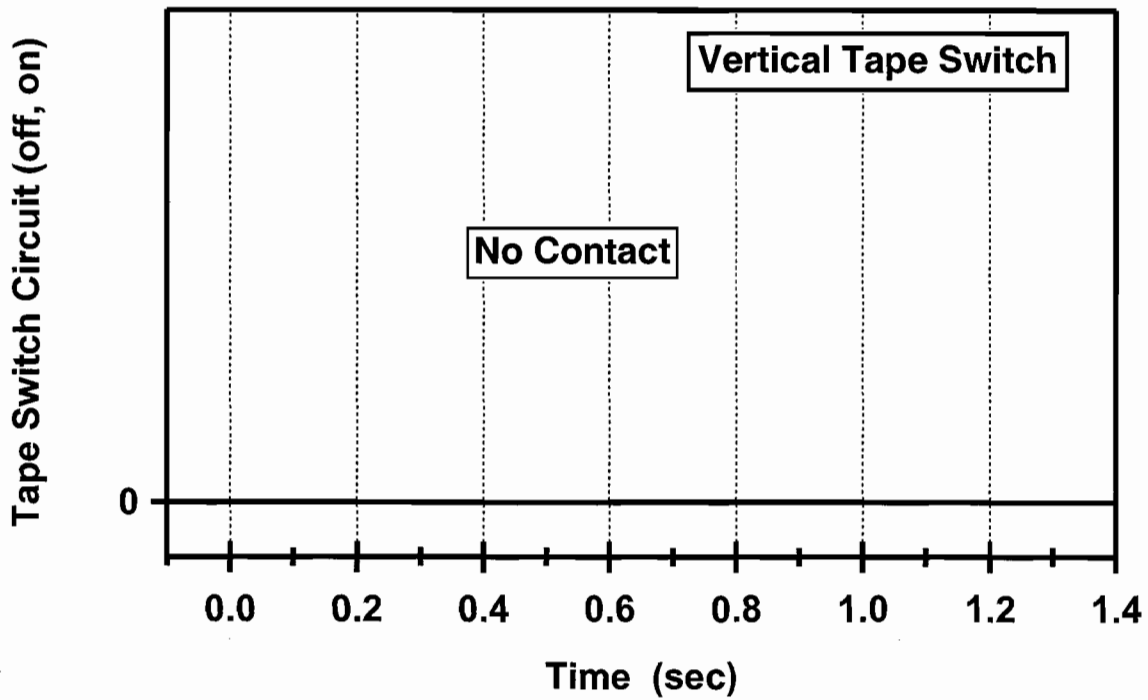


Figure 138. Lead Car, B-End, Coupler Pocket Vertical Tape Switch

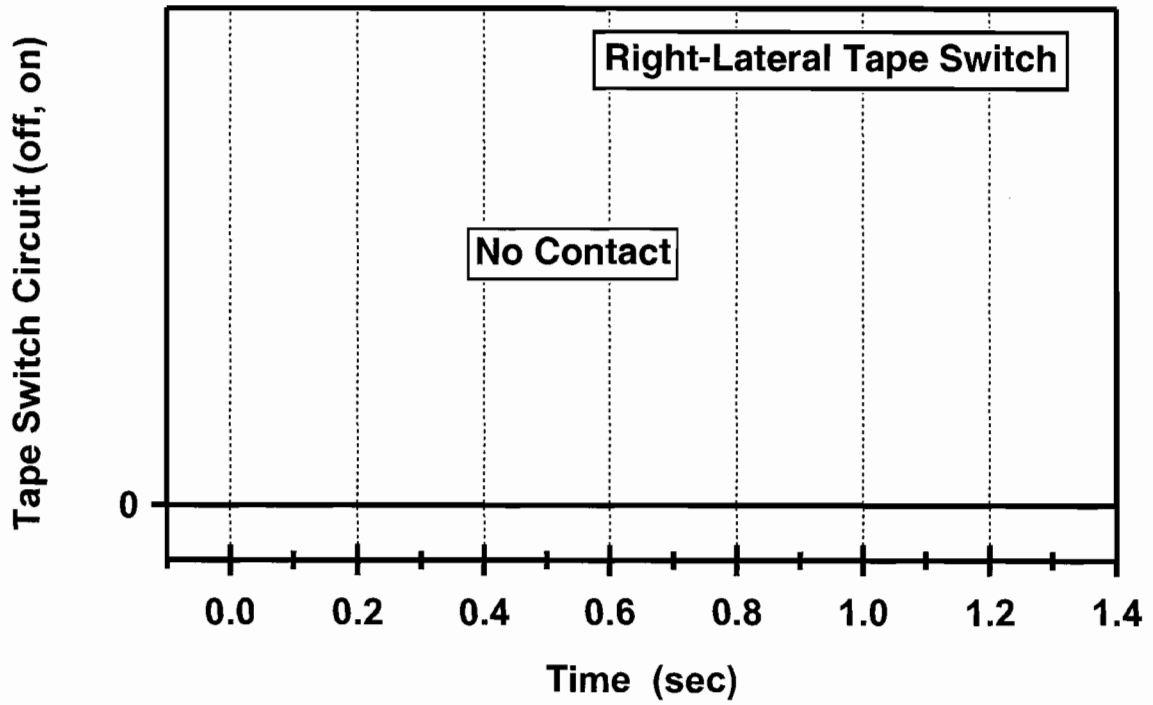


Figure 139. Lead Car, B-End, Coupler Pocket Right Lateral Tape Switch

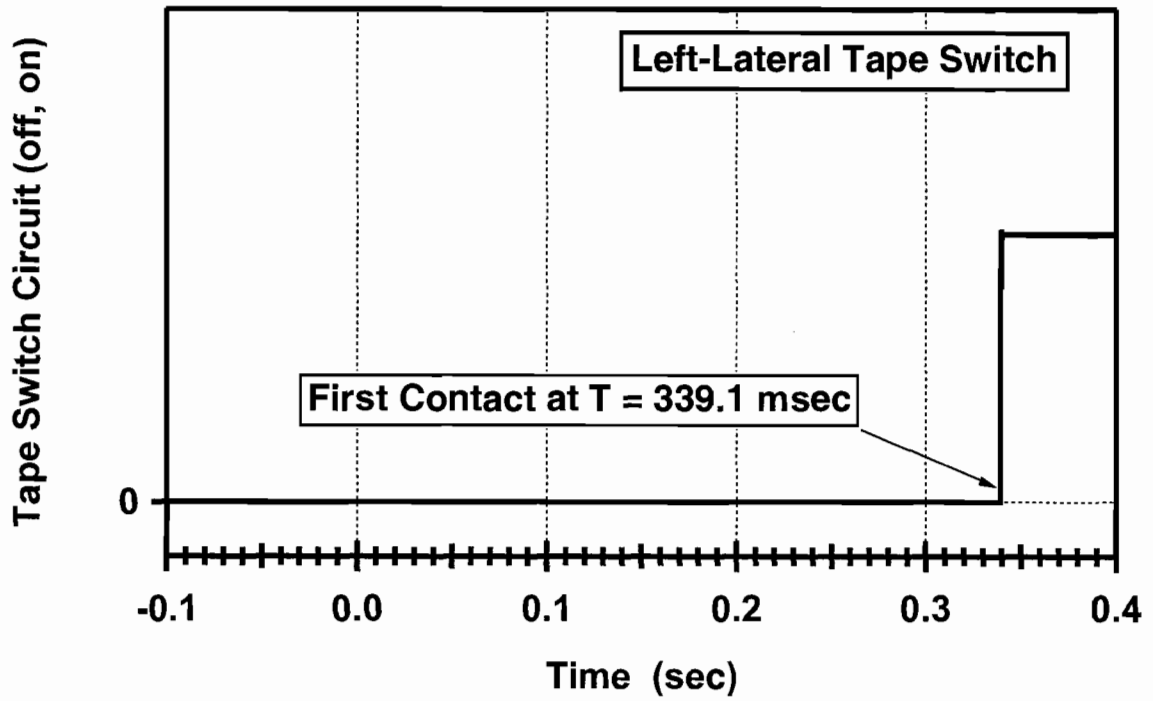


Figure 140. Lead Car, B-End, Coupler Pocket Left Lateral Tape Switch

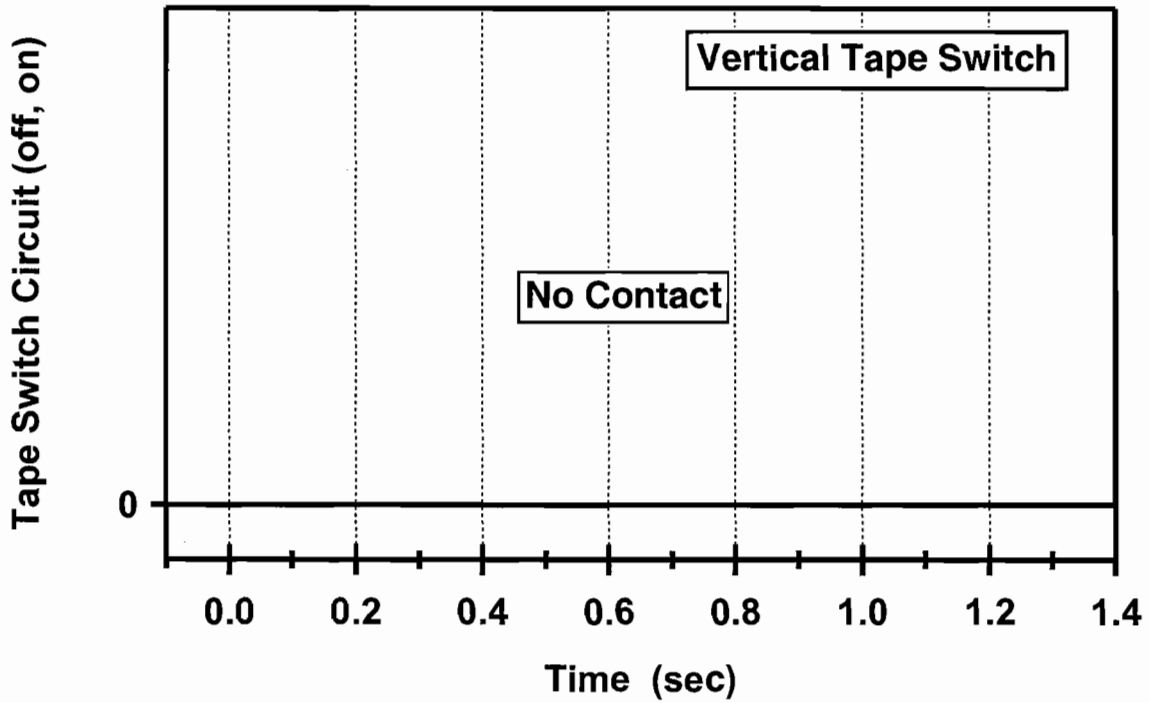


Figure 141. Trailing Car, A-End, Coupler Pocket Vertical Tape Switch

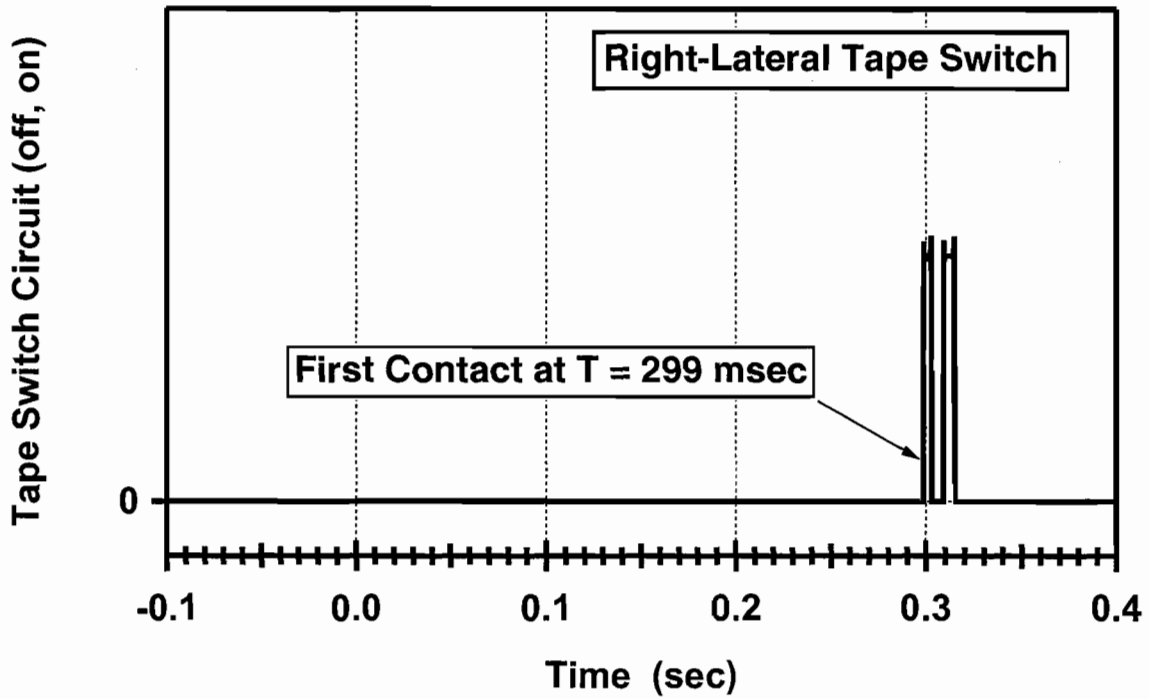


Figure 142. Trailing Car, A-End, Coupler Pocket Right Lateral Tape Switch

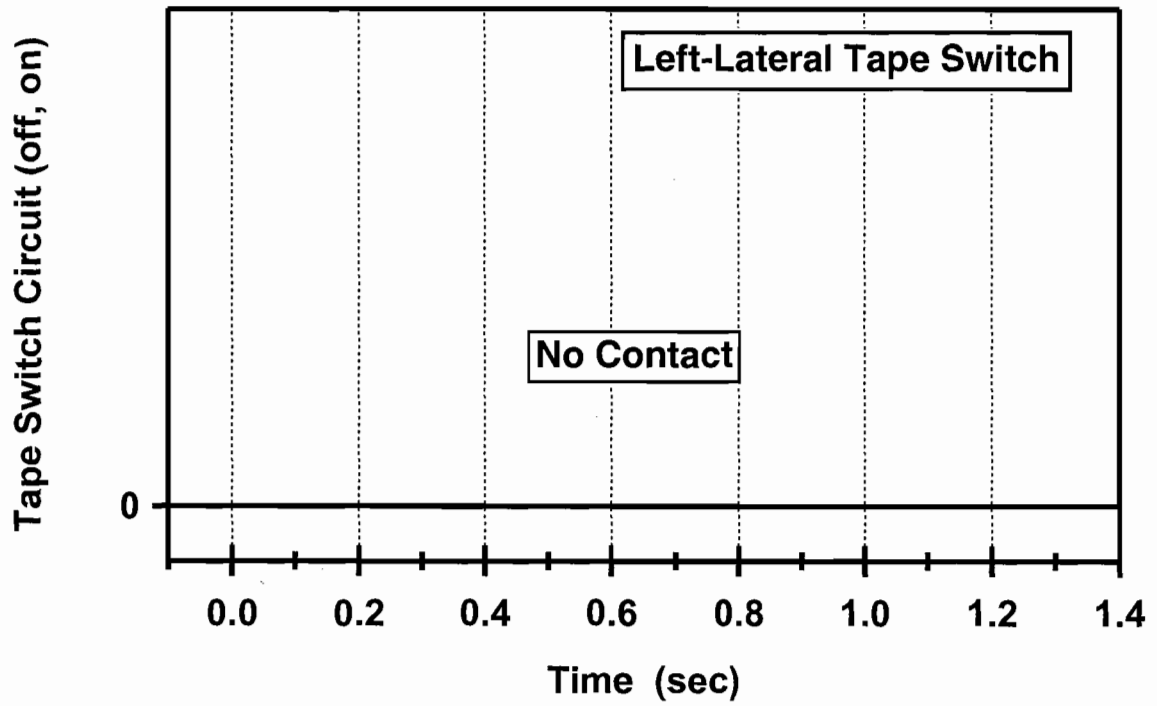


Figure 143. Trailing Car, A-End, Coupler Pocket Left Lateral Tape Switch

APPENDIX A
TEST IMPLEMENTATION PLAN FOR
TWO-CAR DYNAMIC IMPACT TEST

1.0 Purpose

To run two coupled cars into a rigid barrier so that the lead car crushes by at least four feet, and to measure material strains, structural accelerations, suspension displacements, coupler forces and coupler displacements throughout the vehicle in sufficient quantity to allow correlation with analytical predictions.

2.0 Requirements

To impact two passenger cars coupled together into a rigid barrier at a speed of 26 mph (+ or - 2 mph).

3.0 Test Cars

The test will be conducted using two Pioneer type commuter passenger cars, provided by SEPTA.

The test cars will be modified internally so that a total of four interior tests will be conducted simultaneously: the lead car will have the same three configurations as tested in the single car impact test carried out on November 16, 1999. The trailing car will have forward facing unrestrained dummies. The interior experiments will be provided by SIMULA.

Weights will be added to both the test cars to replace the seats and other equipment removed from them before the test.

4.0 Test Method

The test will be performed at TTC by impacting the coupled test cars into a rigid barrier at a speed of 26 mph. This will be carried out by pushing the test cars with a locomotive and then releasing them and allowing them to roll down a constant gradient slope into the rigid barrier. The release distance and the speed of the locomotive at the release point will be determined from a series of calibration runs carried out on a parallel track to the impact track. Both tracks have the same slope.

An on-board radar speed measuring system will be used for speed calibration of the test cars. 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 to measure the speed of the test cars just before impact.

On-board instrumentation will record accelerations, displacements and strains at various points on both test cars during the impact. High speed film cameras will be used to record both the impact at the wall and the impact between the two cars.

5.0 Measured Items

The following items will be measured on each car before the test:

1. Car length measured from buffer-beam to buffer-beam.
2. Longitudinal distance from buff stop to body bolster, at both ends of car.
3. Longitudinal distance between body bolsters.

4. Vertical distance between mid-point of car and a line extending between body bolsters.
5. Vertical distance between buffer beam and a line extending between body bolsters.
6. The weight of each test car.

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 gages 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 test vehicle. The following items will be measured during the test:

1. The speed of the car just before impact using a laser based speed trap.
2. Longitudinal strains at draft sill, center sill, side sills and cant rails at the impact end of the leading car (23 strain gages)
3. Accelerations of center sill, left and right side sills, and at the body bolster of the leading car (21 accelerometers).
4. Acceleration of each truck of the leading car in the vertical direction (2 accelerometers)
5. Displacement across each secondary suspension of the leading car (4 string potentiometers)
6. Displacement across each secondary suspension of the trailing car (4 string potentiometers).
7. Lateral and vertical displacements of couplers relative to car body (3 string potentiometers on each coupler; i.e., total of 6 string potentiometers).
8. Longitudinal strain on coupler (1 strain gage bridge)
9. Accelerations of center sill, left and right side sill, and at the body bolster of the trailing car (12 accelerometers).
10. Acceleration of each truck of the trailing car in the vertical direction (2 accelerometers).
11. Longitudinal strains at the draft sill, center sill, side sills and cant rails at the rear end of the leading car (16 strain gages)
12. Longitudinal strains at the draft sill, center sill, side sills and cant rails at the front end of the trailing car (16 strain gages).
13. Tape switches on each corner post of impact end of leading car (2 channels).
14. Tape switches on each side of coupler housing and one on top to indicate vertical movement (3 tape switches on each coupler).

This amounts to a total of 115 channels

Table 6.1.1.2 Lead Car , Impact End, Strain gage location and type, Side Sills

| Location | Strain Gage | Channel |
|--------------------------------------|--|---------|
| Side Sill Left –1- Upper SS-L-1-U | High Elongation (200,000 maximum strain) | 1 |
| SS-L-2-U | | 2 |
| SS-L-1-L | | 3 |
| SS-L-2-L | | 4 |
| SS-R-1-U | | 5 |
| SS-R-2-U | | 6 |
| SS-R-1-L | | 7 |
| SS-R-2-L | | 8 |

Figure 6.1.1.4 shows the detailed arrangement of the high elongation strain gages on the left cant rail. Table 6.1.1.3 lists the locations and strain gage types for all the strain gages on the cant rails.

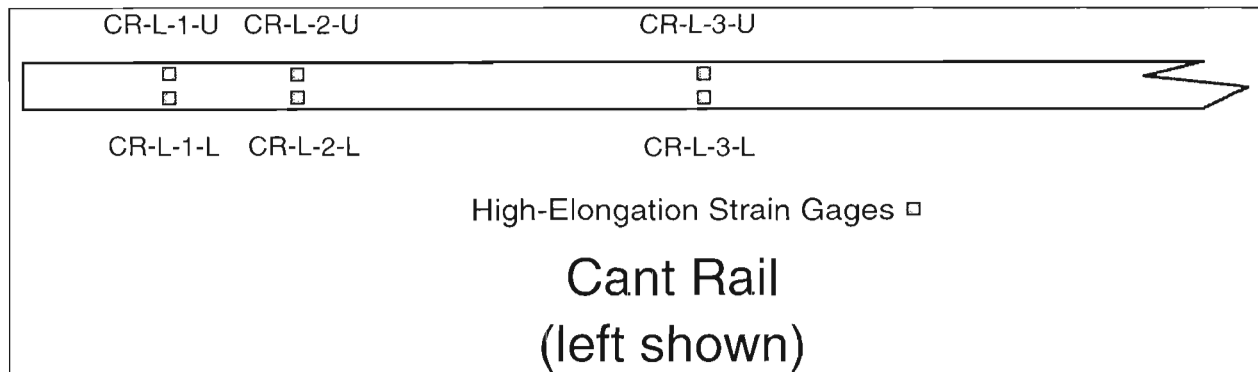


Figure 6.1.1.4 Detailed arrangement of high elongation strain gages on the left cant rail.

Table 6.1.1.3 Trailing Car, Leading End, Strain gage location and type, Cant rails

| Location | Strain Gage | Channel |
|-----------------------|---|---------|
| Cant Rail CR-L-2-U | High Elongation 200,000 maximum strain | 1 |
| CR-L-2-L | | 2 |
| CR-R-2-U | | 3 |
| CR-R-2-L | | 4 |

6.1.2 Strain Measurements, Lead Car, Trailing End

Table 6.1.2.1 Lead Car, Trailing End, Strain gage location and type, Center Sill

| Location | Strain Gage | Channel |
|--|--|---------|
| Center Sill Right –1-Upper CS-R-1-U | (20,000 maximum strain). Yield strain. | 1 |
| CS-R-2-U | | 2 |
| CS-L-1-U | | 3 |
| CS-L-2-U | | 4 |
| CS-L-1-L | | 5 |
| CS-L-2-L | | 6 |
| CS-R-1-U | | 7 |
| CS-R-2-U | | 8 |

Table 6.1.2.2 Lead Car, Trailing End, Strain gage location and type, Side Sills

| Location | Strain Gage | Channel |
|--------------------------------------|--|---------|
| Side Sill Left –1- Upper SS-L-1-U | (20,000 maximum strain). Yield strain. | 1 |
| SS-L-1-L | | 2 |
| SS-R-1-U | | 3 |
| SS-R-1-L | | 4 |

Table 6.1.2.3 Lead Car, Trailing End, Strain gage location and type, Cant rails

| Location | Strain Gage | Channel |
|-----------------------|---|---------|
| Cant Rail CR-L-2-U | (20,000 maximum strain). Yield strain. | 1 |
| CR-L-2-L | | 2 |
| CR-R-2-U | | 3 |
| CR-R-2-L | | 4 |

6.1.3 Strain Measurements, Trailing Car, Leading End

Table 6.1.3.1 Trailing Car, Leading End, Strain gage location and type, Center Sill

| Location | Strain Gage | Channel |
|--|-------------------------|---------|
| Center Sill Right –1-Upper CS-R-1-U | (20,000 maximum strain) | 1 |
| CS-R-2-U | | 2 |
| CS-L-1-U | | 3 |
| CS-L-2-U | | 4 |
| CS-L-1-L | | 5 |
| CS-L-2-L | | 6 |
| CS-R-1-U | | 7 |
| CS-R-2-U | | 8 |

Table 6.1.3.2 Trailing Car , Leading End, Strain gage location and type, Side Sills

| Location | Strain Gage | Channel |
|--------------------------------------|-------------------------|---------|
| Side Sill Left –1- Upper SS-L-1-U | (20,000 maximum strain) | 1 |
| SS-L-1-L | | 2 |
| SS-R-1-U | | 3 |
| SS-R-1-L | | 4 |

Table 6.1.3.3 Trailing Car, Leading End, Strain Gage location and type, Cant rails

| Location | Strain Gage | Channel |
|-----------------------|--------------------------|---------|
| Cant Rail CR-L-2-U | (20,000 maximum strain) | 1 |
| CR-L-2-L | | 2 |
| CR-R-2-U | | 3 |
| CR-R-2-L | | 4 |

6.1.4 Coupler Force

The coupler will be strain gaged with a single gage bridge measuring the longitudinal force.

6.2 Acceleration Measurements

The car body gross and flexible motions will be measured using accelerometers. The gross motions of the car body are the longitudinal, lateral, and vertical translational displacements, as well as the pitch, yaw and roll angular displacements. The gross motions of the car shall be measured in or near the operator’s control stand, and in the passenger volume. The flexible modes of concern include vertical and lateral bending

as well as torsional displacement about axis of the car. Measurements of these motions are required to fully characterize the secondary collision environment.

Figure 6.2.1 shows the location of the accelerometers schematically. Table 6.2.1 lists the accelerometer locations, accelerometer types, and data channels.

All the accelerometers are critically damped. The accelerometers will be calibrated prior to installation. The accelerometers possess 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.

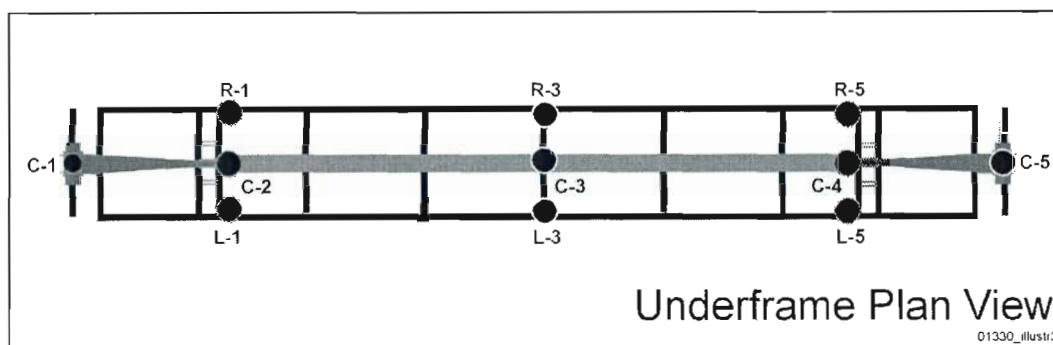


Figure 6.2.1 Schematic Diagram of Accelerometer Locations.

Table 6.2.1 Lead Car, Accelerometers

| Location | Accelerometer | Measurement | Channel |
|-------------|---------------|--------------------|---------|
| C-1 | Single axis | Longitudinal 400g | 1 |
| C-2 | Three axis | Vertical 400g | 2 |
| | | Lateral 400g | 3 |
| | | Longitudinal 1000g | 4 |
| C-3 | Three axis | Vertical 200g | 5 |
| | | Lateral 200g | 6 |
| | | Longitudinal 400g | 7 |
| C-4 | Three axis | Vertical 400g | 8 |
| | | Lateral 400g | 9 |
| | | Longitudinal 400g | 10 |
| C-5 | Single axis | Longitudinal 200g | 11 |
| R-1 | Single axis | Vertical 400g | 12 |
| R-3 | Three axis | Vertical 100g | 13 |
| | | Lateral 100g | 14 |
| | | Longitudinal 200g | 15 |
| R-5 | Single axis | Vertical 100g | 16 |
| L-1 | Single axis | Vertical 400g | 17 |
| L-3 | Three axis | Vertical 100g | 18 |
| | | Lateral 100g | 19 |
| | | Longitudinal 200g | 20 |
| L-5 | Single axis | Vertical 100g | 21 |
| B-1 (Bogie) | Single axis | Vertical 400g | 22 |
| B-2 (Bogie) | Single axis | Vertical 400g | 23 |

Table 6.2.2 Trailing Car, Accelerometers

| Location | Accelerometer | Measurement | Channel |
|-------------|---------------|-------------------|---------|
| C-1 | Single axis | Longitudinal 200g | 1 |
| C-2 | Three axis | Vertical 200g | 2 |
| | | Lateral 400g | 3 |
| | | Longitudinal 200g | 4 |
| C-3 | Three axis | Vertical 100g | 5 |
| | | Lateral 100g | 6 |
| | | Longitudinal 200g | 7 |
| C-4 | Three axis | Vertical 50g | 8 |
| | | Lateral 50g | 9 |
| | | Longitudinal 50g | 10 |
| R-3 | Single axis | Vertical 50g | 11 |
| L-3 | Single axis | Vertical 50g | 12 |
| B-1 (Bogie) | Single axis | Vertical 400g | 13 |
| B-2 (Bogie) | Single axis | Vertical 200g | 14 |

6.3 String Potentiometers

Four string potentiometers will be fixed across each secondary suspension on the lead car and trailing car, between body bolster and bogie bolster to measure the relative vertical displacement (Total of 8 string potentiometers).

Three string potentiometers will be fixed between the coupler and each car body, between the leading and trailing cars, to measure lateral and vertical displacements (Total of 6 potentiometers).

All the string potentiometers have a range of plus or minus 5 inches.

6.4 High-speed and real-time photography

Ten high-speed film cameras and ten video cameras will document the impact test. Locations of the cameras are shown in Fig. 6-4-1. Coverage and frame rates appear in Table 6-4-1. Cameras 1,3,4 and 7 will view from just below the top of the rail to just above the car bodies. Thus the height of the view at the side of the car-body will be approximately 12 ft, and the width of the view will be approximately 18 ft. These cameras will be located approximately 25 ft away from the side of the car bodies. Camera 2 will be positioned on top of the barrier wall looking down at the impact zone. Cameras 5 and 8 will be placed on the ground looking up, while camera 6 will be positioned on the bridge looking down at the cars. Camera 9 will be mounted on the front of the trailing car looking down at the coupler. Camera 10 is a panning camera and camera 11 is looking along the side of the car. All the cameras are equipped with sights that allow the photographer to view the expected image. Thus the final siting will be done at the time of camera setup to achieve the views described above. Adjustments will be made, if necessary, to the above distances to achieve the desired 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 (LED) in the high-speed cameras. Illumination of the LED 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. Film for the on-board camera will be Kodak 16-mm 7249, ISO 500, for tungsten on 100-ft spools.

Four-in. diameter targets will be placed on the vehicle 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 the 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 the 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 running at a nominal speed of 500 frames per second will run for about 8 seconds before the 100-ft film is entirely exposed.

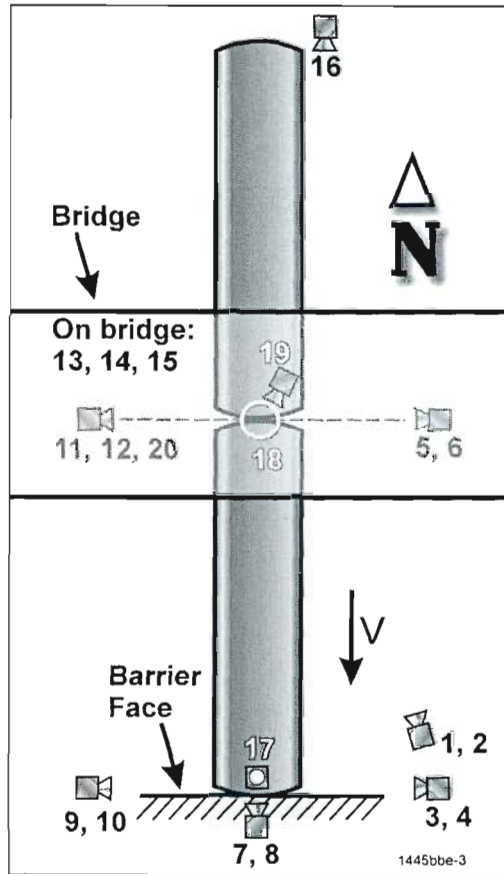


Figure 6.4.1 Film Camera Positions

Table 6.4.1 Film Camera information

| No. | Type | Manufacturer Model | Speed | Coverage | Position | Lens |
|-----|-------|--------------------|---------|----------|-------------|-------|
| 1 | Film | Locam | 500 fps | Panning | Ground | - |
| 2 | Video | JVC | 120 fps | Panning | Ground | - |
| 3 | Video | Sony | RT | Close | Ground | - |
| 4 | Film | Millikan | 500 fps | Close | Ground | 25 mm |
| 5 | Video | Sony | RT | Close | Ground | - |
| 6 | Film | Millikan | 400 fps | Close | Ground | 15 mm |
| 7 | Video | Sony | RT | Close | Barrier | - |
| 8 | Film | Millikan | 500fps | Close | Barrier | 10 mm |
| 9 | Video | JVC | RT | Close | Ground | - |
| 10 | Film | Millikan | 500fps | Close | Ground | 25 mm |
| 11 | Video | Sony | RT | Close | Hill | - |
| 12 | Film | Locam | 500 fps | Close | Hill | 25 mm |
| 13 | Video | Sony | RT | Close | Bridge | - |
| 14 | Video | Sony | RT | Close | Bridge | - |
| 15 | Film | Locam | 500 fps | Close | Bridge | 10 mm |
| 16 | Film | Millikan | 500 fps | Close | Rear | 25 mm |
| 17 | Film | Millikan | 500 fps | Close | Barrier pit | 10 mm |
| 18 | Film | Millikan | 400 fps | Close | Coupler pit | 10 mm |
| 19 | Film | Locam | 500 fps | Close | On-board | 10 mm |
| 20 | Video | XC-999 | RT | Close | Ground | - |

6.5 Data Acquisition

Fifteen, 8-channel battery-powered on-board data acquisition systems will provide excitation to the strain gages and accelerometers, analog anti-aliasing filtering of the signals, analog-to-digital conversion, and recording. 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 four systems 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. GMH Engineering will provide on-board battery power — 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.

6.6 Tape Switches

Tape Switches will be installed on the front of the vehicle in the leading contact position. Closure of these switches at impact will indicate contact between the test vehicle and the barrier. The switch closures will trigger each Data Brick. At least 50 ms of pre-trigger data will be recorded. Separate Tape Switches will also be attached at the front of the vehicle and at a corresponding location on the barrier to fire flash bulbs and to synchronize film cameras. The tape switches will be manufactured by Tapeswitch Corporation, model 1201-131-A).

Tape switches will also be mounted on the corner posts of the impacting car to indicate the time of contact of each corner post (2 tape switches).

Tape switches will also be mounted on each coupler, between the cars, to indicate lateral and vertical contact with each car body (6 tape switches).

6.7 Speed Trap

A dual channel speed trap will accurately measure impact speed of the test vehicle within 0.5 meter of the barrier. 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 vehicle. Final rod location will be determined prior to installation.

7.0 Test Procedure

- (1) The car bodies will be modified internally with the appropriate seating arrangements.
- (2) Strain gages will be attached on the center sills, side sills and cant rails of the car bodies.

- (3) The car lengths will be measured from buffer beam to buffer beam. The longitudinal distance from buff stop to body bolster will be measured at both ends of the cars. The longitudinal distance body bolsters will be measured. The vertical distance between the mid-point of the cars and a line extending between body bolsters will be measured. The vertical distance between buffer beam and a line extending between the body bolsters will be measured.
- (4) The mass of each car will be calculated by measuring the weight of each end of the car on a weigh bridge (Elevation of the TTC = 5,013 ft., $g = 32.14 \text{ ft/sec}^2$).
- (5) Speed calibration runs will be carried out using the test cars. These will be carried out on the PTT track, which is parallel to the track leading to the barrier. This track has the same gradient as the track leading to the barrier and both are tangent. The test cars will be pushed by a locomotive and then released at points of varying distance from the crash barrier and allowed to run freely down the slope. The speed of the test cars will be measured as they pass the crash barrier, using a laser speed trap. These runs will be carried out at different ambient temperatures and wind speeds. Having passed the barrier, the test cars will be stopped by a locomotive catching them up, catching the coupler, and then slowing down and bringing the cars back to the start point. A calibration chart of speed versus distance for different ambient temperatures and wind speeds will be produced from these tests.
- (6) Calibration runs will be carried out with the test cars on the track leading to the crash barrier in a similar manner to those described above except that the vehicles will not be allowed to travel as far as the crash barrier. A calibration chart of speed versus distance will be produced.
- (7) The test equipment including the accelerometers and data acquisition system will be mounted on the test vehicles. The strain gages will be connected to the data acquisition system and tested.
- (8) The cameras will be set up.
- (9) The weight of the test cars will be measured.
- (10) A check on the calibration speed will be run on the PTT track.
- (11) All instruments will be calibrated and a zero reading carried out.
- (12) A trial low speed soft impact (less than 1 mph) of the test cars will be carried out into the barrier to confirm all the instruments work properly.
- (13) The instruments will be re-calibrated, the Tape switches replaced and the test cars pulled back.
- (14) The test cars will be released at the appropriate distance from the barrier, triggering the cameras and the instrumentation just before impact.
- (15) After the test the longitudinal and vertical distances mentioned in paragraph (3) will be re-measured.
- (16) Visual inspection of the car bodies will be carried out. Photographs will be taken of the car bodies.

A checklist will be utilized for the actual test, based on the above list, which 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 vehicle's impact with the barrier and subtract the offset from the entire data set for each channel. It is expected that between 0.05 and 0.50 s 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 Output

Every channel as recorded (raw data) will be plotted against time

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 longitudinal velocity will be integrated to give the crush displacement against time.

The longitudinal accelerations at the center of gravity of the car body will be averaged and multiplied by the mass of the car body to give the force against time during the impact.

The strain gage time histories will be presented

All data recorded by the Data Bricks, and the derived values mentioned above, will be presented to the FRA in digital form on a zip disc as well as on paper.

The film from each side 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 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.

The amount of energy absorbed by the vehicle on impact with the rigid barrier (E) will be calculated from the speed of the car just before impact (V_0) and the mass of the test car (m), according to the formula:

$$E = \frac{1}{2} \cdot m \cdot V_0^2$$

The longitudinal and vertical distances measured before and after the test will be presented in tabular form.

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.

APPENDIX B

**STRAIN GAGE RESULTS FOR THE LEAD CAR (A-END)
FOR THE COMPLETE RANGE RECORDED;
I.E., -0.1 S TO 1.4 S. SAE CFC 1,000 HZ**

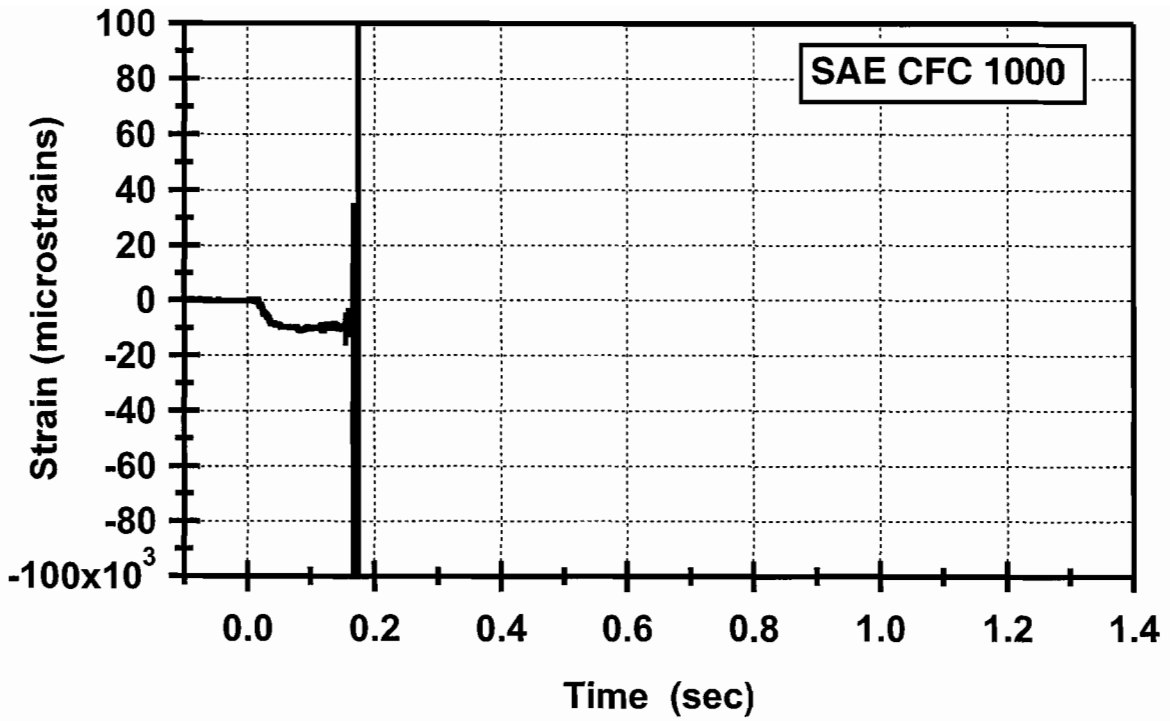


Figure B1. Strain Gage, Lead Car, A End, CS-R-1-U

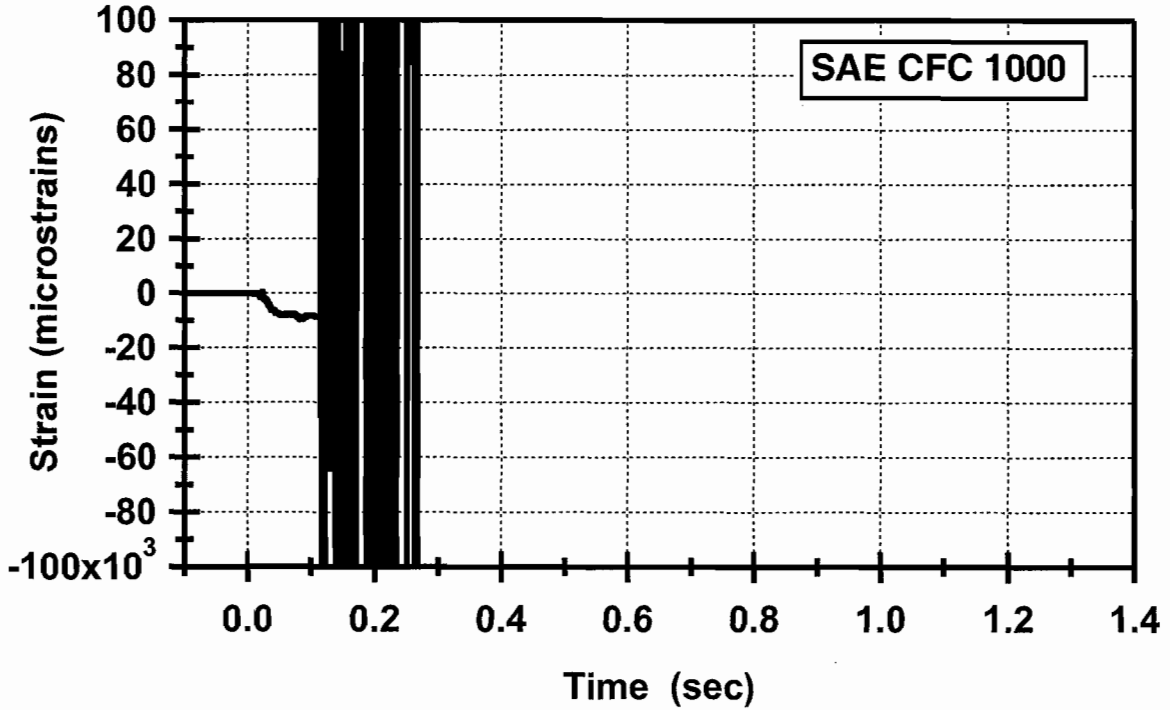


Figure B2. Strain Gage, Lead Car, A End, CS-R-2-U

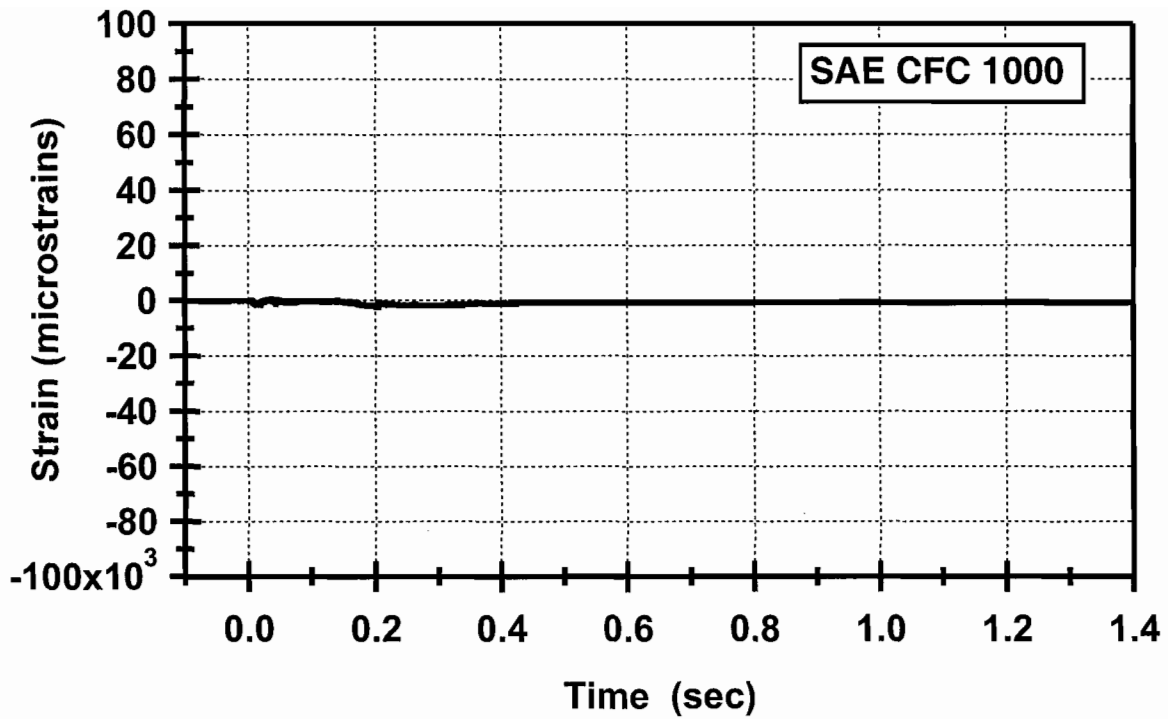


Figure B3. Strain Gage, Lead Car, A End, CS-R-6-U

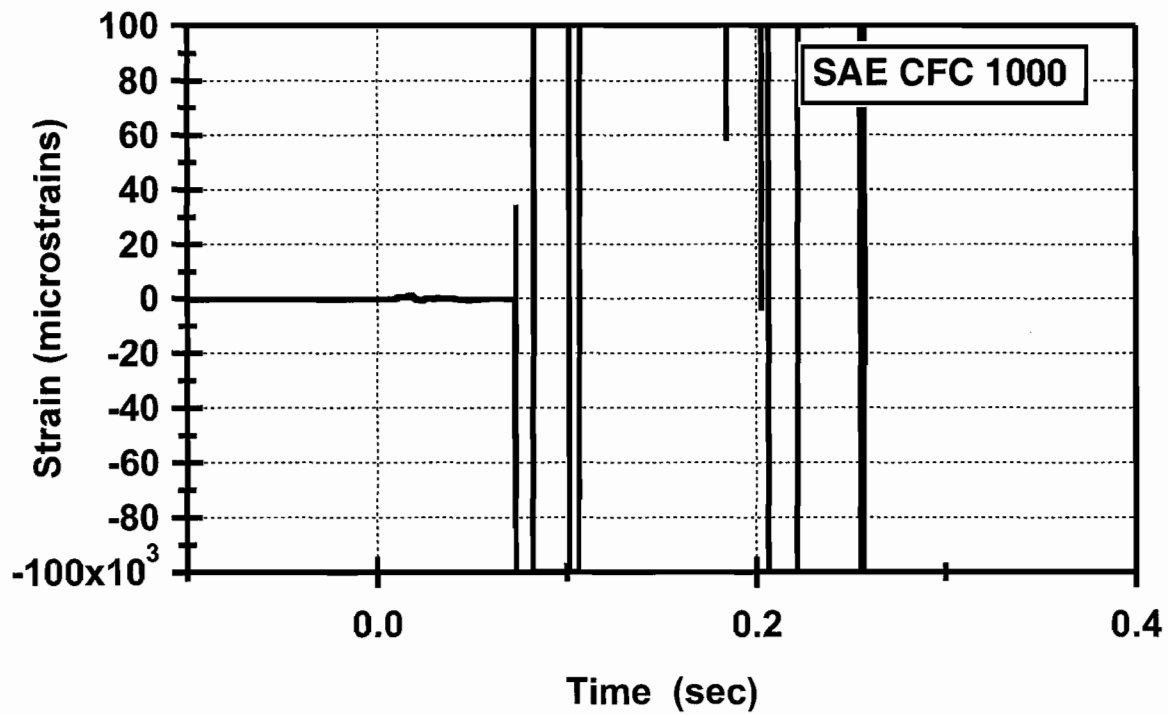


Figure B4. Strain Gage, Lead Car, A End, CS-L-1-U

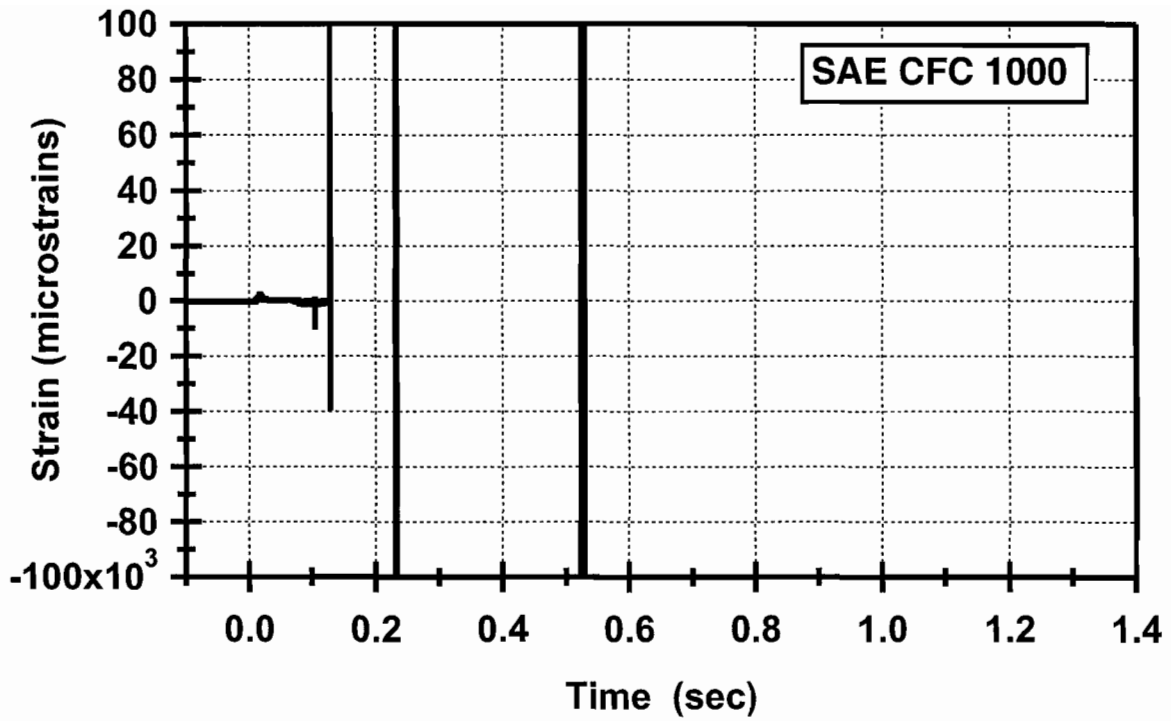


Figure B5. Strain Gage, Lead Car, A End, CS-L-2-U

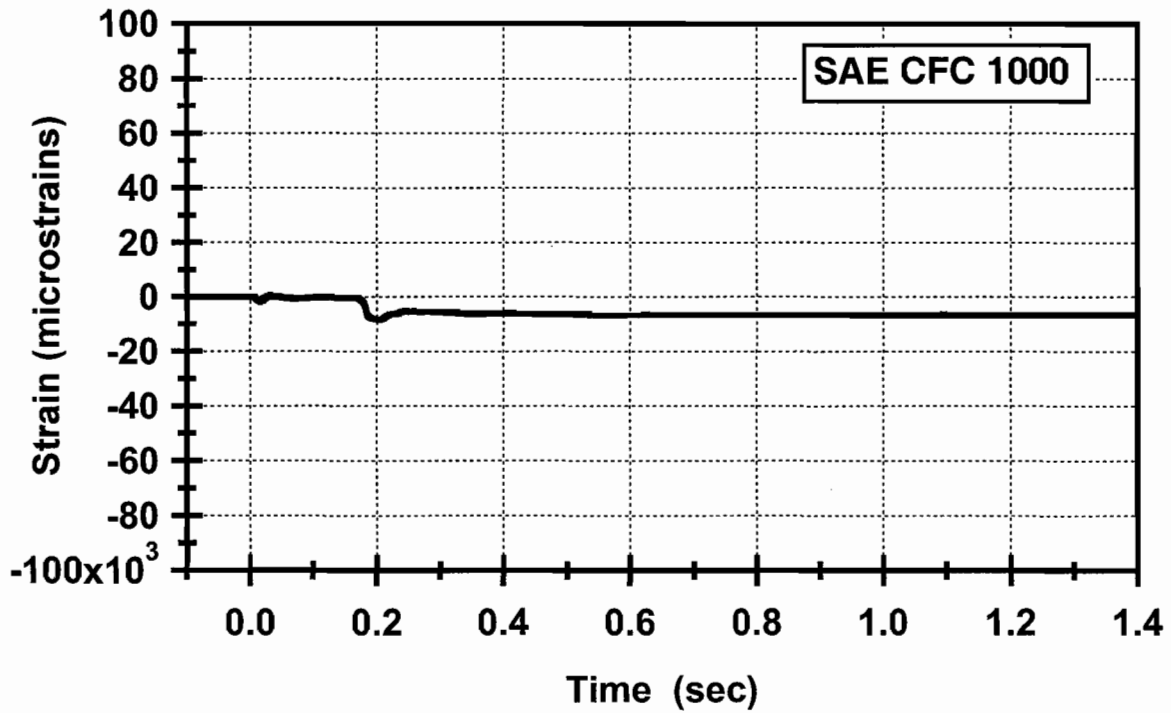


Figure B6. Strain Gage, Lead Car, A End, CS-L-6-U

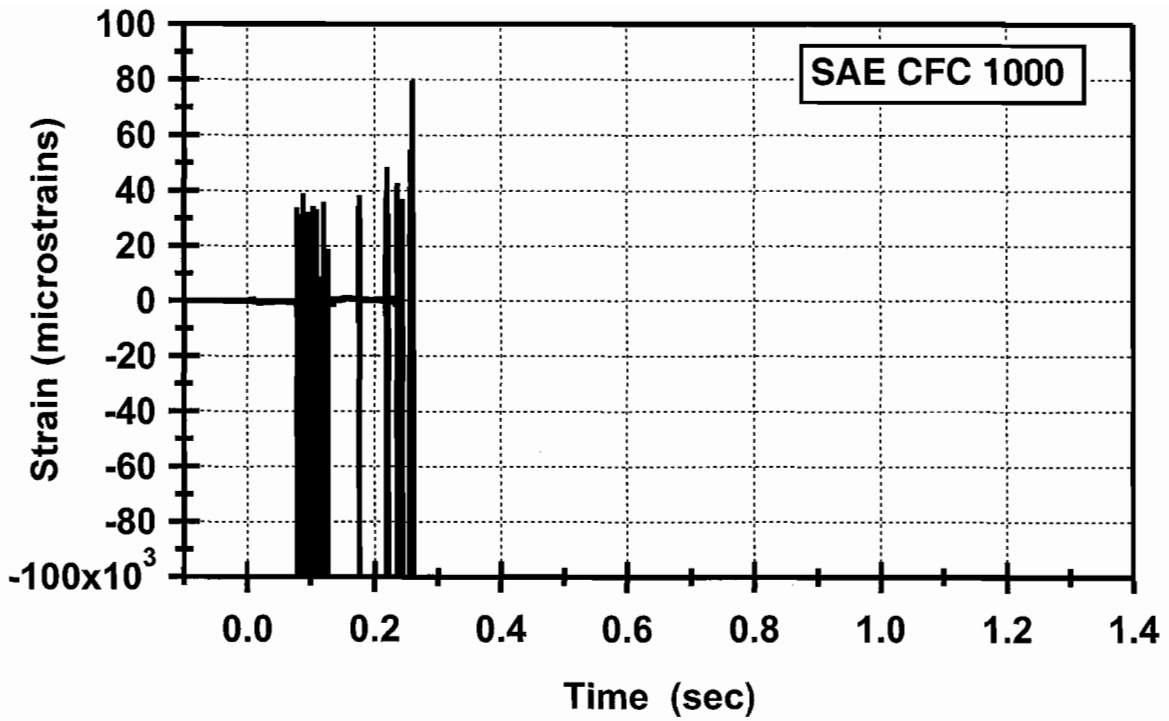


Figure B7. Strain Gage, Lead Car, A End, CS-L-1-L

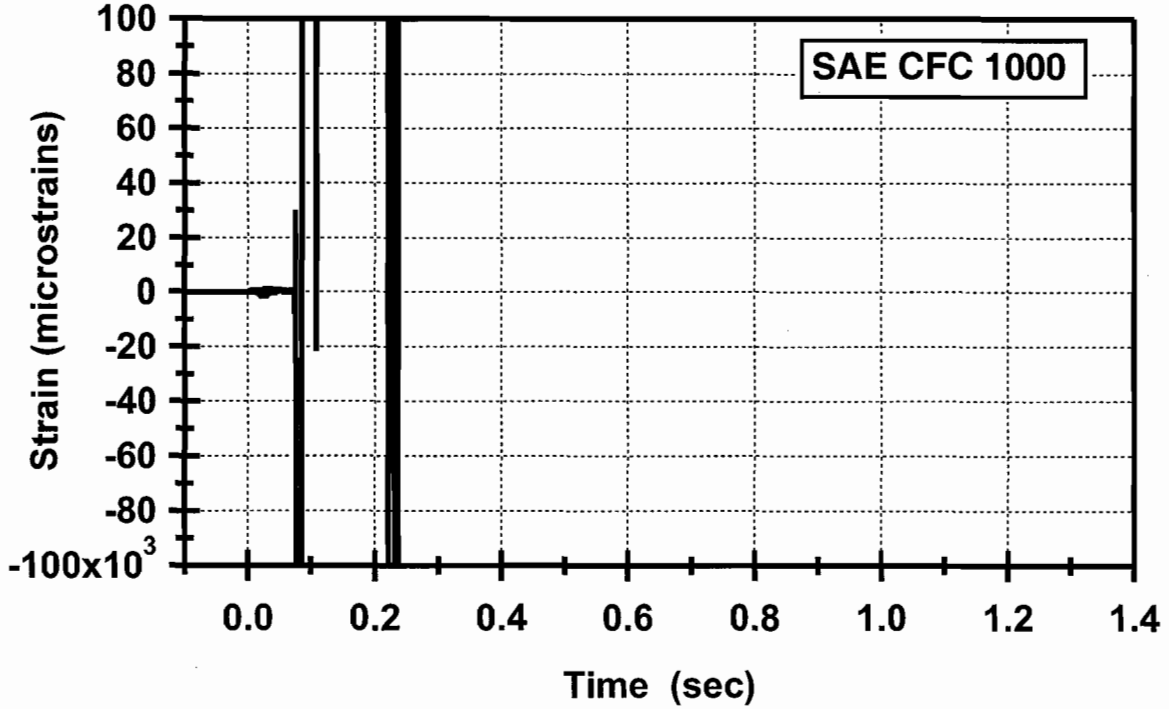


Figure B8. Strain Gage, Lead Car, A End, CS-L-2-L

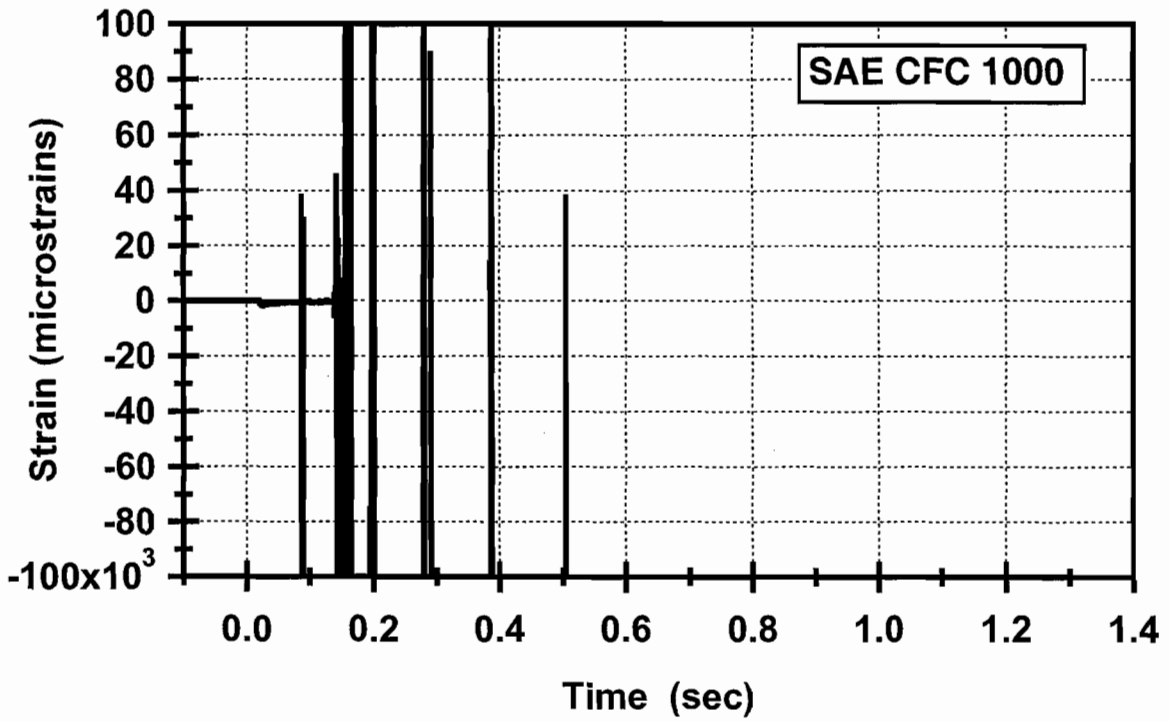


Figure B9. Strain Gage, Lead Car, A End, CS-R-1-L

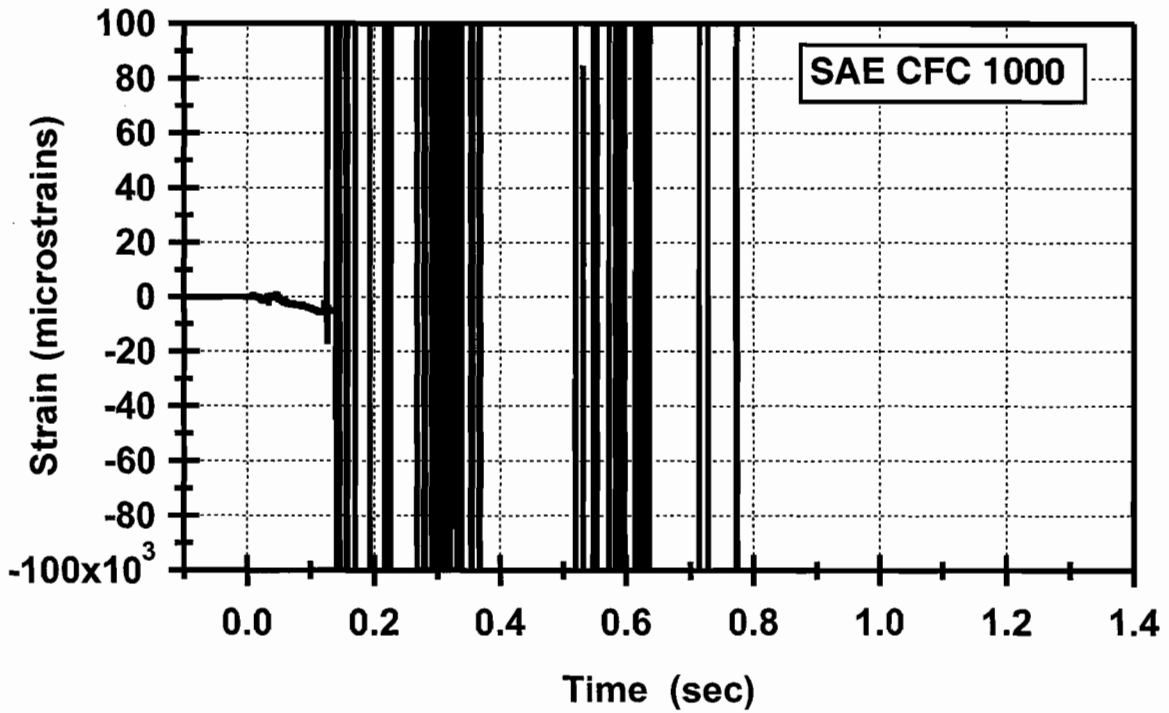


Figure B10. Strain Gage, Lead Car, A End, CS-R-2-L

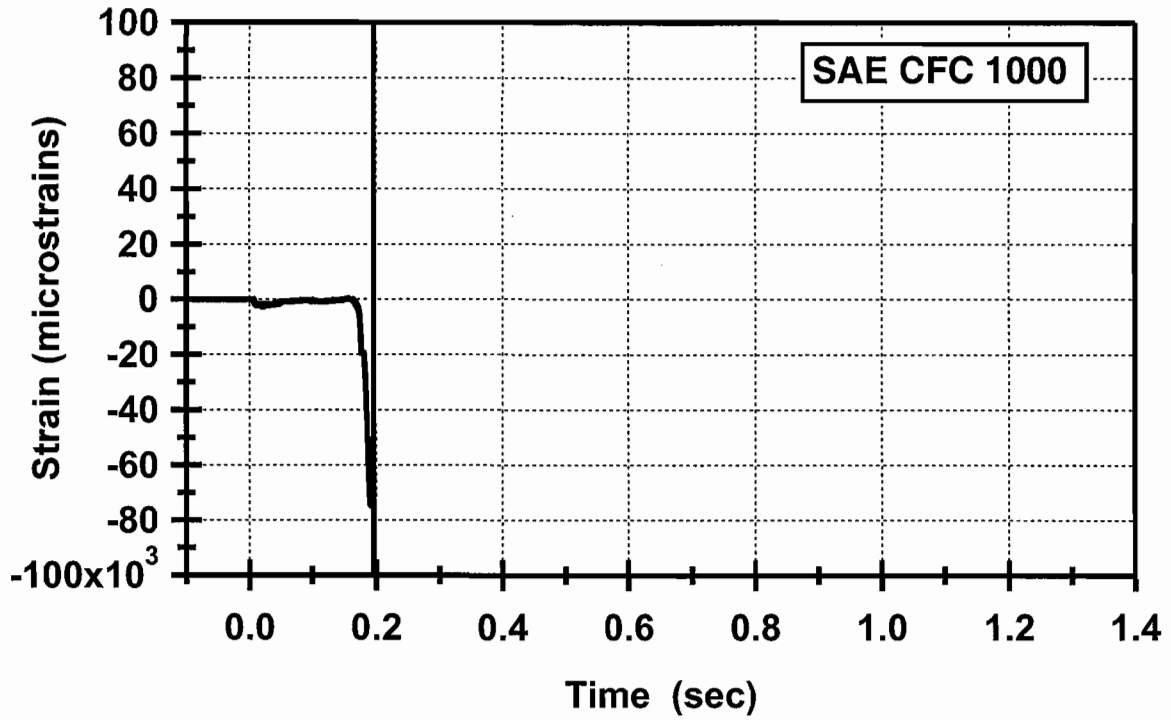


Figure B11. Strain Gage, Lead Car, A End, CS-B-6-C

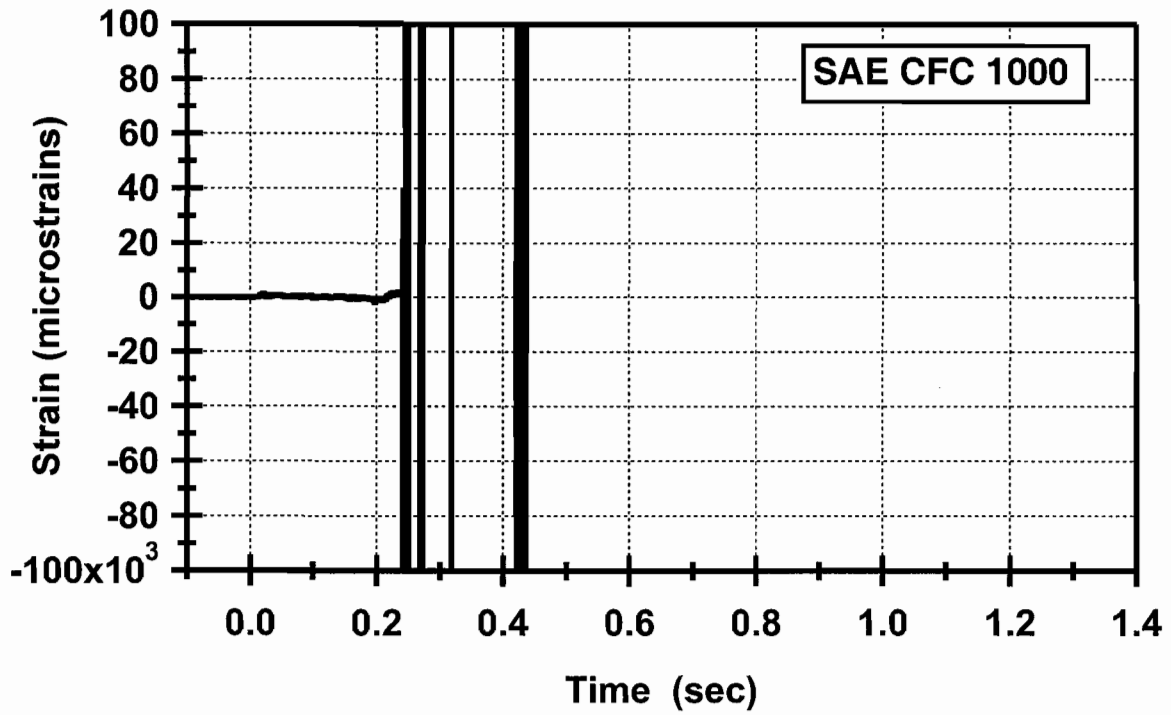


Figure B12. Strain Gage, Lead Car, A End, SS-L-1-U

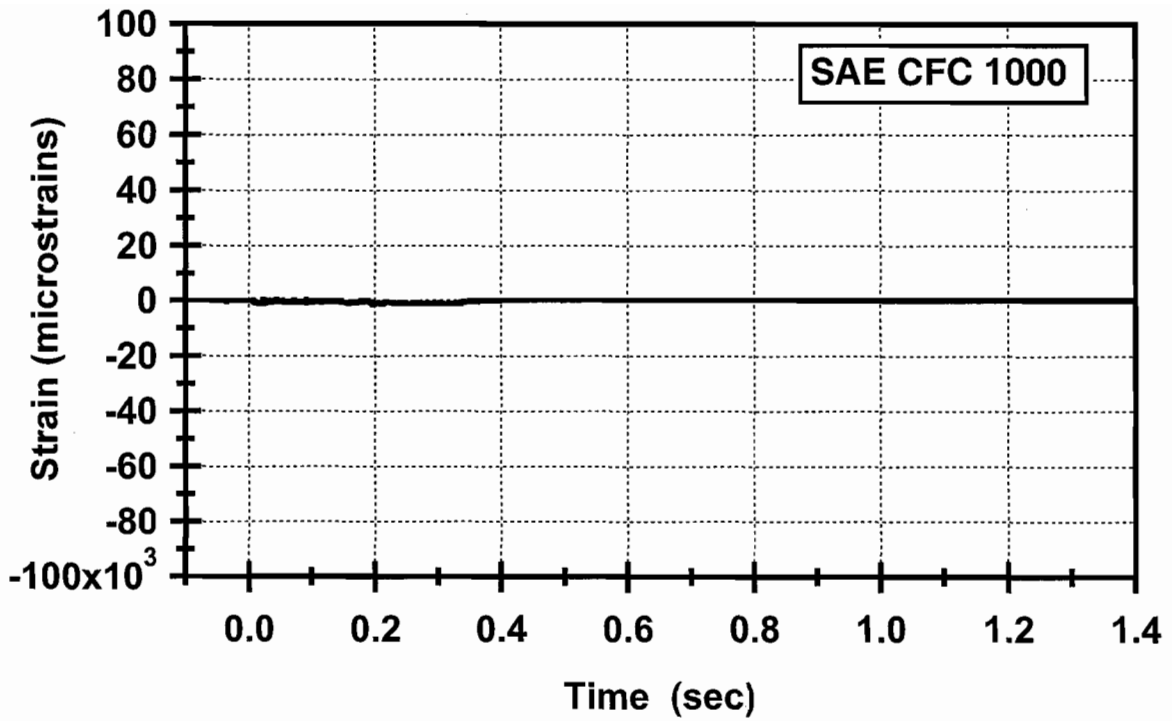


Figure B13. Strain Gage, Lead Car, A End, SS-L-2-U

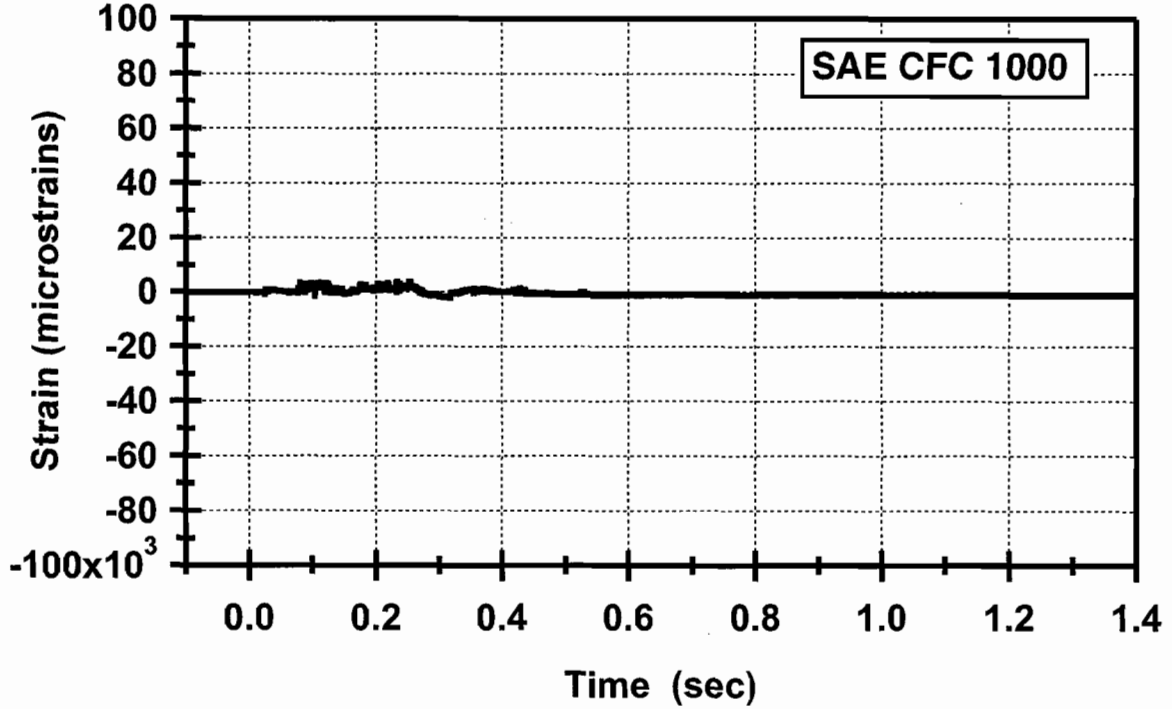


Figure B14. Strain Gage, Lead Car, A End, SS-L-1-L

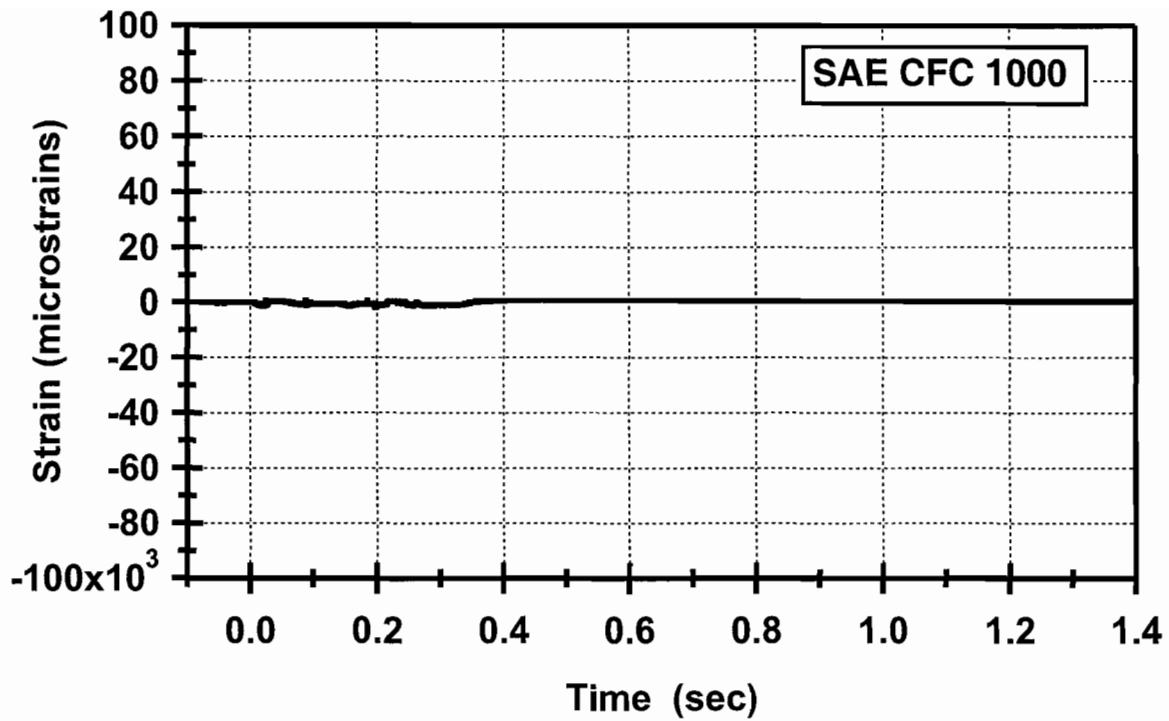


Figure B15. Strain Gage, Lead Car, A End, SS-L-2-L

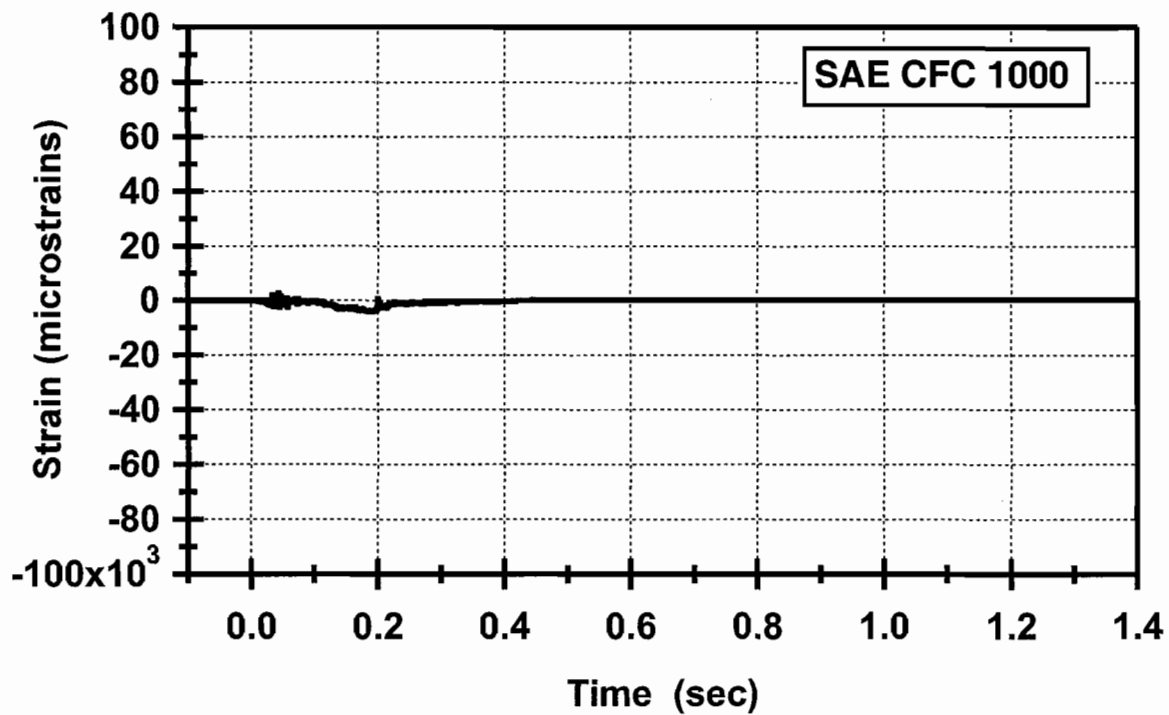


Figure B16. Strain Gage, Lead Car, A End, SS-R-1-U

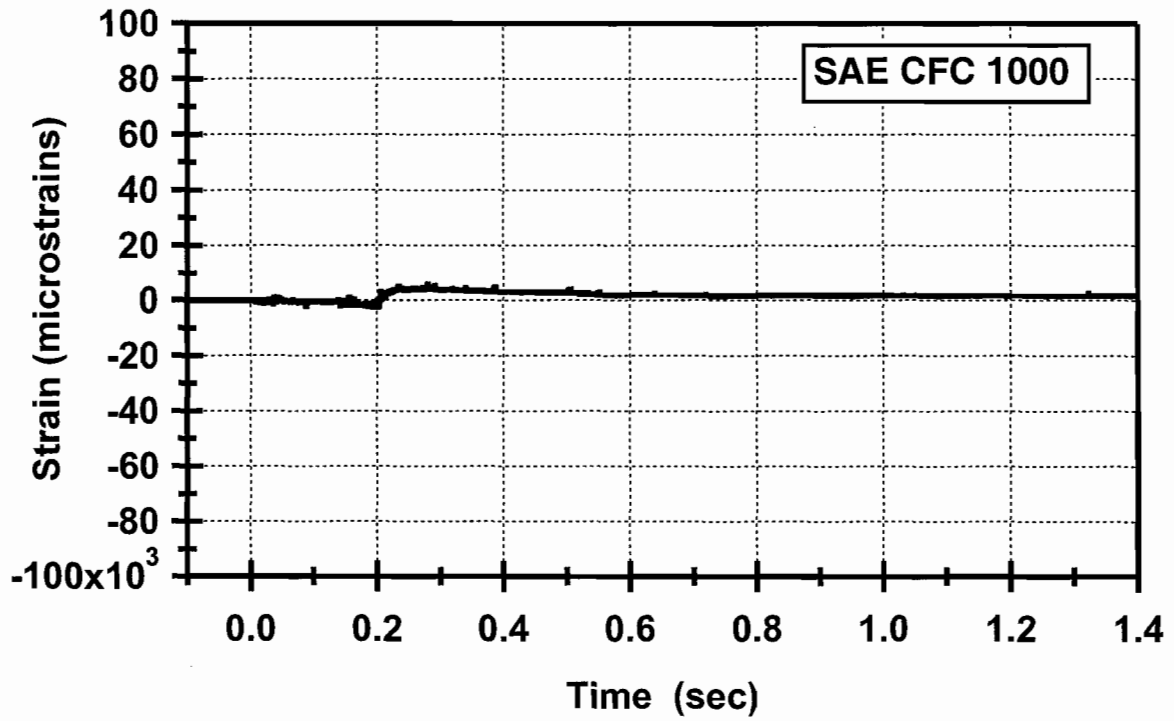


Figure B17. Strain Gage, Lead Car, A End, SS-R-2-U

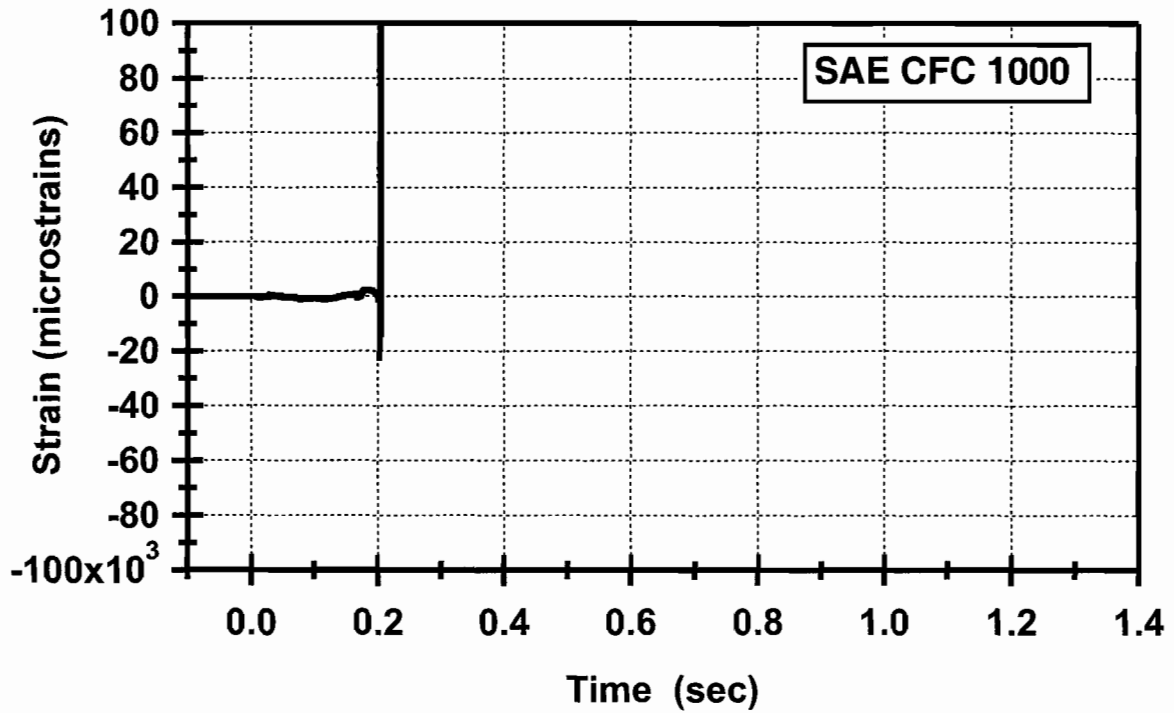


Figure B18. Strain Gage, Lead Car, A End, SS-R-1-L

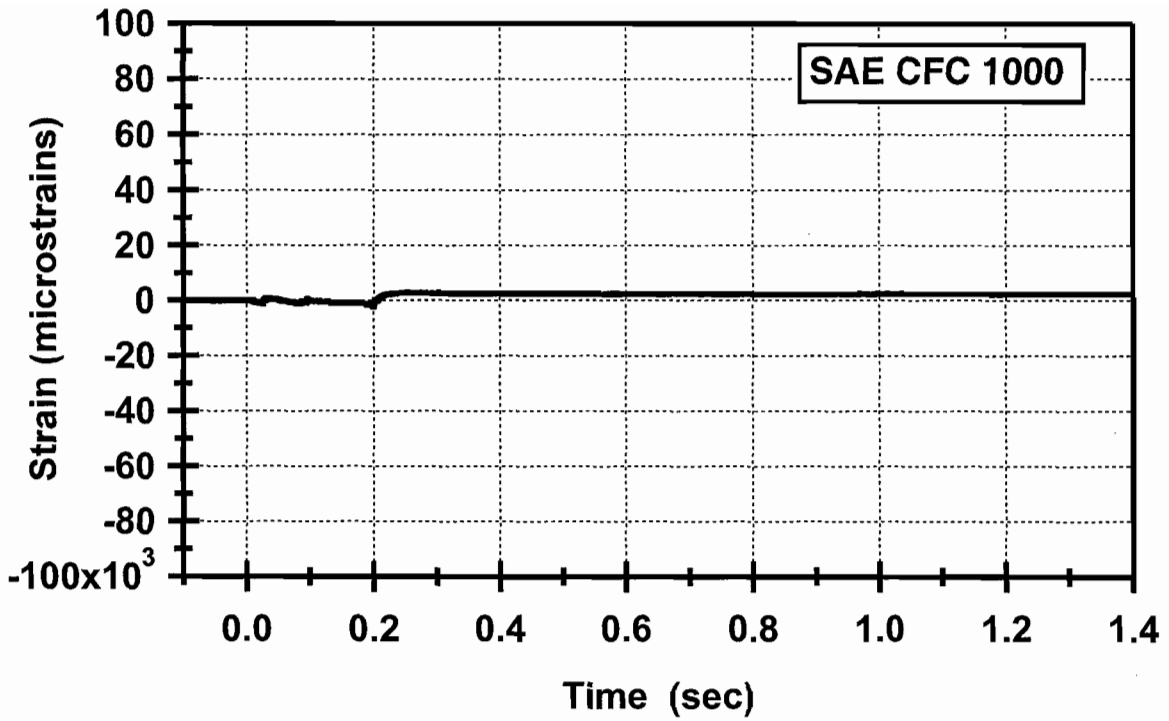


Figure B19. Strain Gage, Lead Car, A End, SS-R-2-L

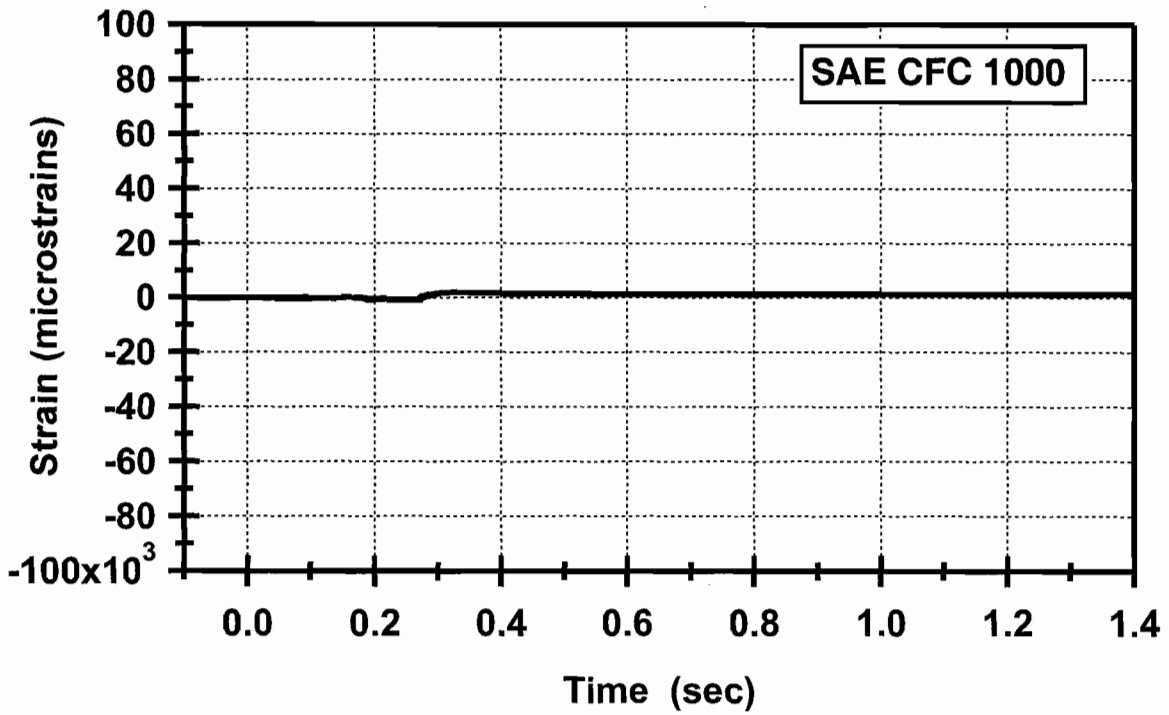


Figure B20. Strain Gage, Lead Car, A End, CR-L-2-U

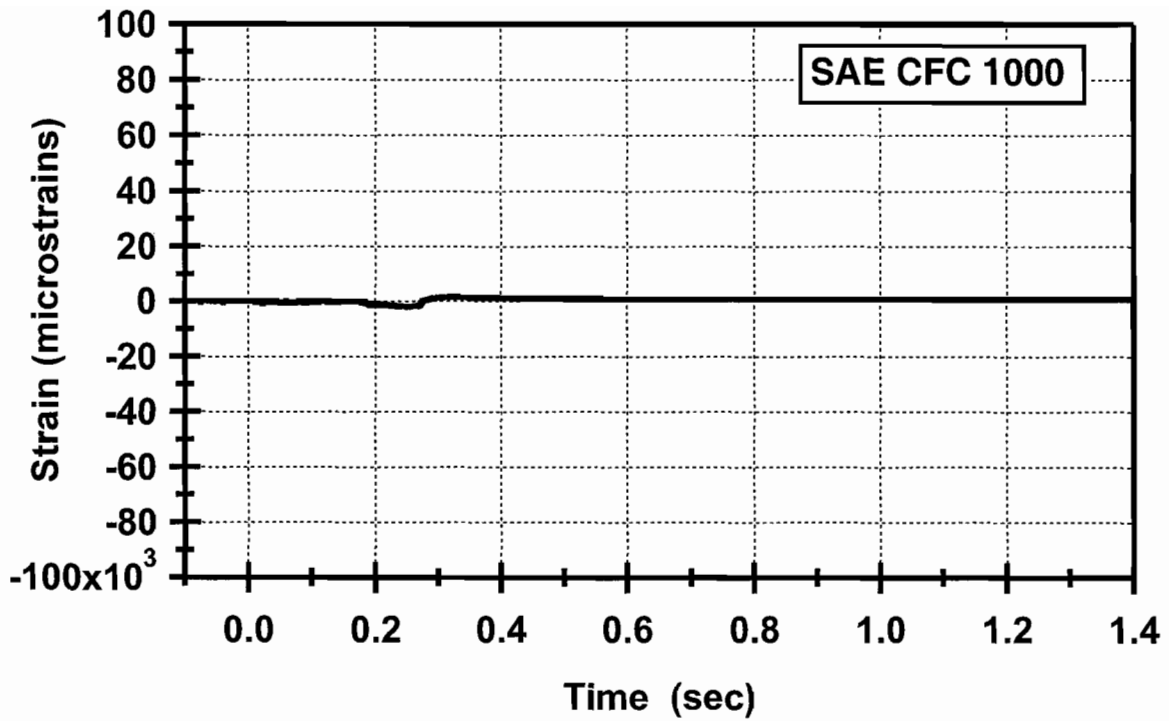


Figure B21. Strain Gage, Lead Car, A End, CR-L-2-L

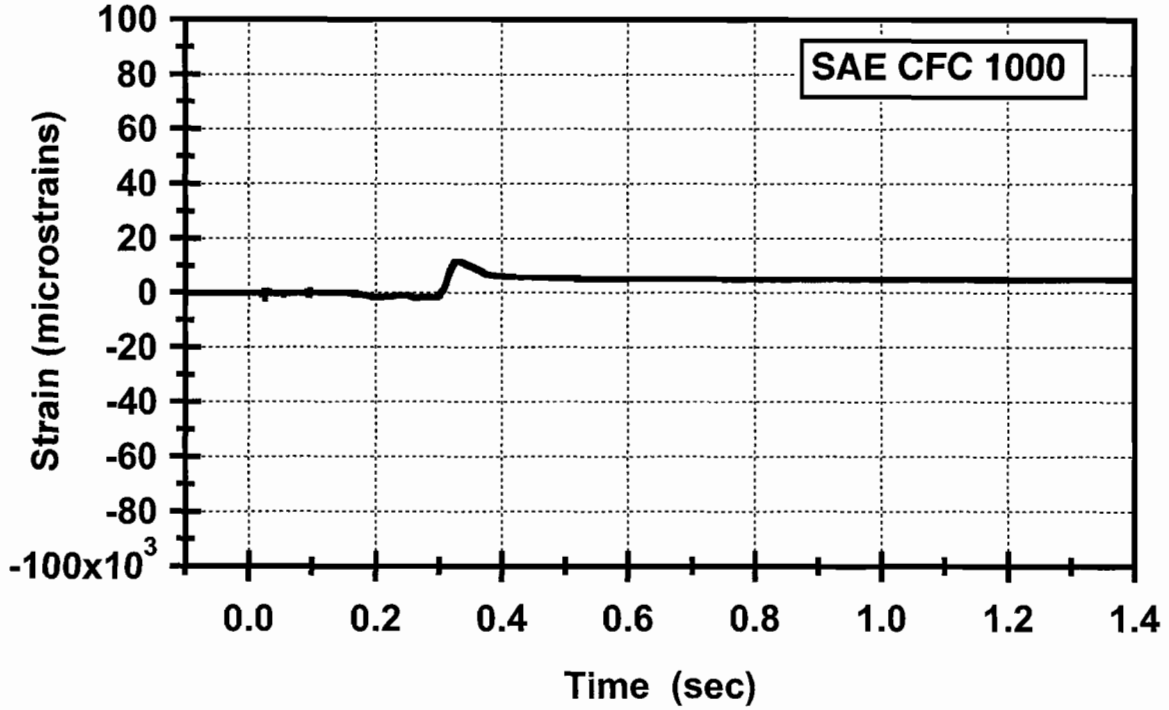


Figure B22. Strain Gage, Lead Car, A End, CR-R-2-U

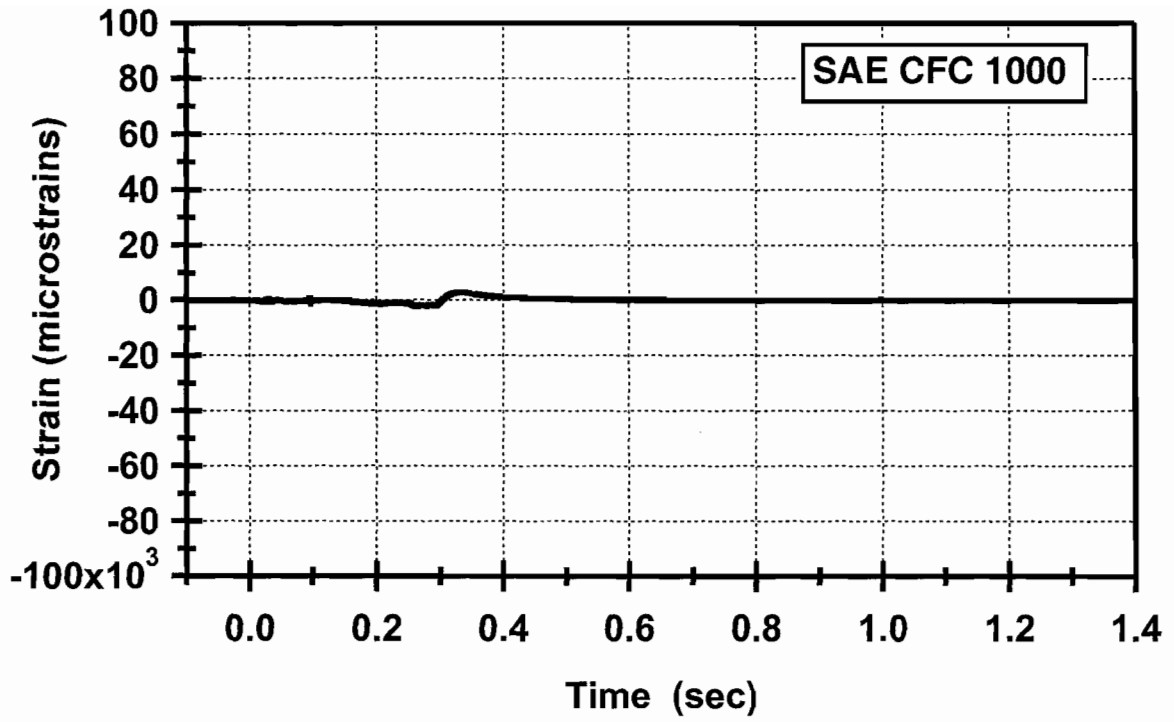


Figure B23. Strain Gage, Lead Car, A End, CR-R-2-L

APPENDIX C

**STRAIN GAGE RESULTS FOR THE LEAD CAR (B-END)
FOR THE COMPLETE RANGE RECORDED;
I.E., -0.1 S TO 1.4 S. SAE CFC 1,000 HZ**

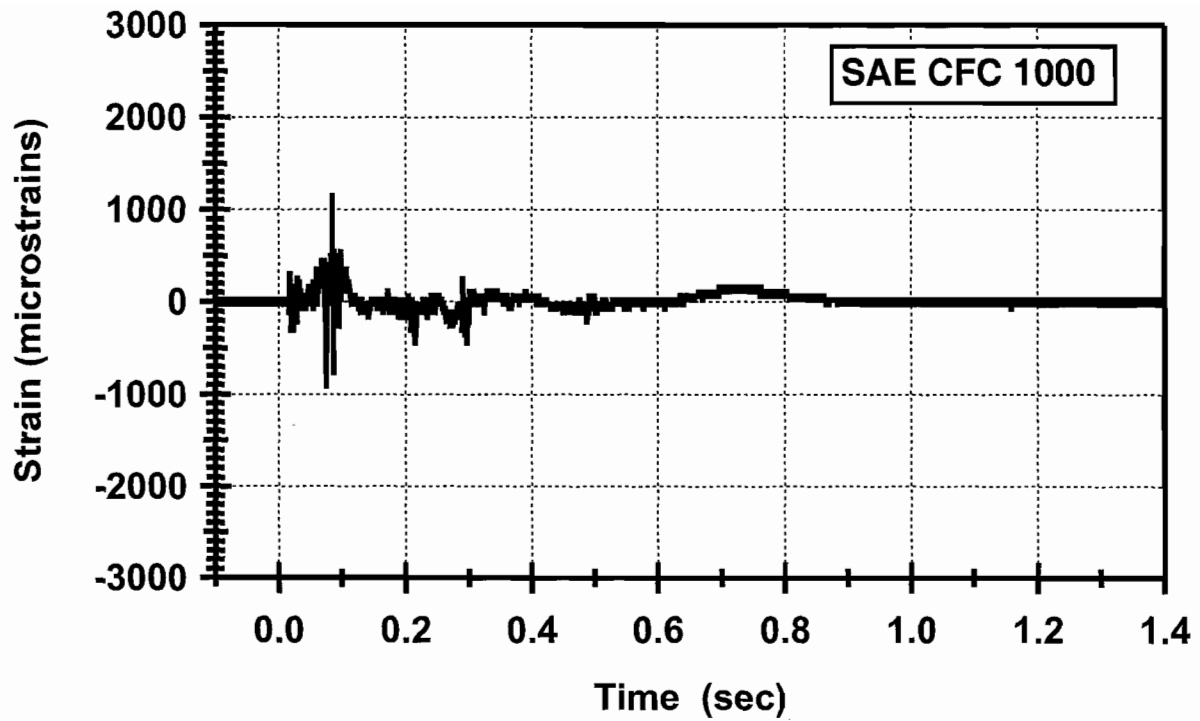


Figure C1. Strain Gage, Lead Car, B End, CS-R-1-L

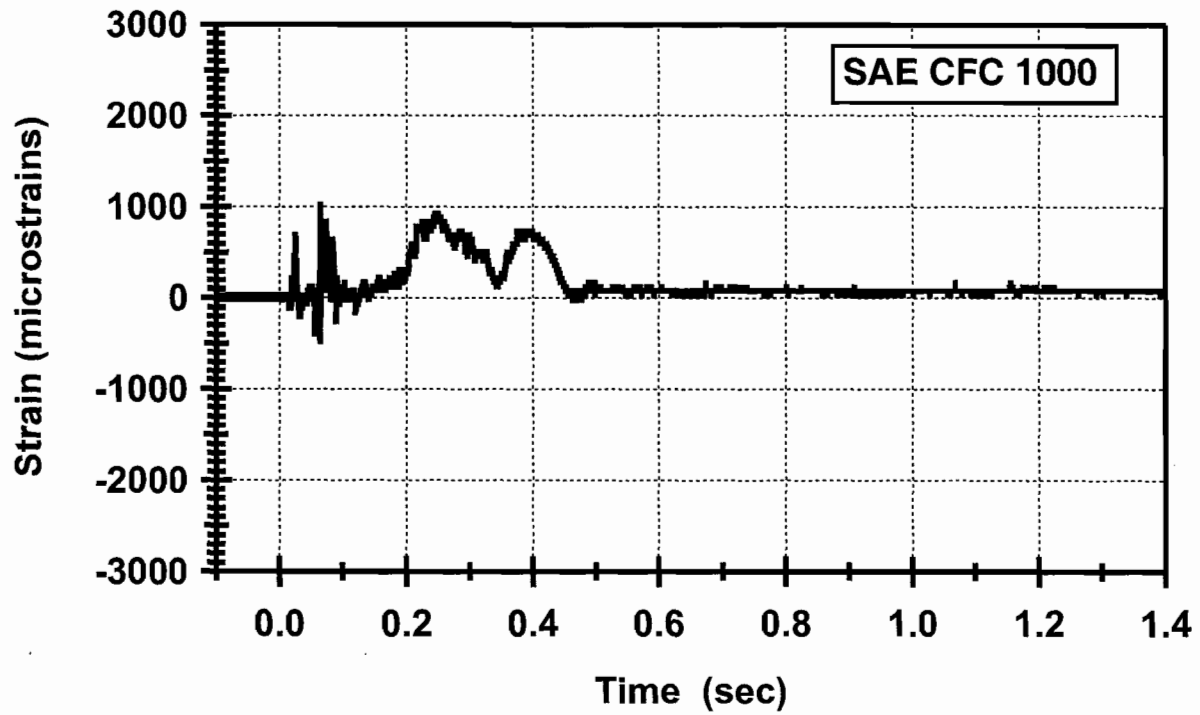


Figure C2. Strain Gage, Lead Car, B End, CS-R-1-U

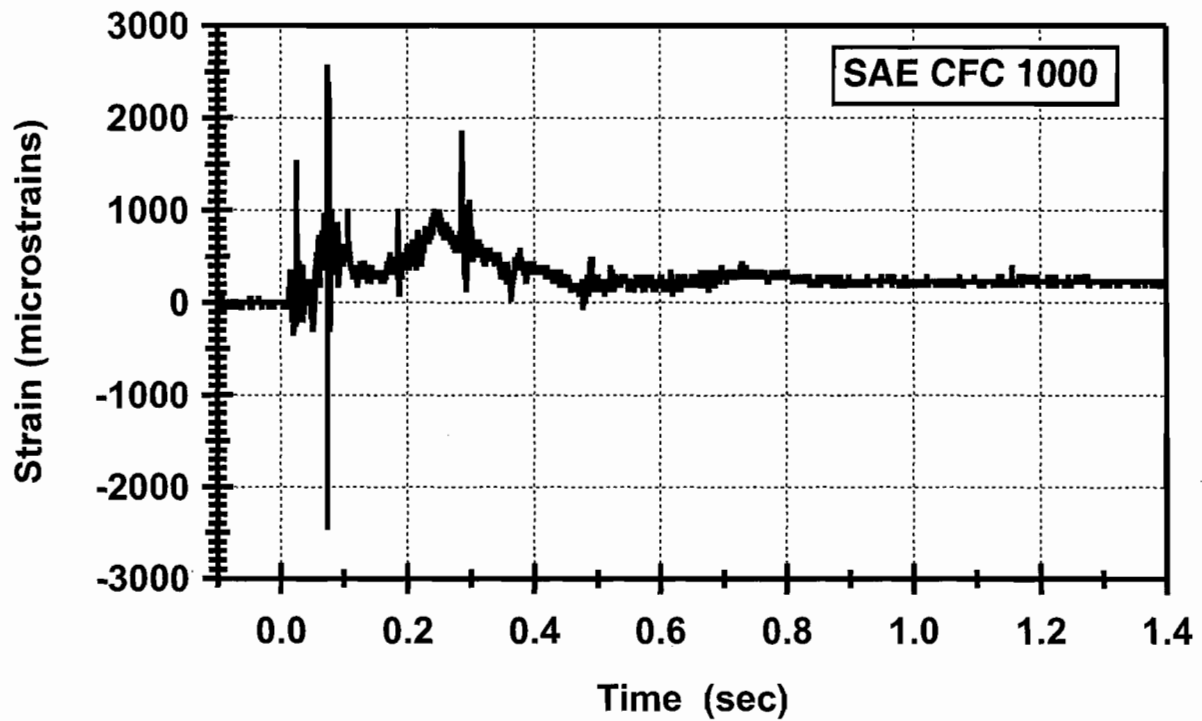


Figure C3. Strain Gage, Lead Car, B End, CS-R-2-L

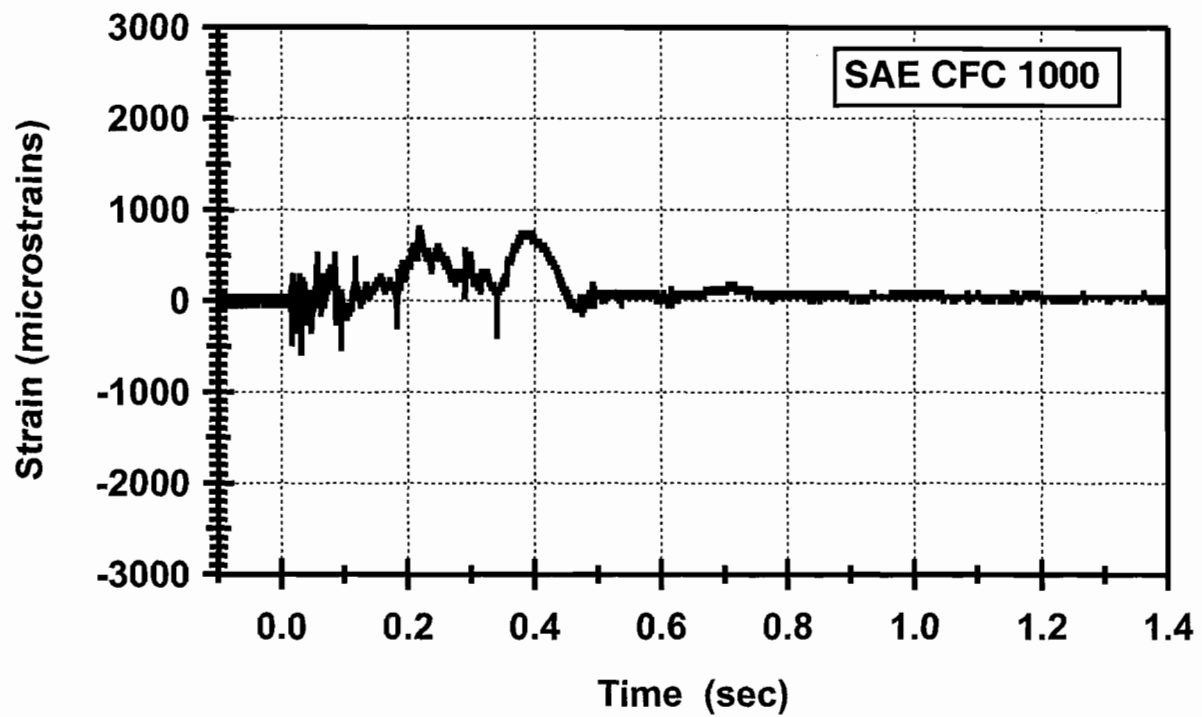


Figure C4. Strain Gage, Lead Car, B End, CS-R-2-U

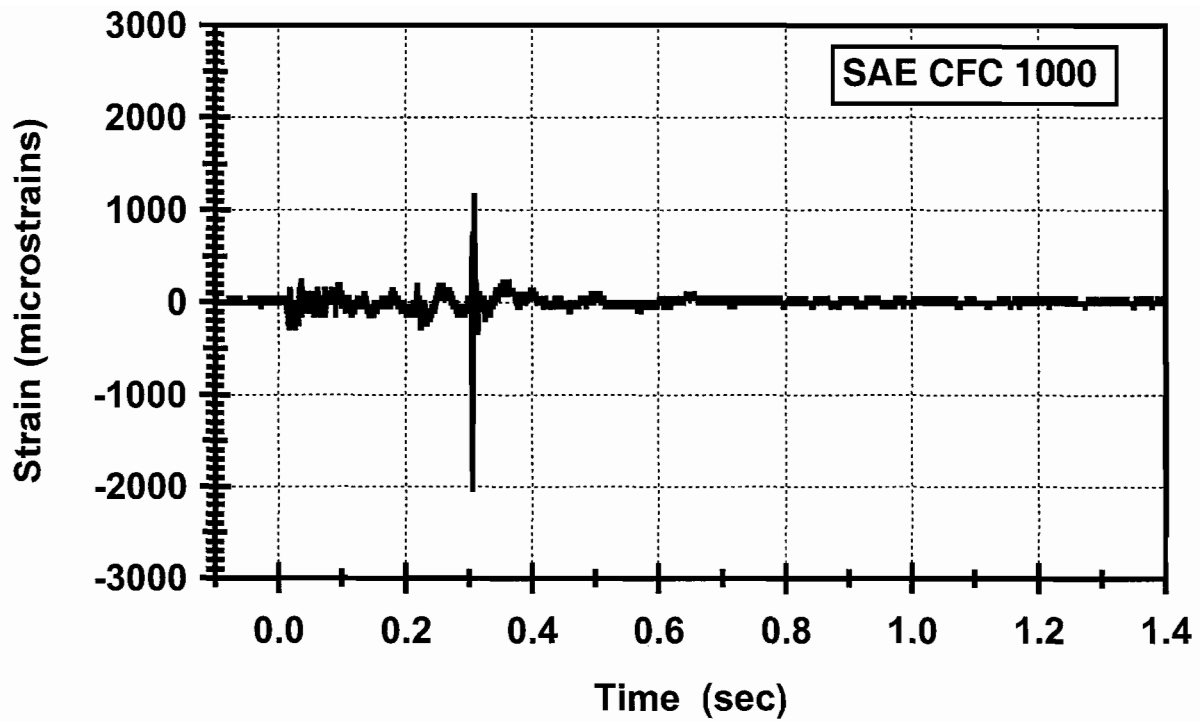


Figure C5. Strain Gage, Lead Car, B End, CR-R-2-L

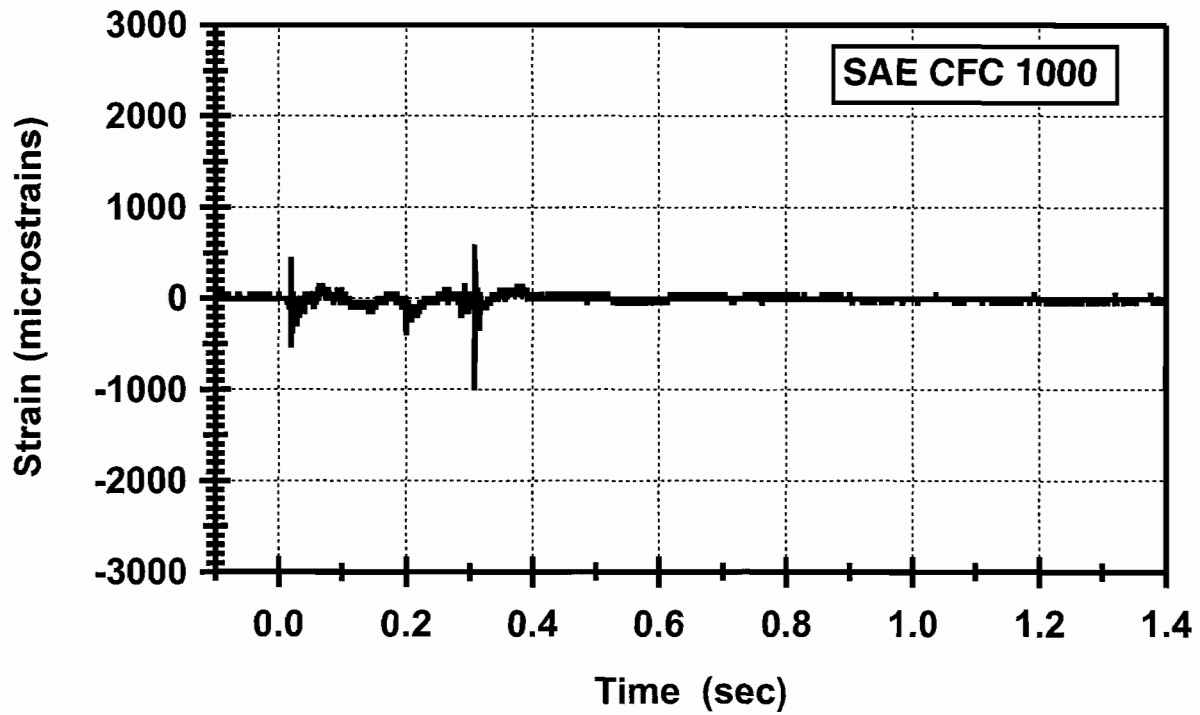


Figure C6. Strain Gage, Lead Car, B End, CR-R-2-U

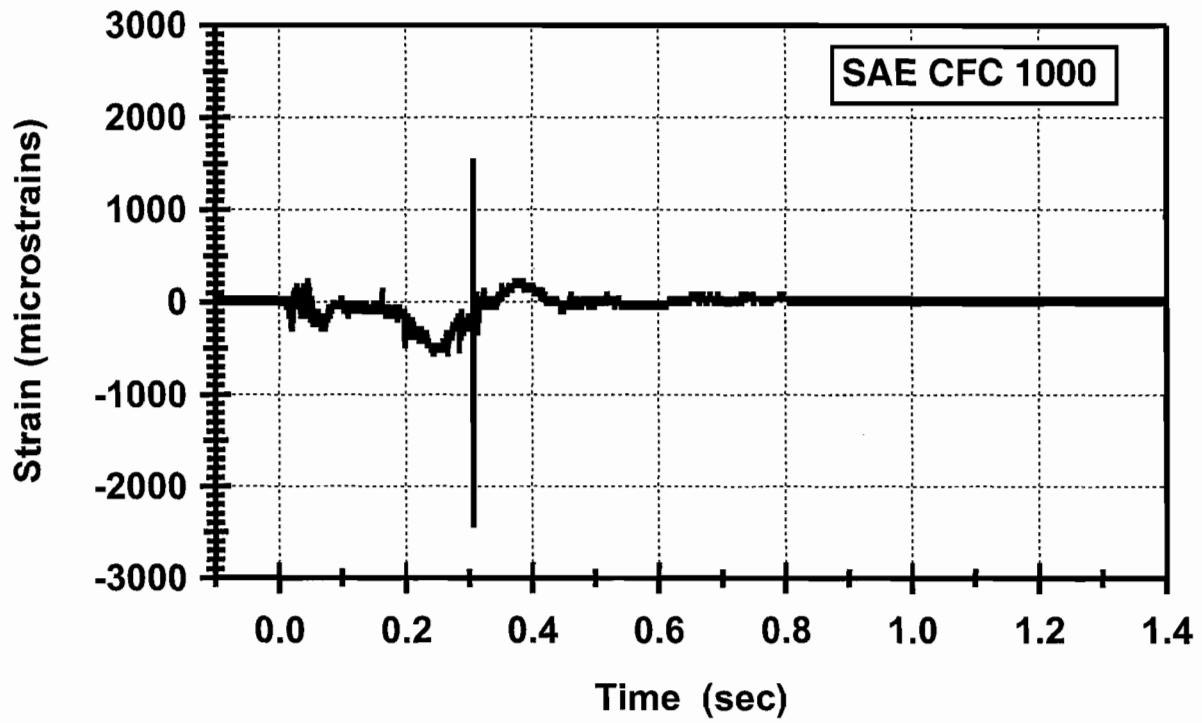


Figure C7. Strain Gage, Lead Car, B End, SS-R-1-L

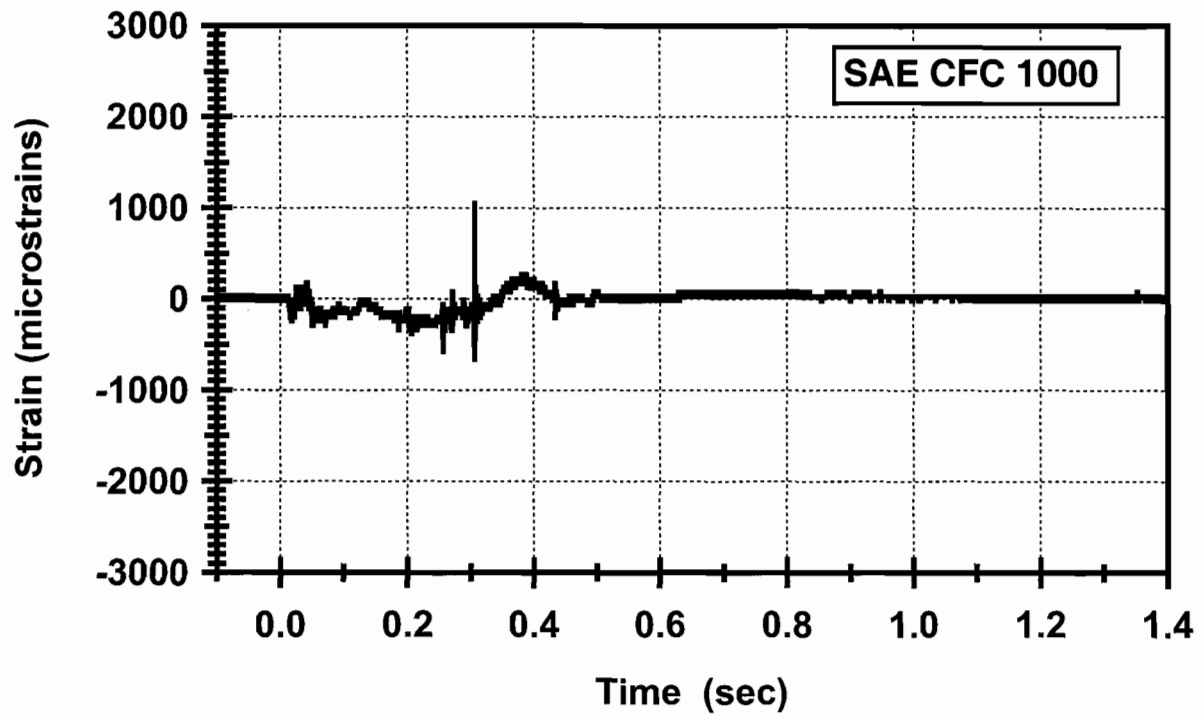


Figure C8. Strain Gage, Lead Car, B End, SS-R-1-U

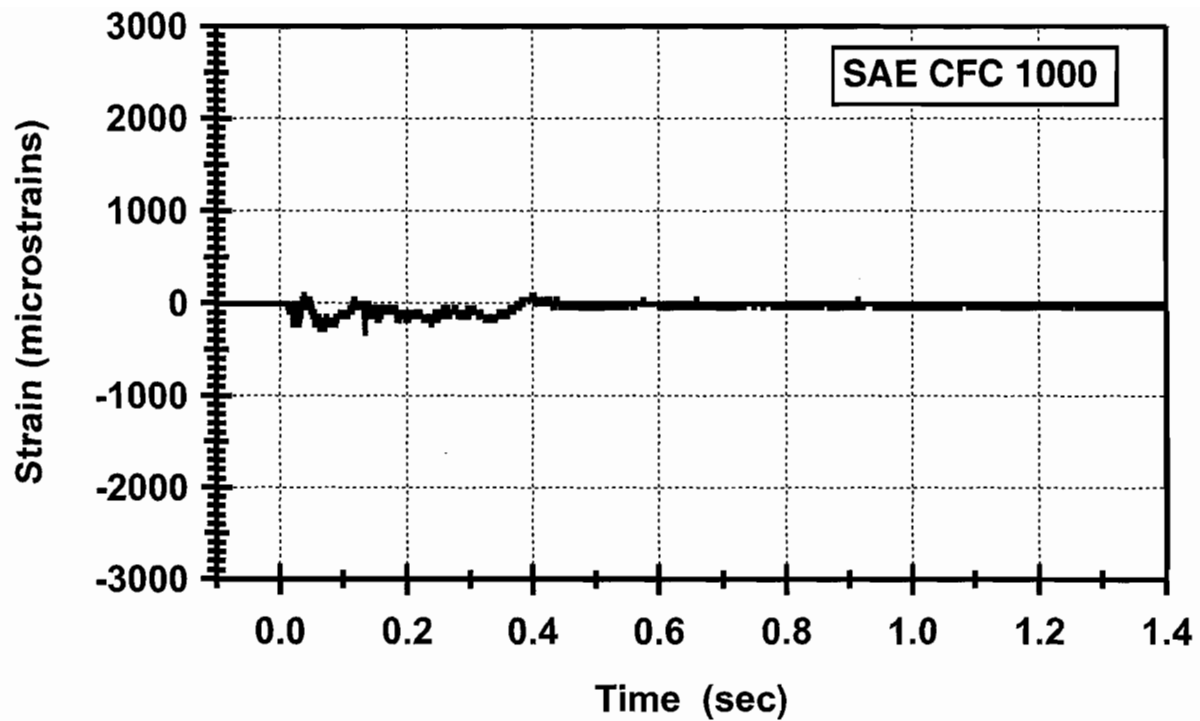


Figure C9. Strain Gage, Lead Car, B End, CR-L-2-L

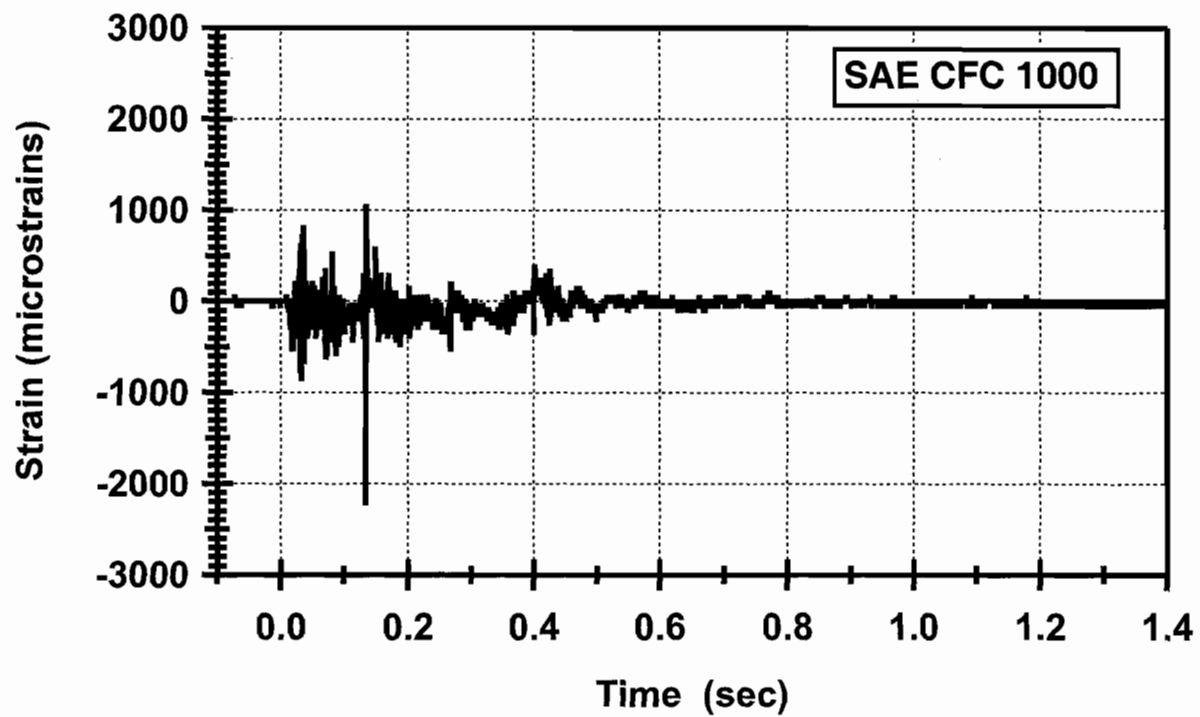


Figure C10. Strain Gage, Lead Car, B End, CR-L-2-U

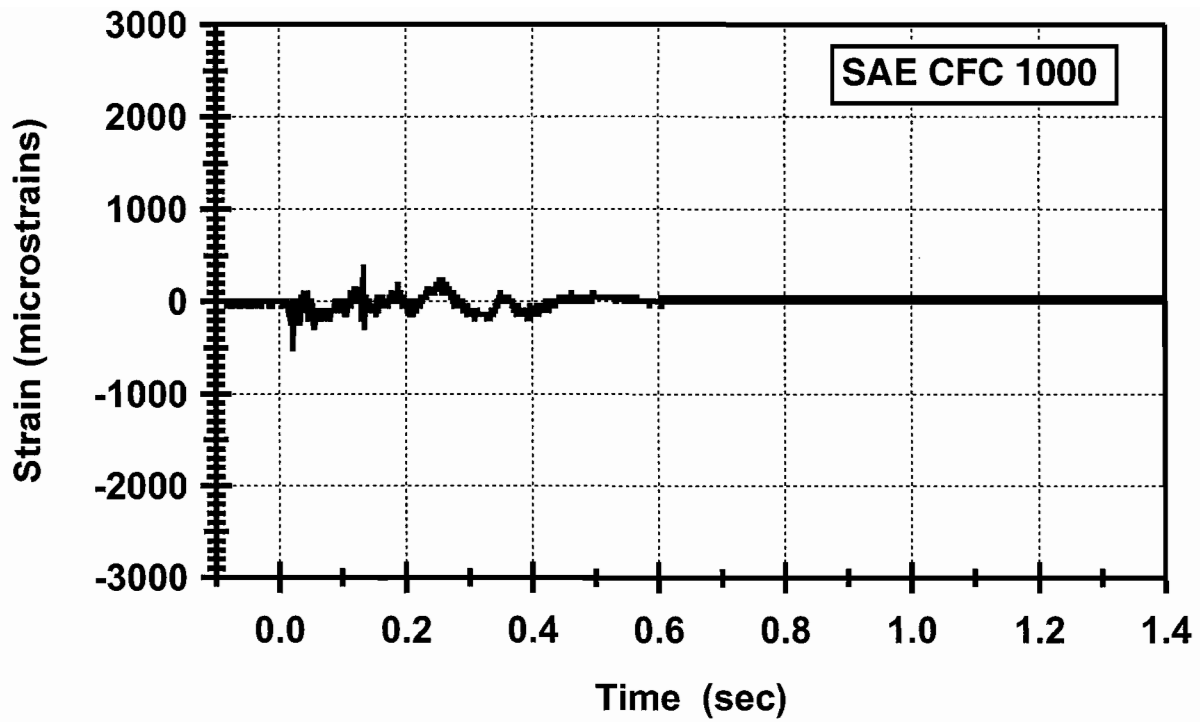


Figure C11. Strain Gage, Lead Car, B End, SS-L-1-L

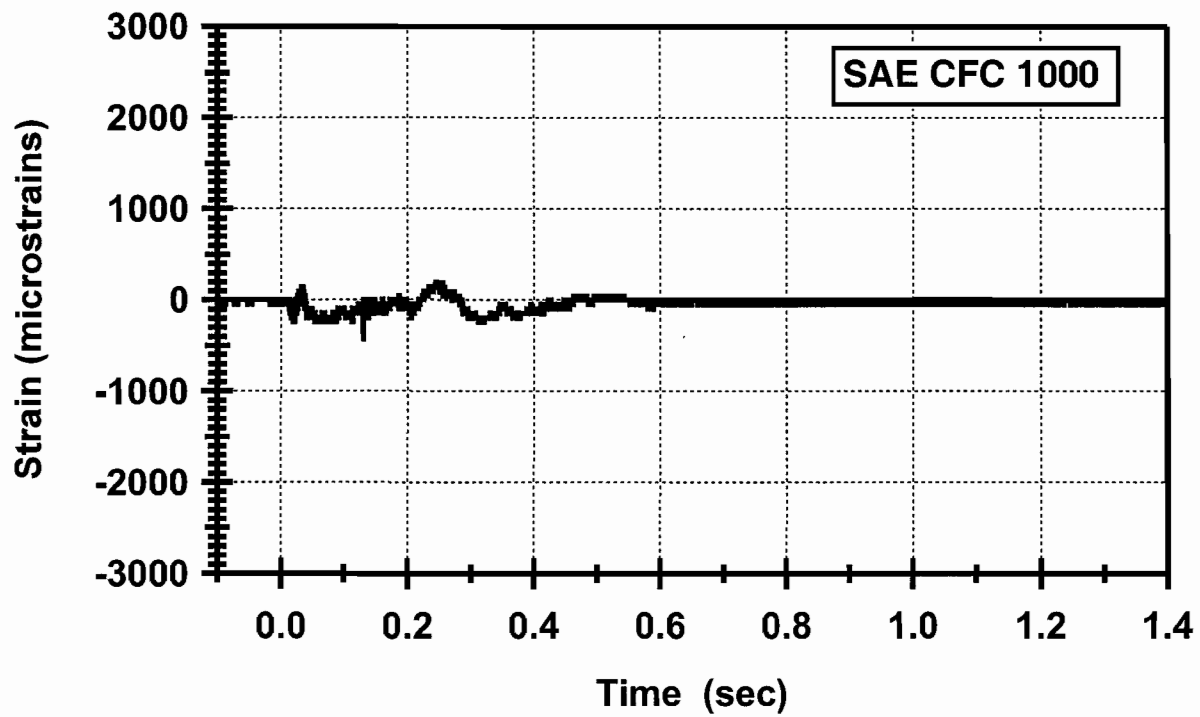


Figure C12. Strain Gage, Lead Car, B End, SS-L-1-U

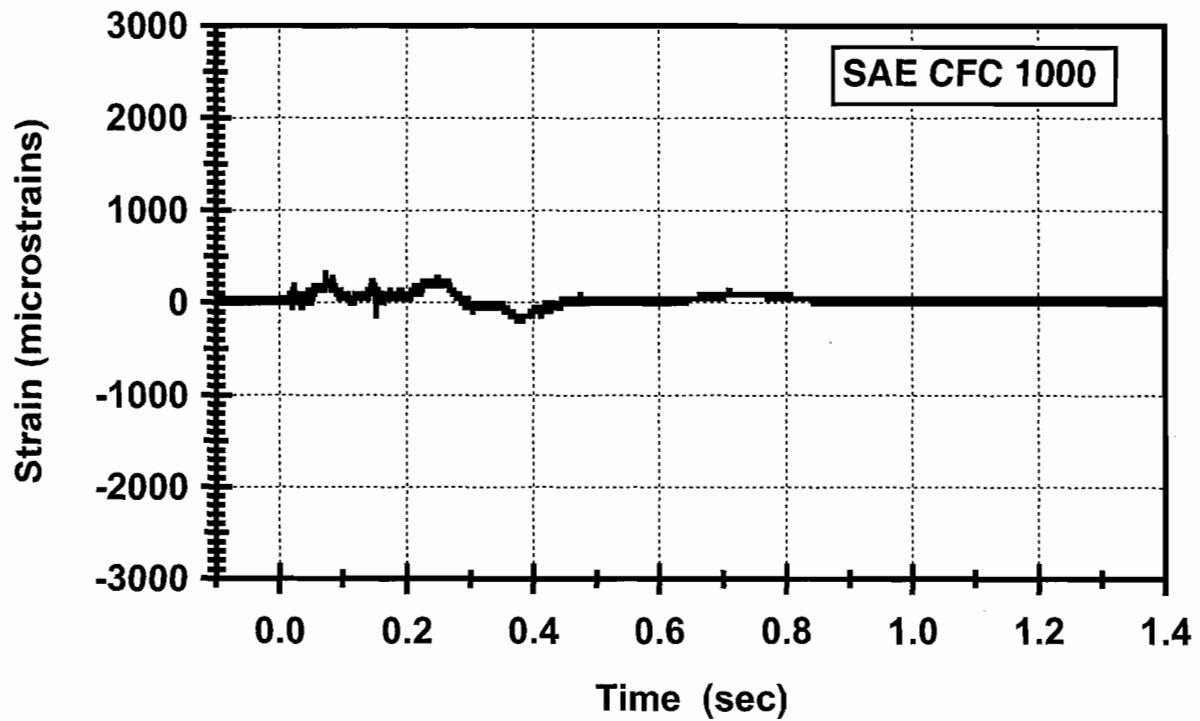


Figure C13. Strain Gage, Lead Car, B End, CS-L-1-L

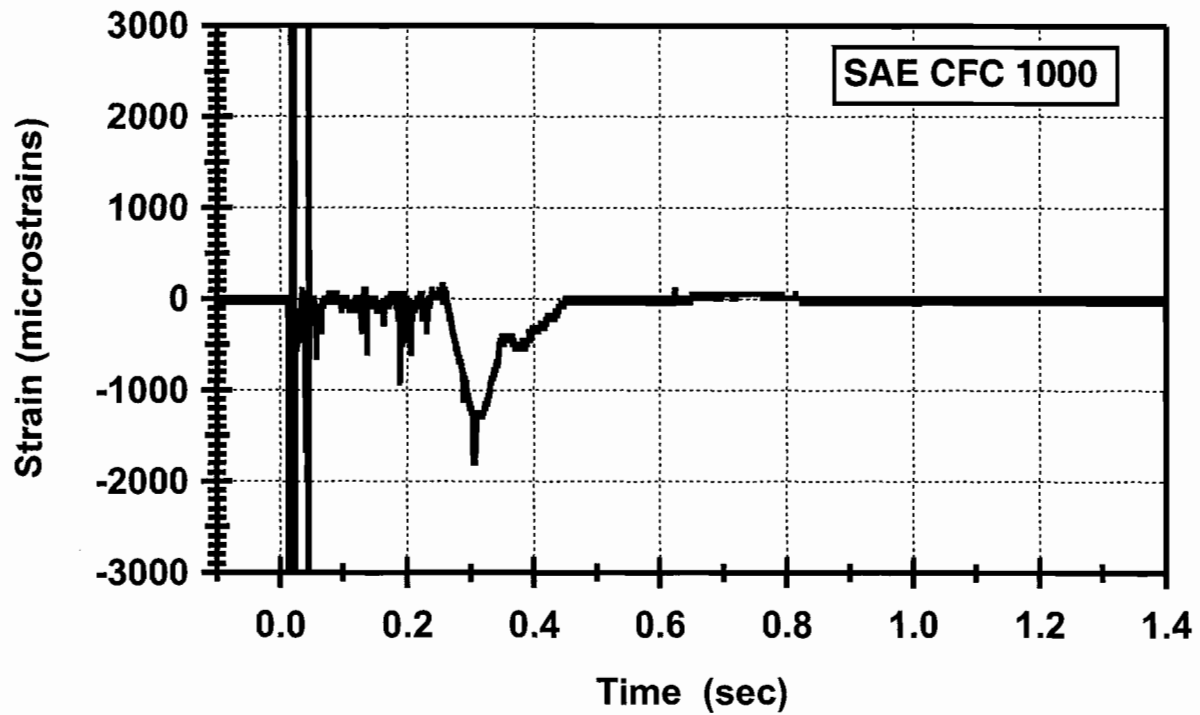


Figure C14. Strain Gage, Lead Car, B End, CS-L-1-U

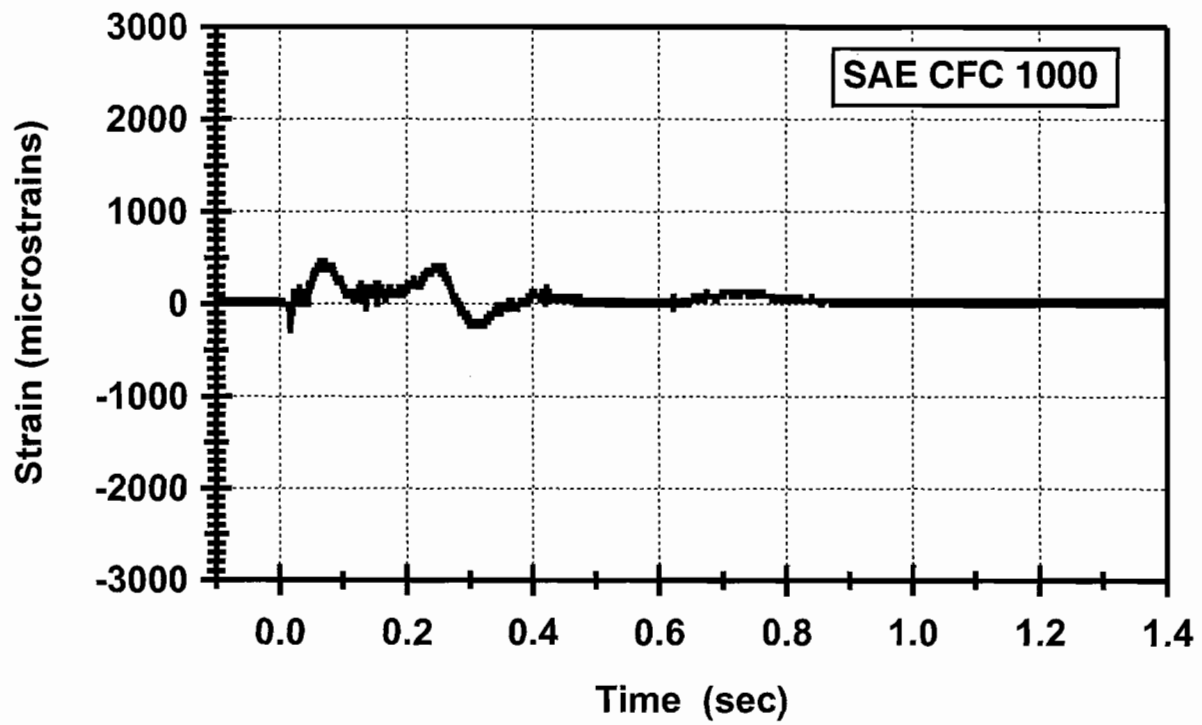


Figure C15. Strain Gage, Lead Car, B End, CS-L-2-L

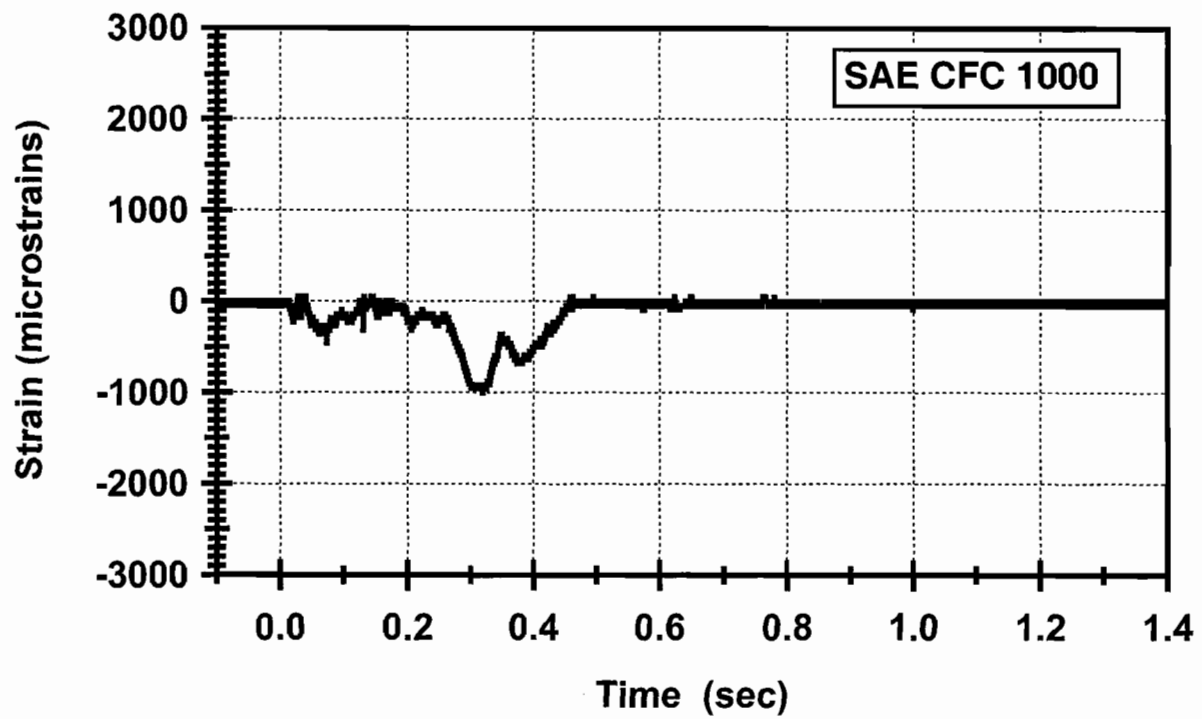


Figure C16. Strain Gage, Lead Car, B End, CS-L-2-U

APPENDIX D

**STRAIN GAGE RESULTS FOR THE TRAILING CAR (A-END)
FOR THE COMPLETE RANGE RECORDED;
I.E., -0.1 S TO 1.4 S. SAE CFC 1,000 HZ**

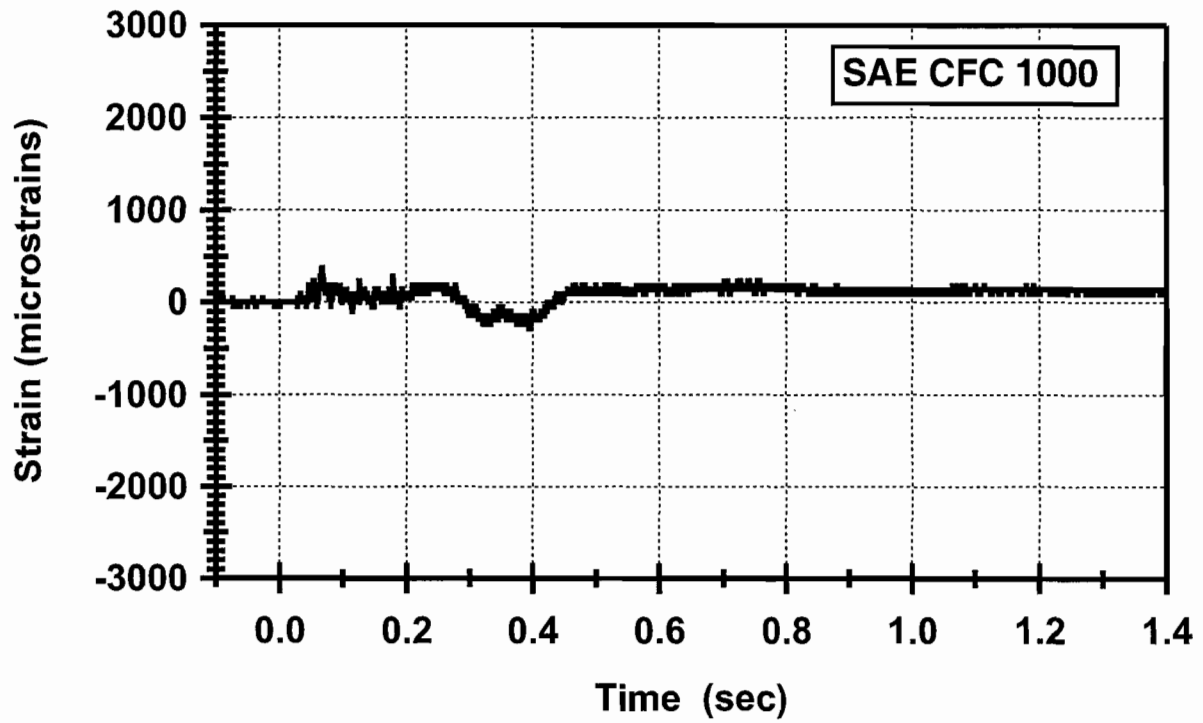


Figure D1. Strain Gage, Lead Car, B End, CS-R-1-L

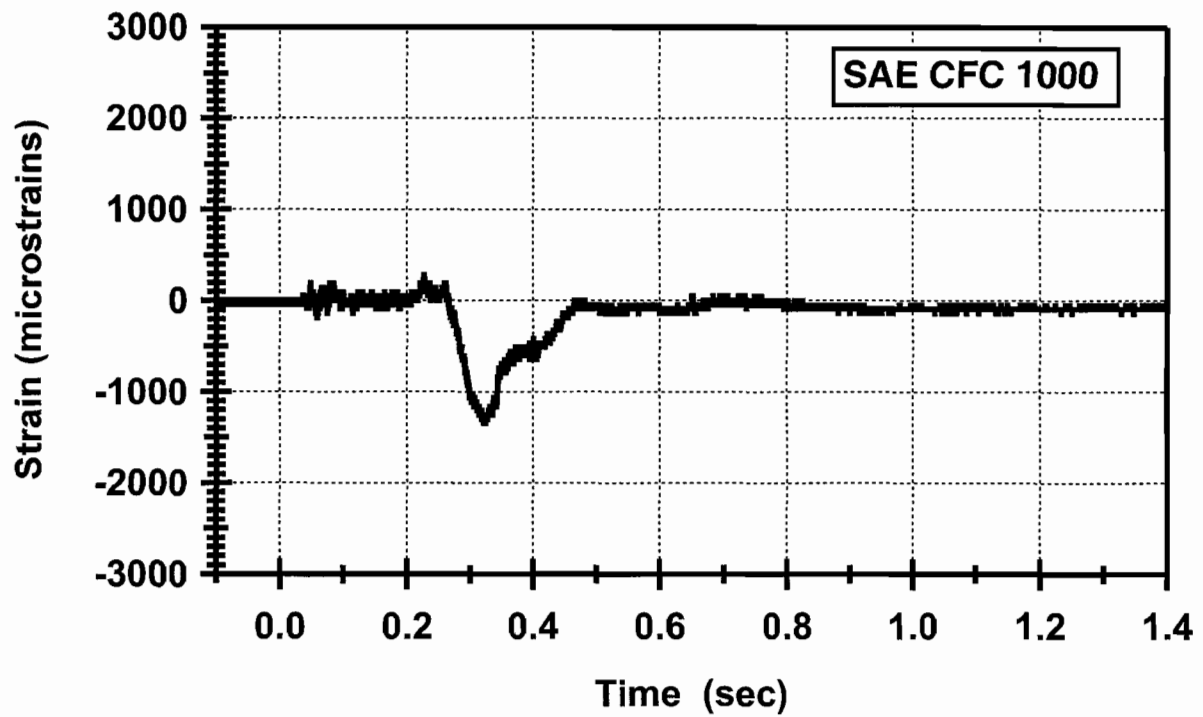


Figure D2. Strain Gage, Lead Car, B End, CS-R-1-U

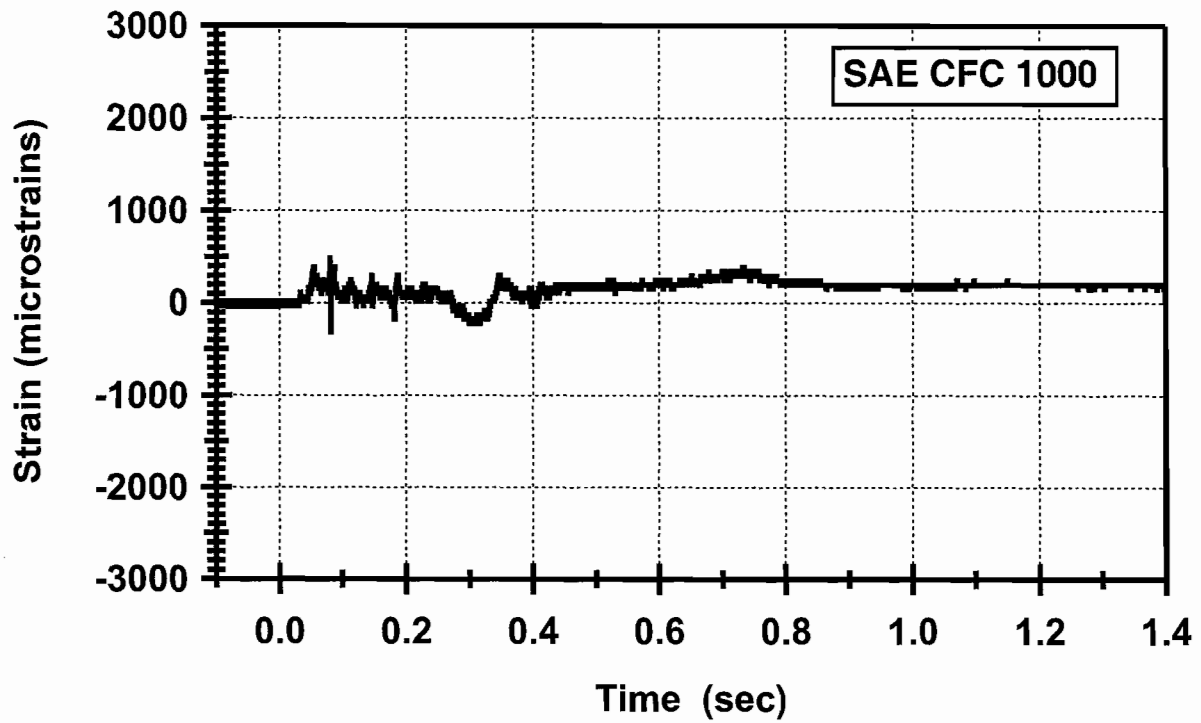


Figure D3. Strain Gage, Lead Car, B End, CS-R-2-L

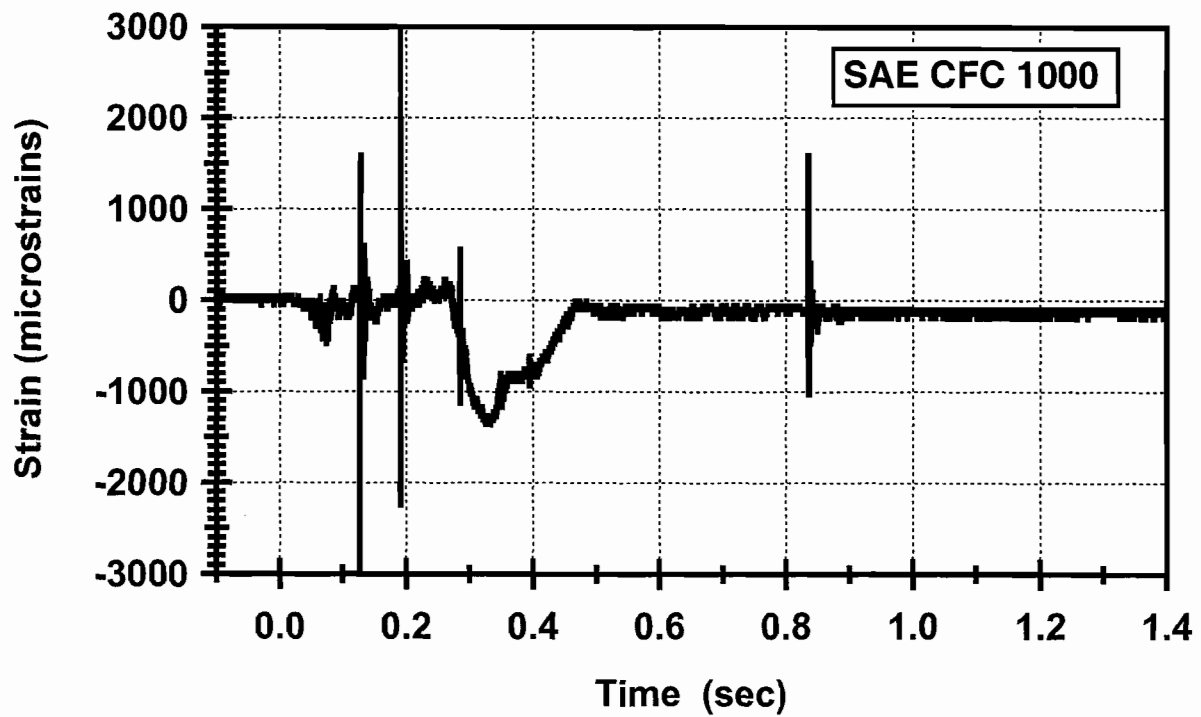


Figure D4. Strain Gage, Lead Car, B End, CS-R-2-U

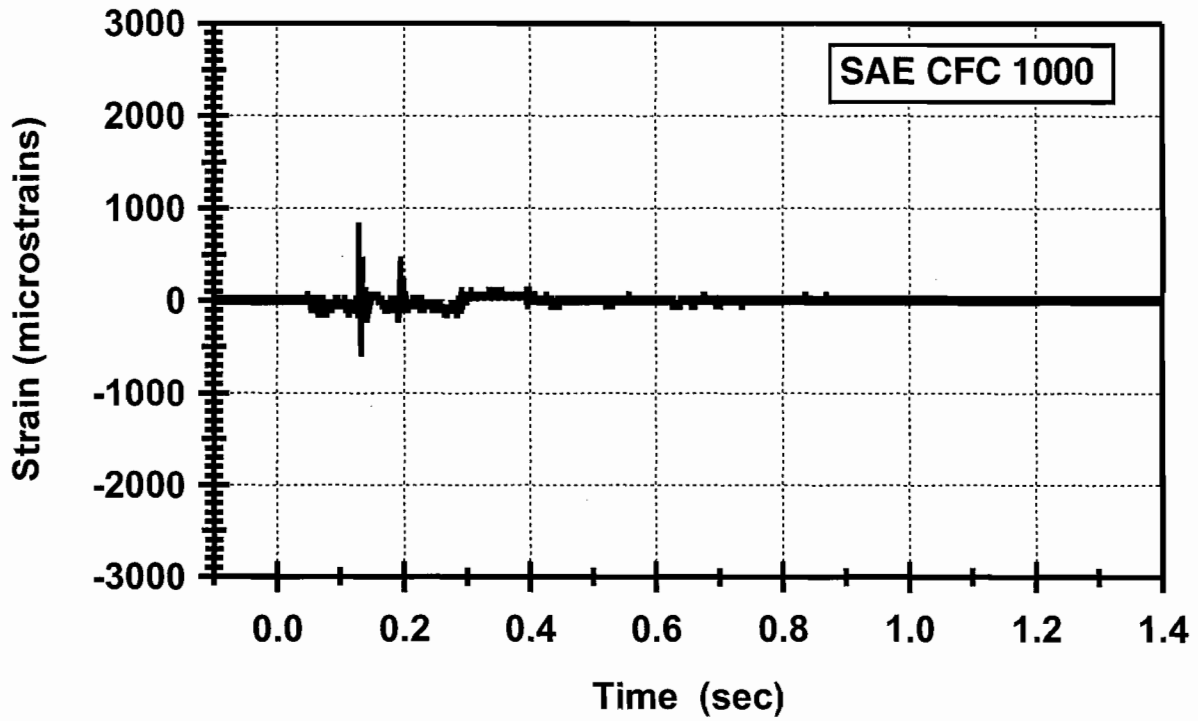


Figure D5. Strain Gage, Lead Car, B End, CR-R-2-L

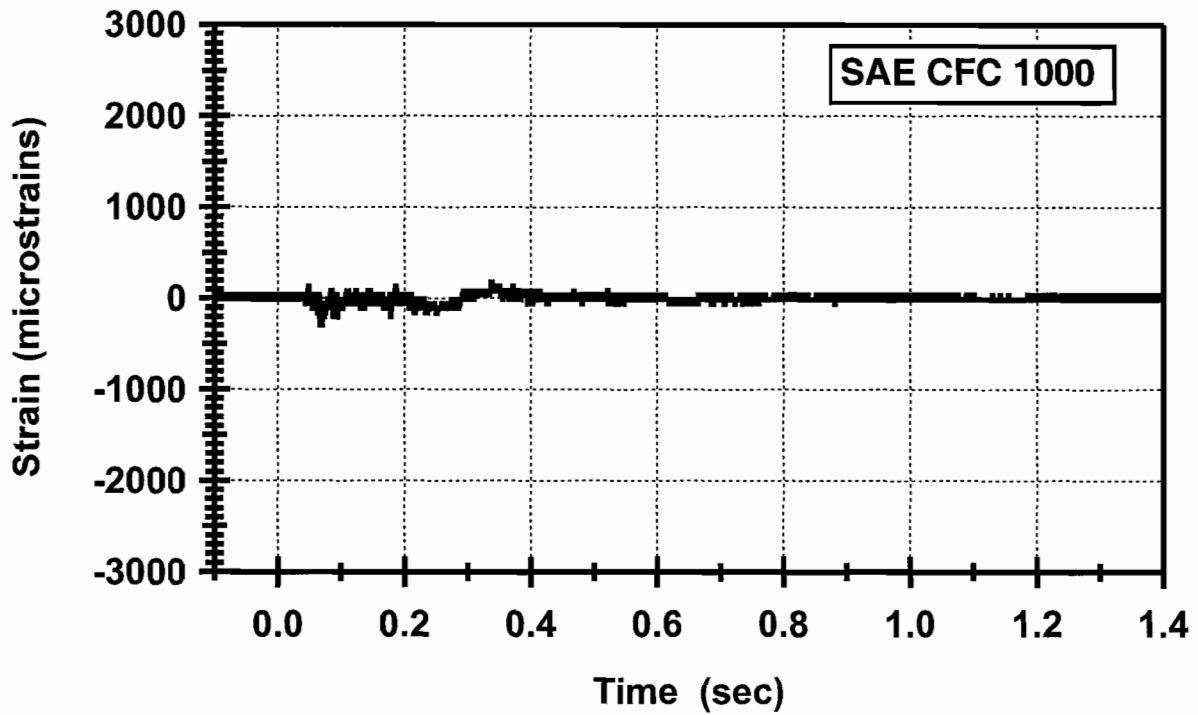


Figure D6. Strain Gage, Lead Car, B End, CR-R-2-U

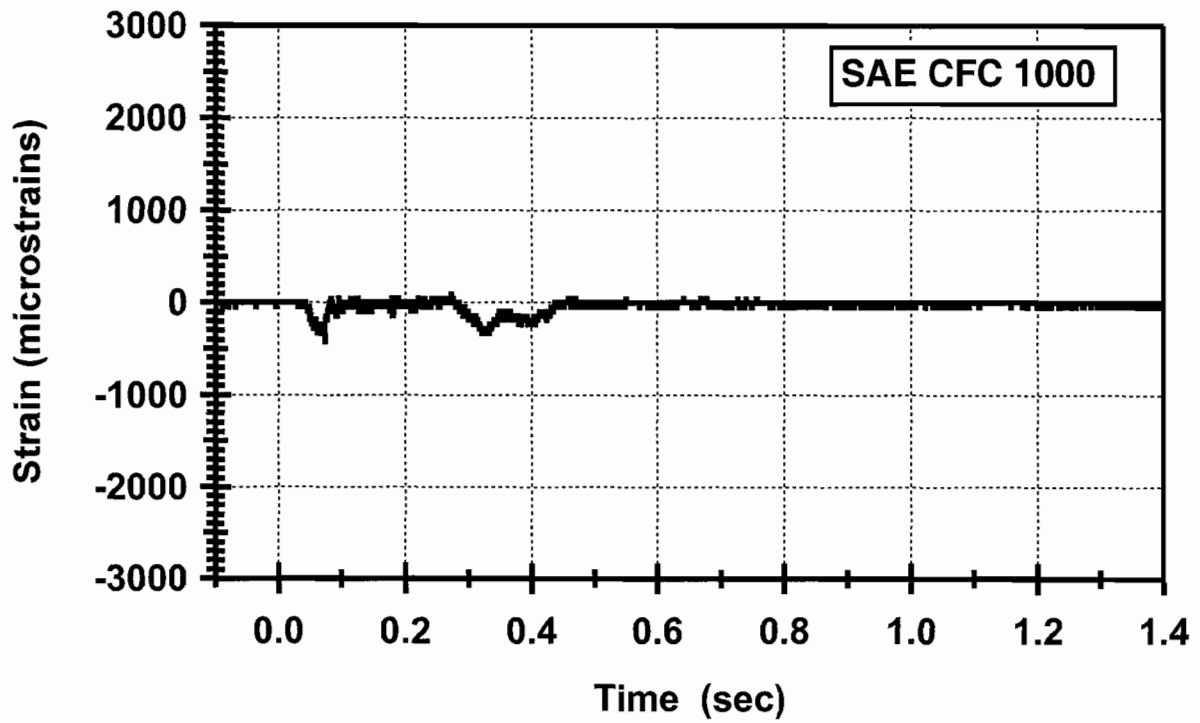


Figure D7. Strain Gage, Lead Car, B End, SS-R-1-L

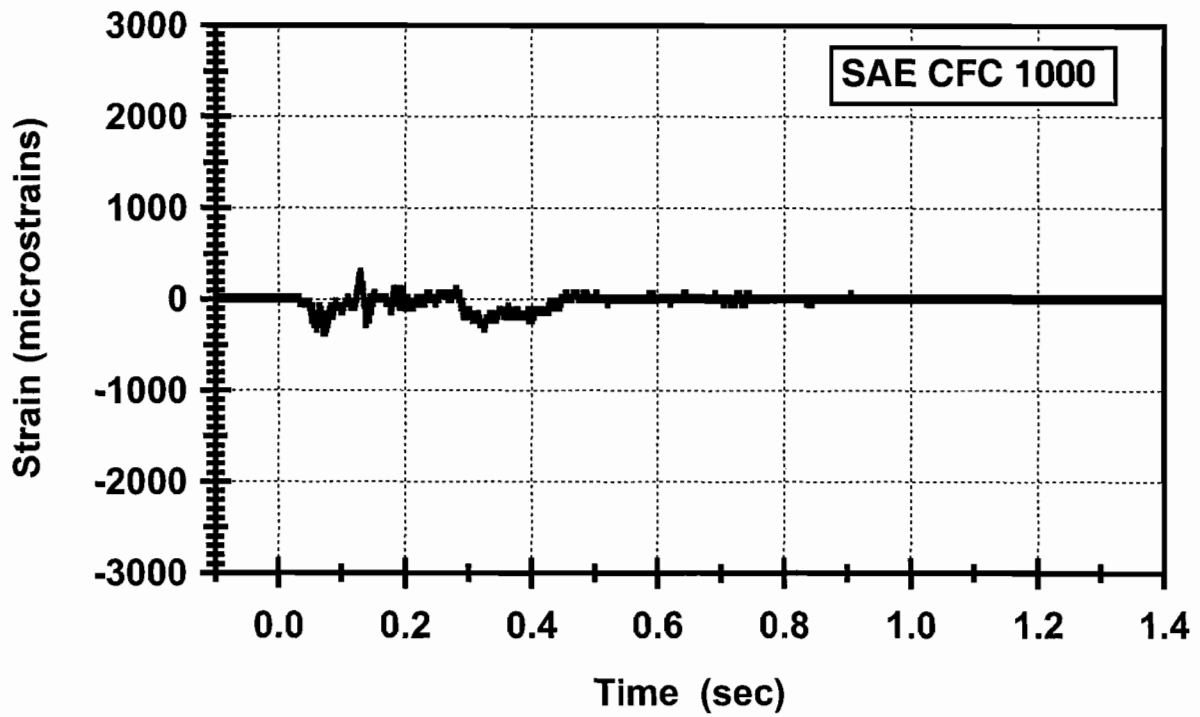


Figure D8. Strain Gage, Lead Car, B End, SS-R-1-U

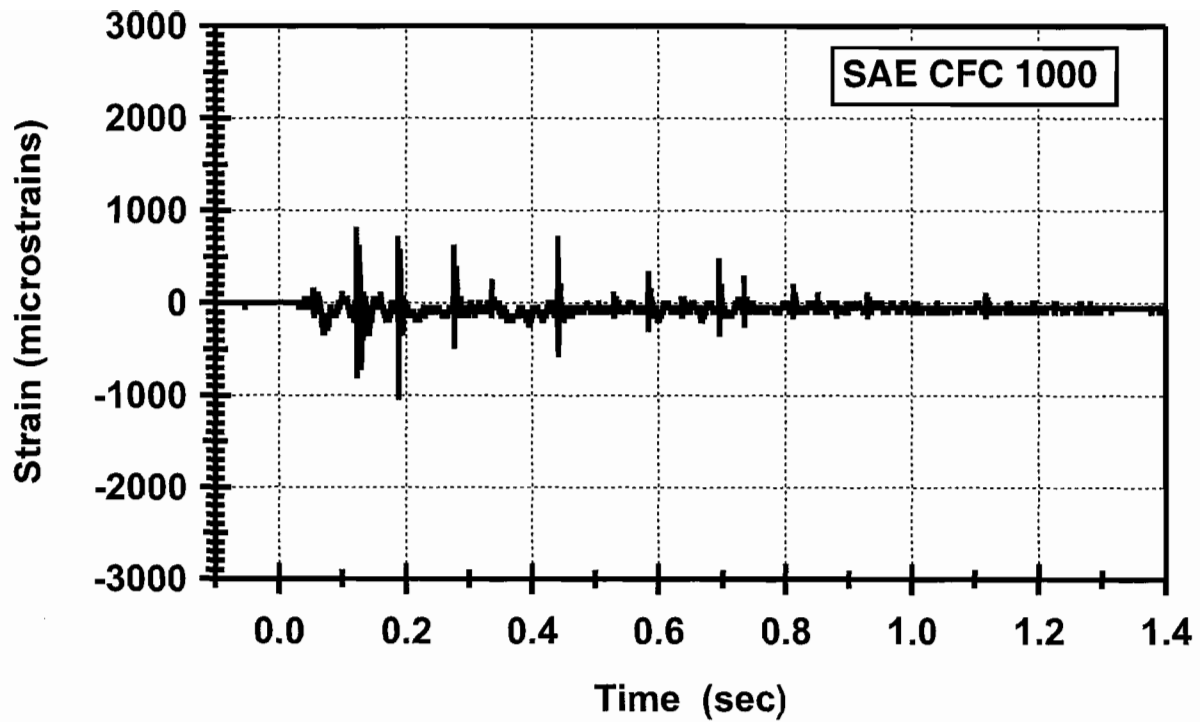


Figure D9. Strain Gage, Lead Car, B End, CR-L-2-L

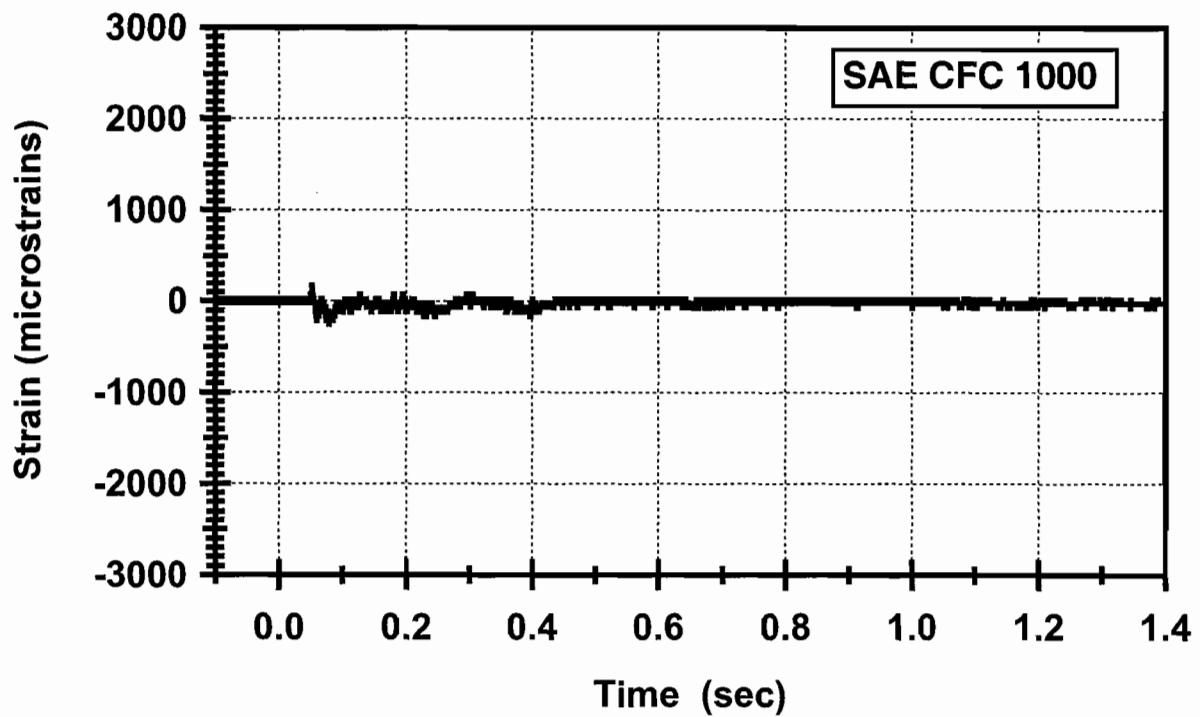


Figure D10. Strain Gage, Lead Car, B End, CR-L-2-U

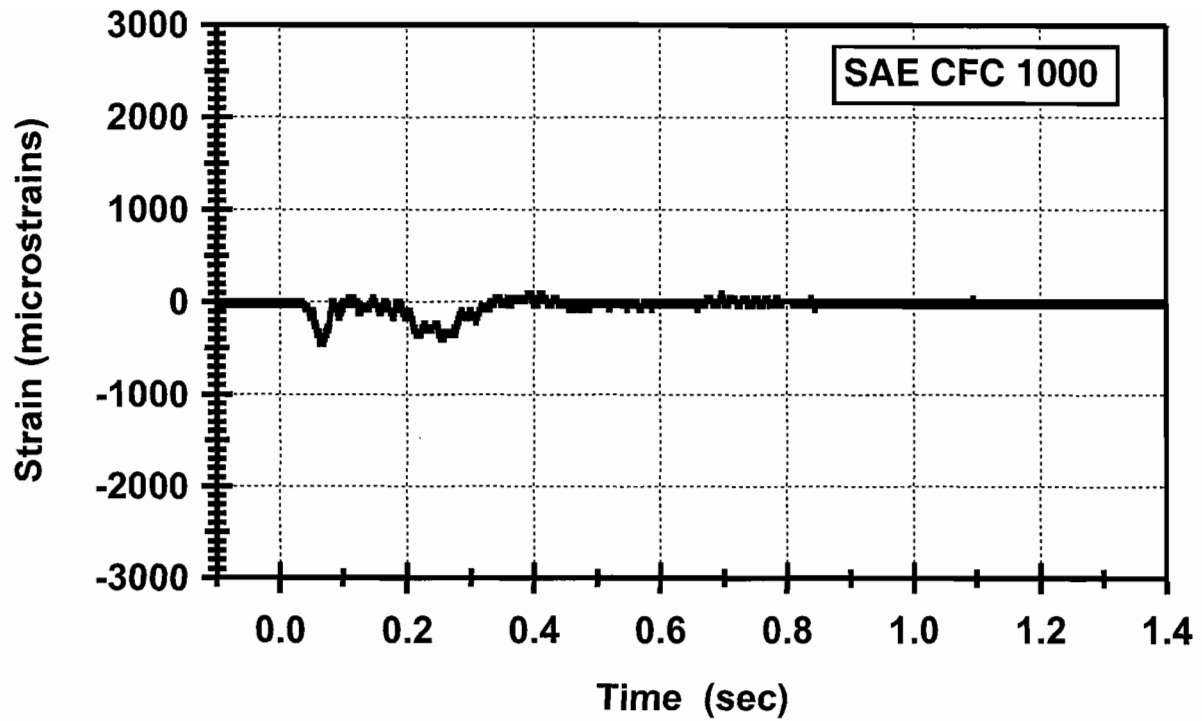


Figure D11. Strain Gage, Lead Car, B End, SS-L-1-L

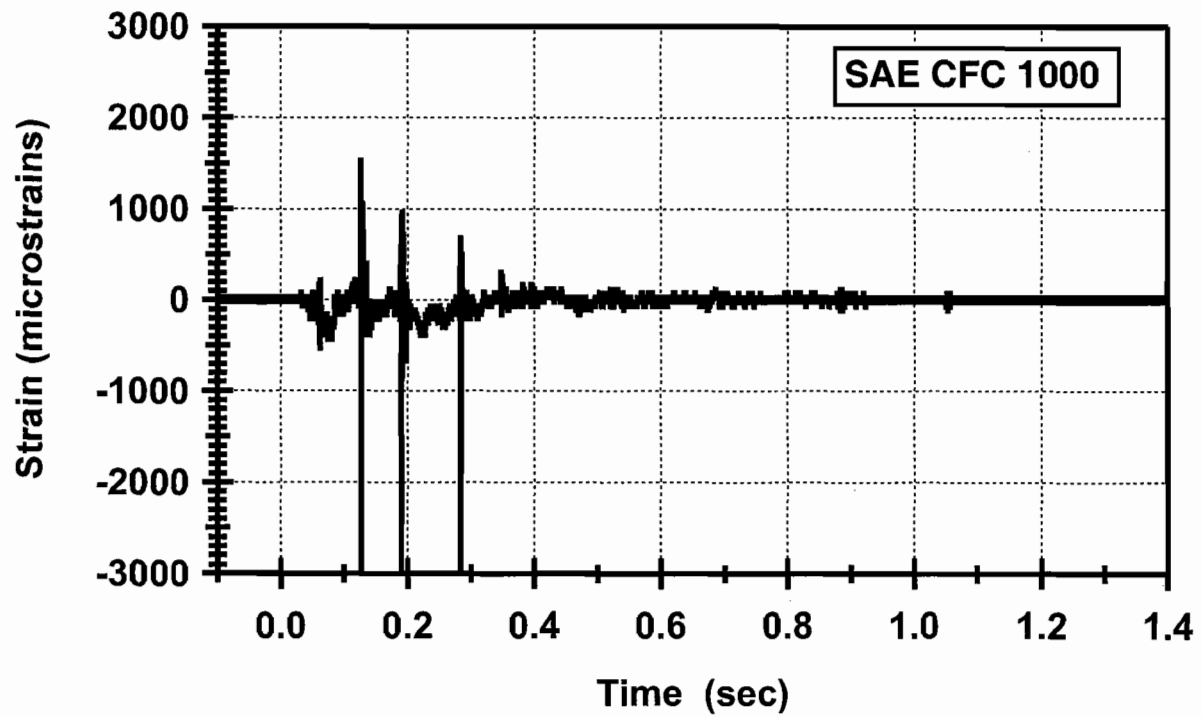


Figure D12. Strain Gage, Lead Car, B End, SS-L-1-U

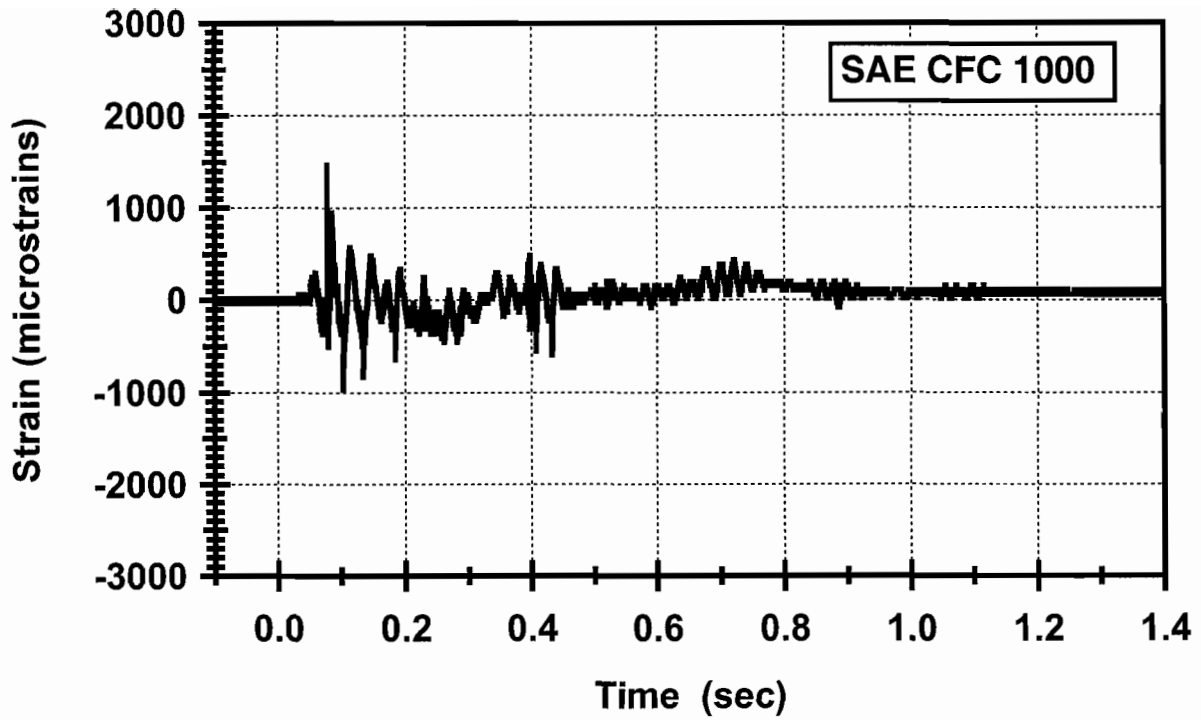


Figure D13. Strain Gage, Lead Car, B End, CS-L-1-L

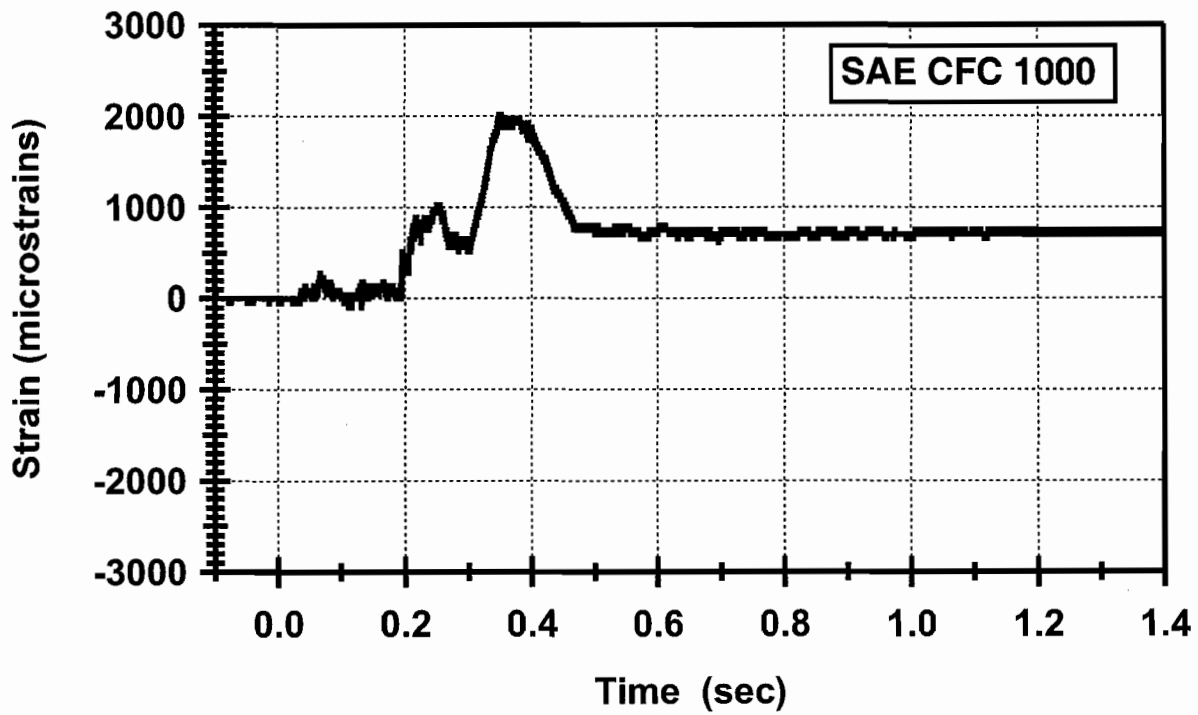


Figure D14. Strain Gage, Lead Car, B End, CS-L-1-U

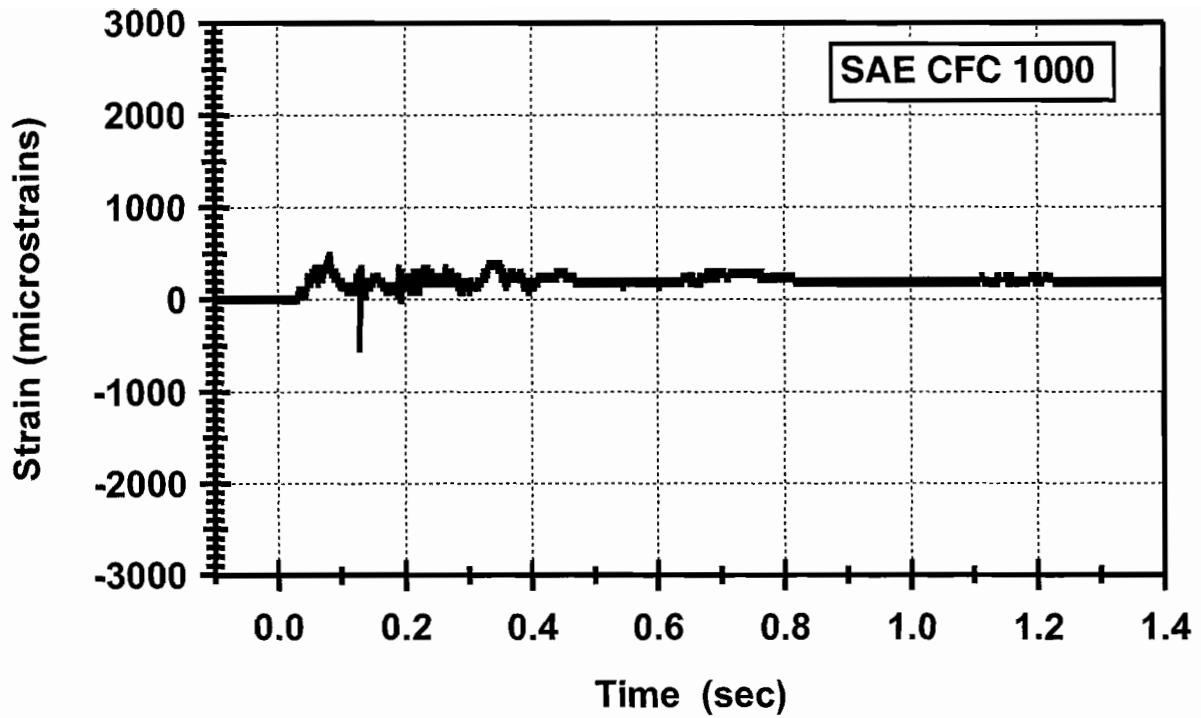


Figure D15. Strain Gage, Lead Car, B End, CS-L-2-L

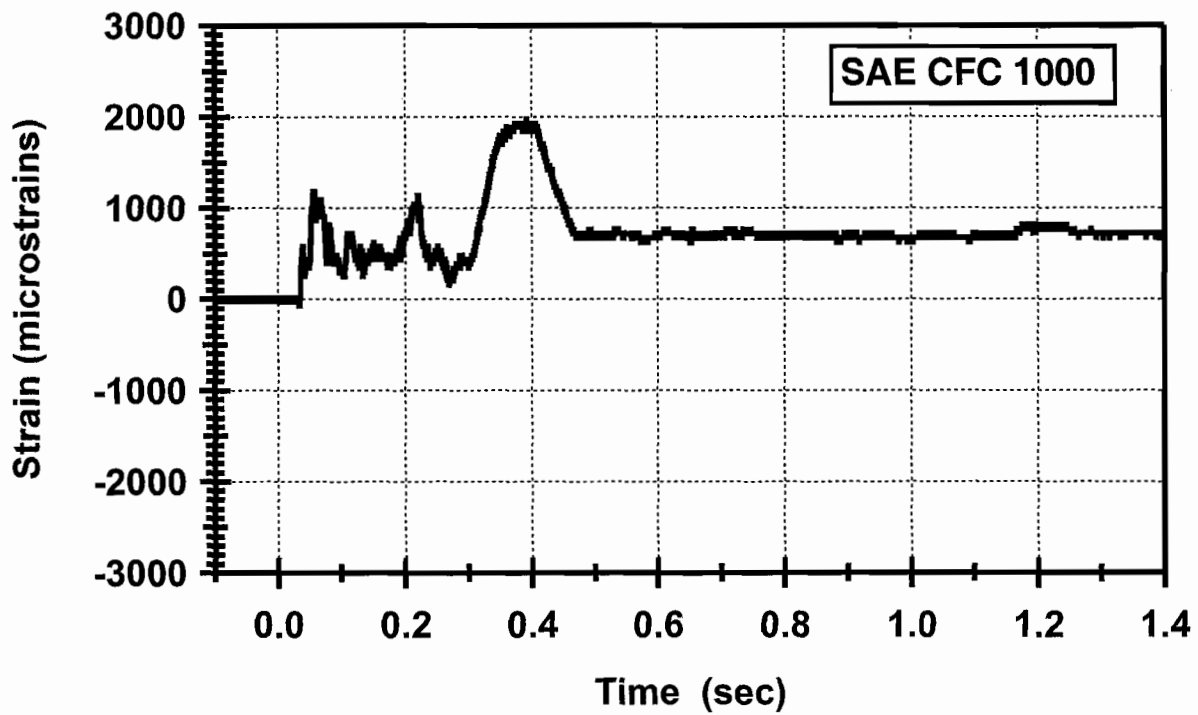
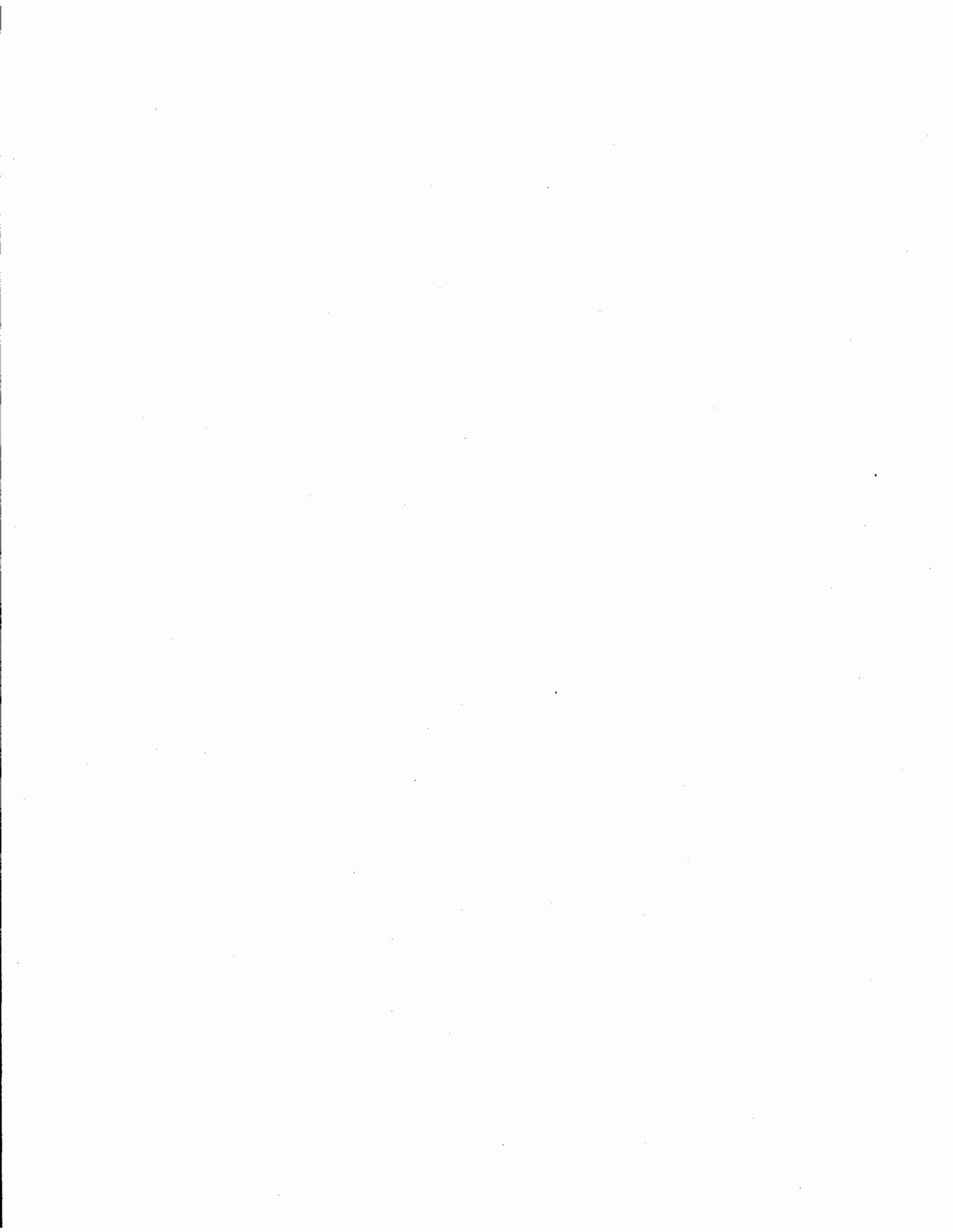


Figure D16. Strain Gage, Lead Car, B End, CS-L-2-U



APPENDIX E
LOW PASS FILTERED ACCELERATIONS
FOR THE LEAD CAR, FC = 25 HZ

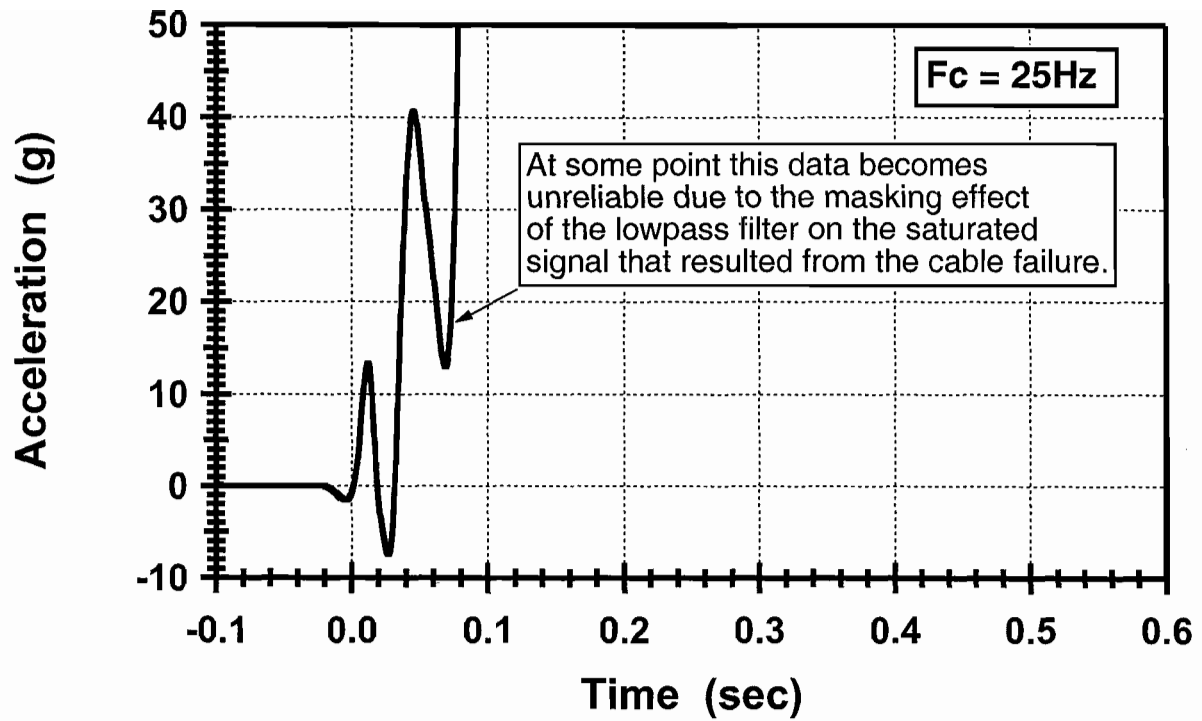


Figure E1. Accel., Lead Car, CS, Position 1, X-Axis

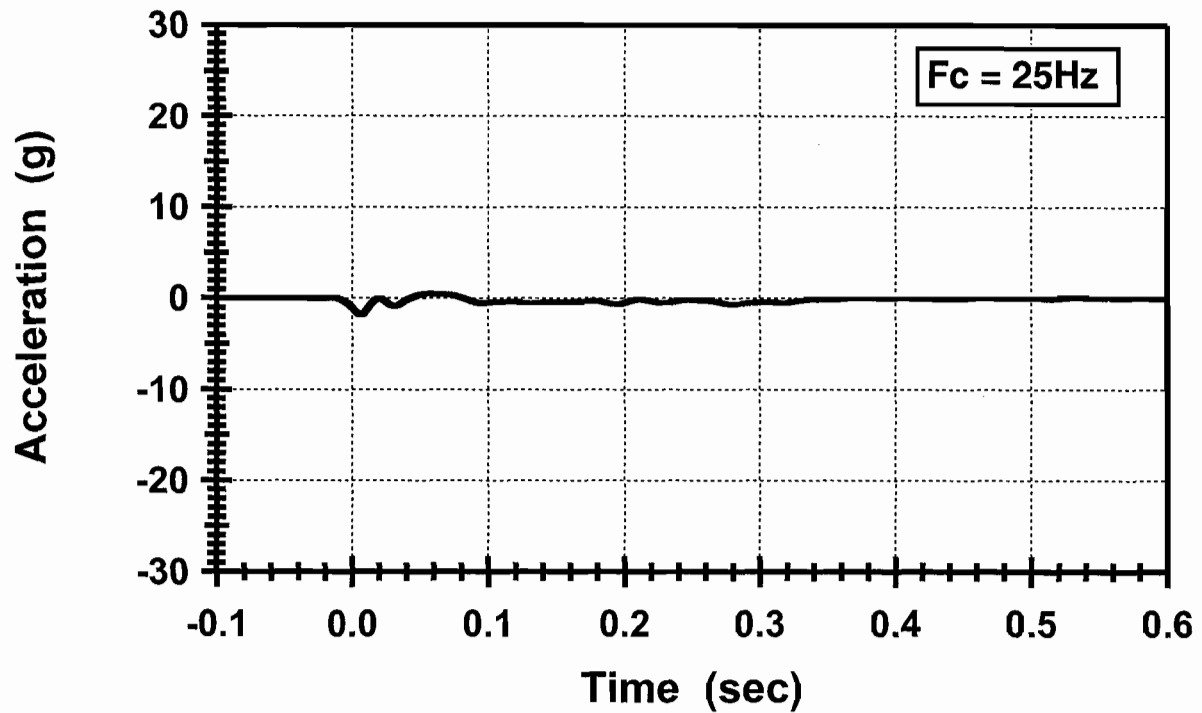


Figure E2. Accel., Lead Car, CS, Position 2, X-Axis

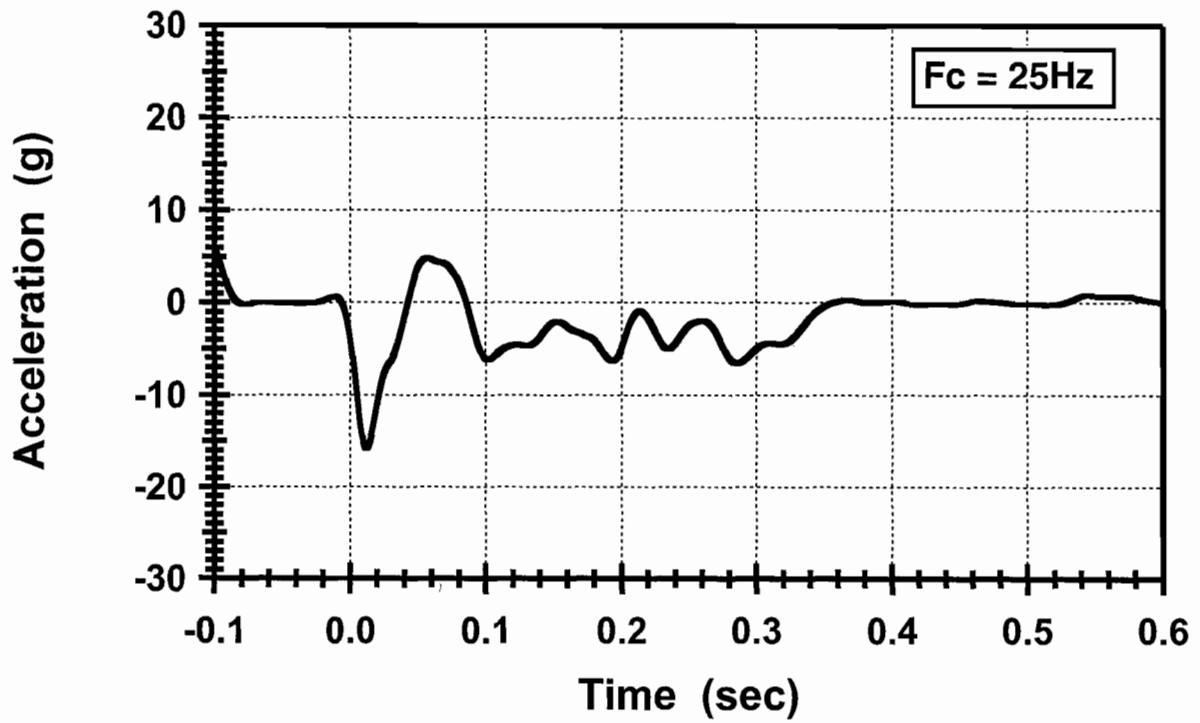


Figure E3. Accel., Lead Car, CS, Position 3, X-Axis

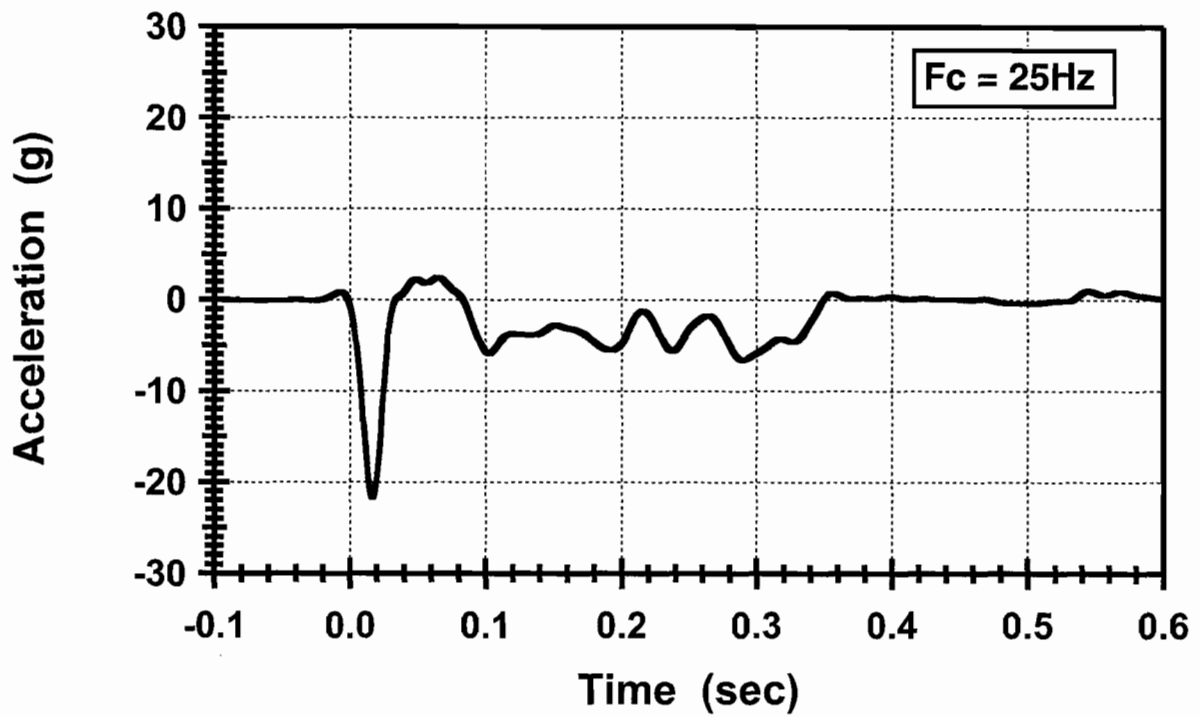


Figure E4. Accel., Lead Car, CS, Position 4, X-Axis

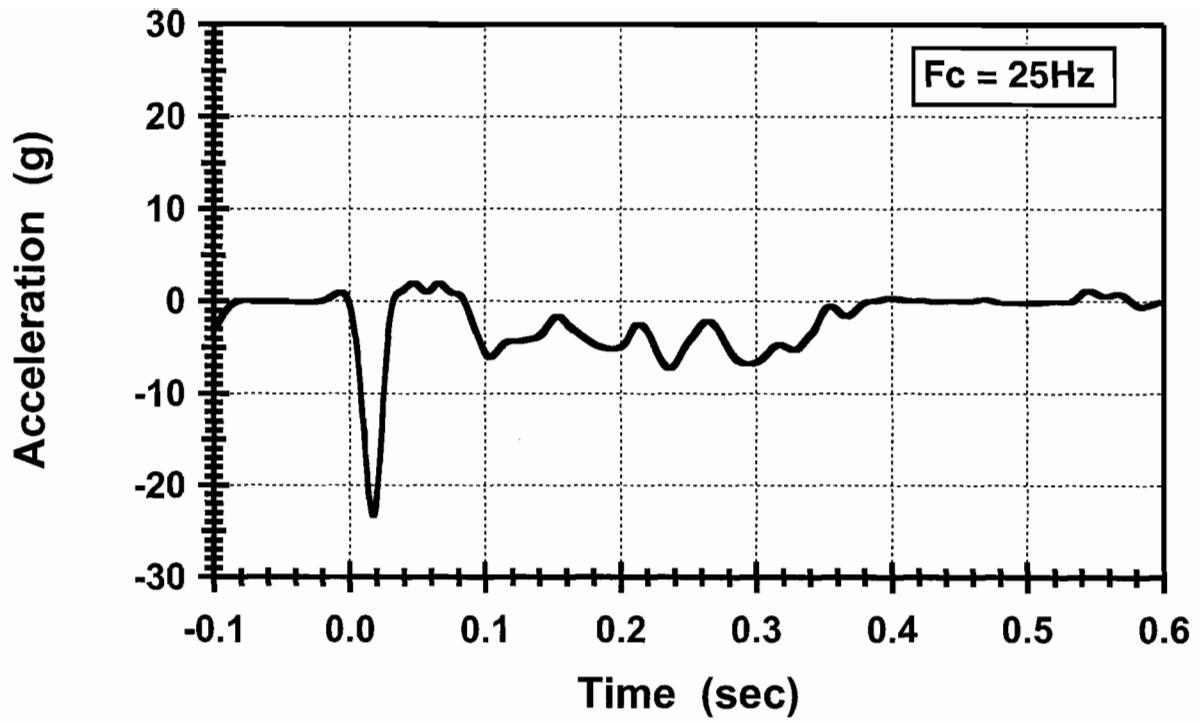


Figure E5. Accel., Lead Car, CS, Position 5, X-Axis

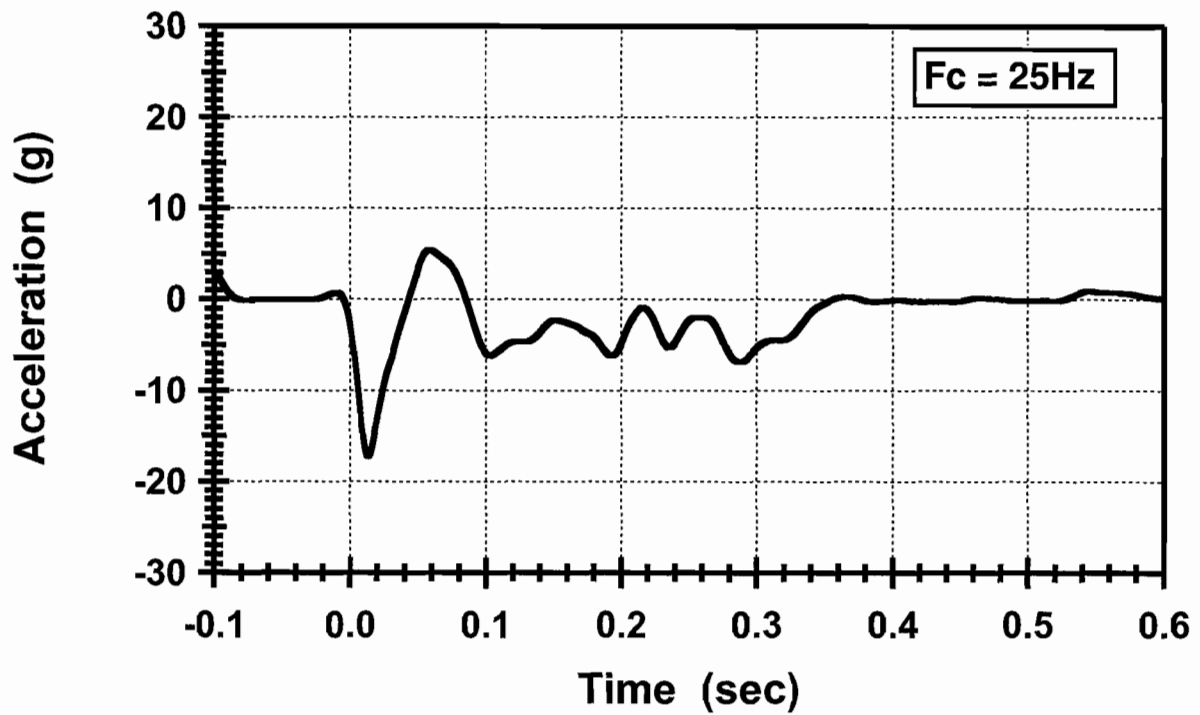


Figure E6. Accel., Lead Car, RS, Position 3, X-Axis

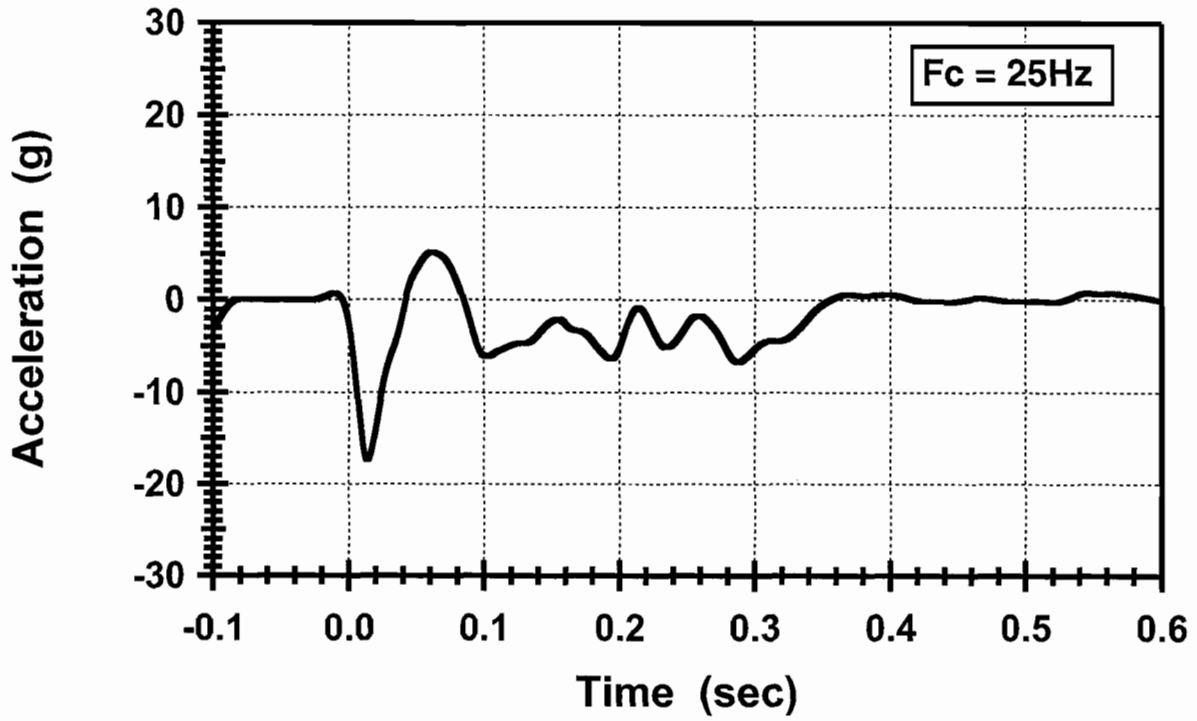


Figure E7. Accel., Lead Car, LS, Position 3, X-Axis

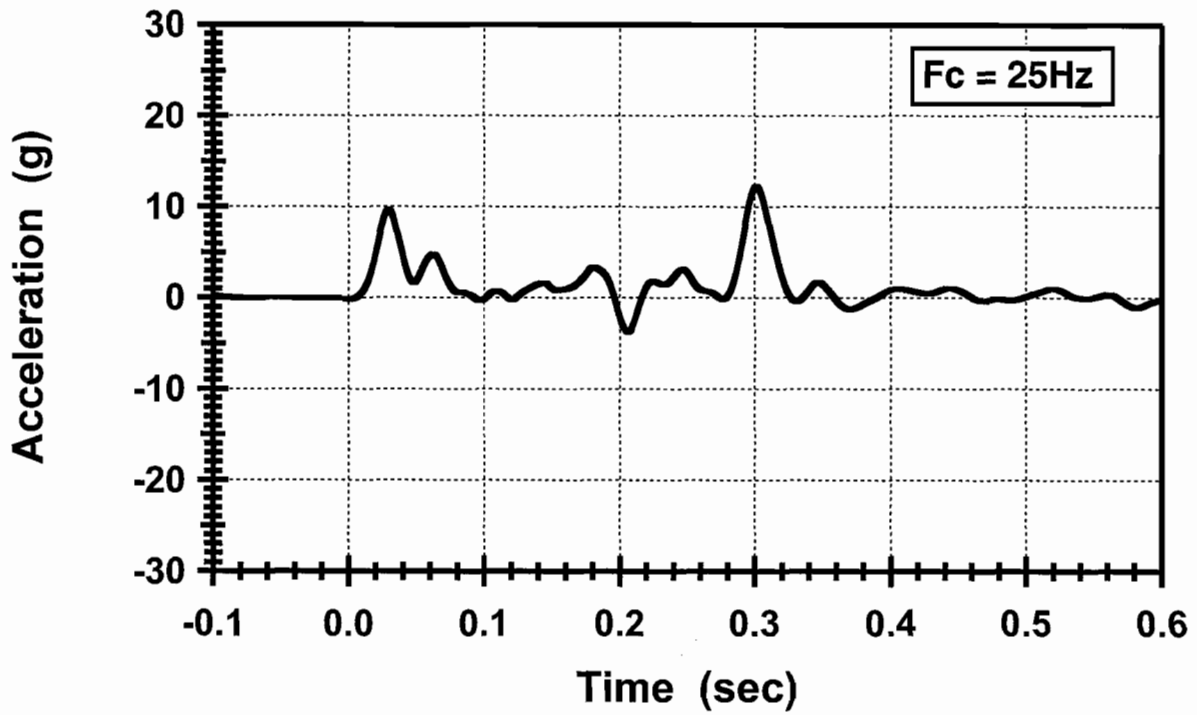


Figure E8. Accel., Lead Car, CS, Position 2, Y-Axis

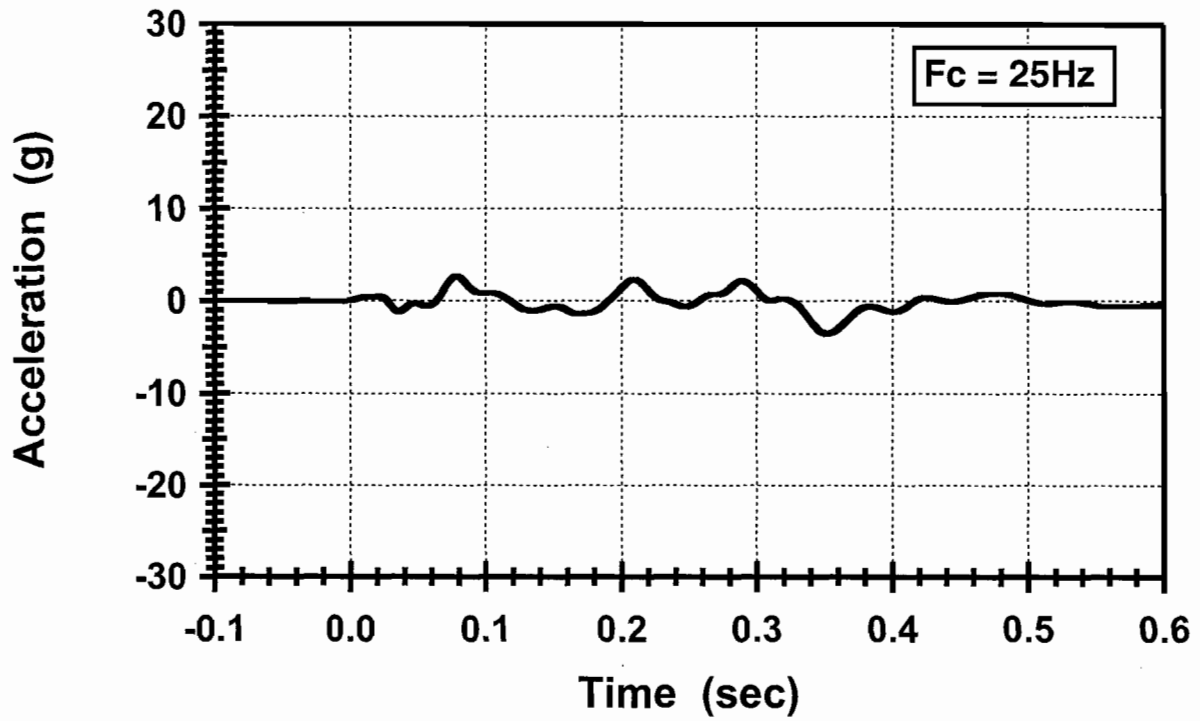


Figure E9. Accel., Lead Car, CS, Position 3, Y-Axis

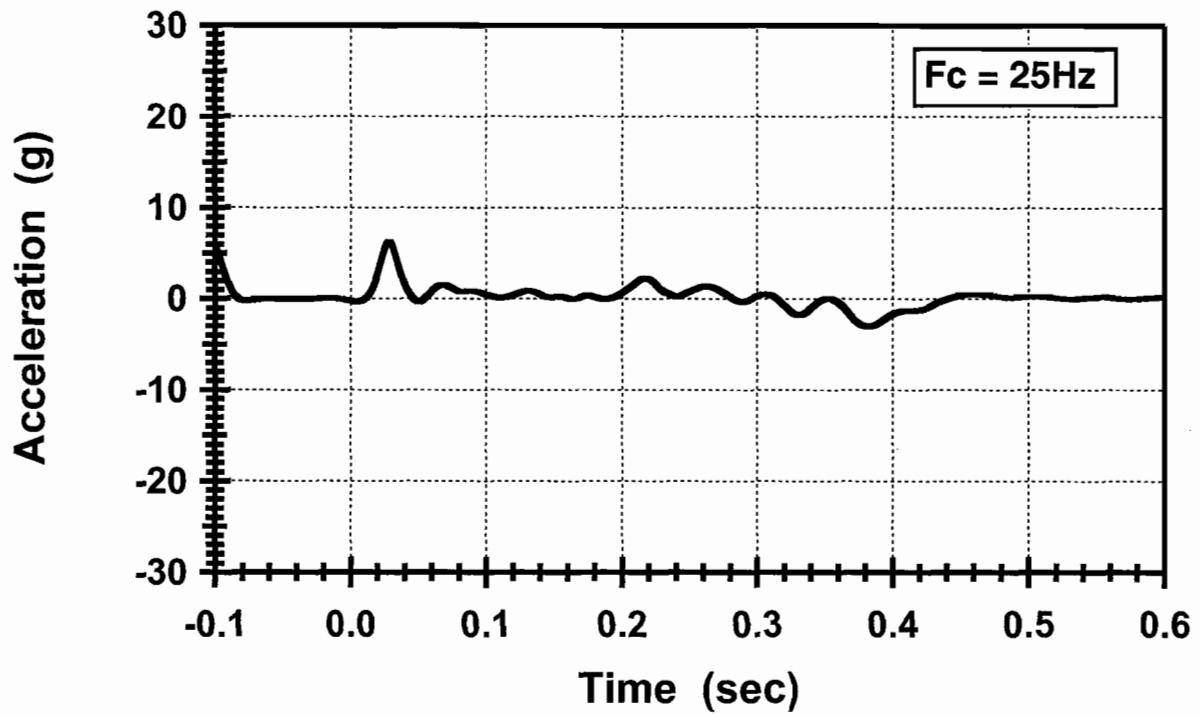


Figure E10. Accel., Lead Car, CS, Position 4, Y-Axis

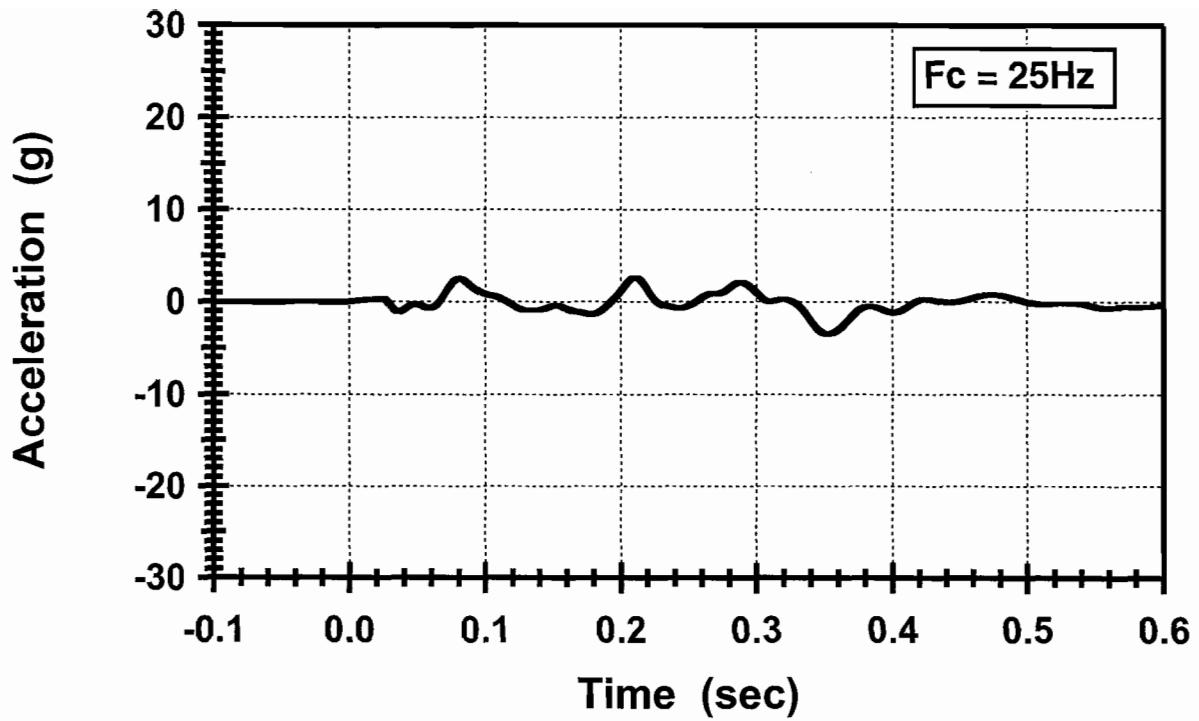


Figure E11. Accel., Lead Car, RS, Position 3, Y-Axis

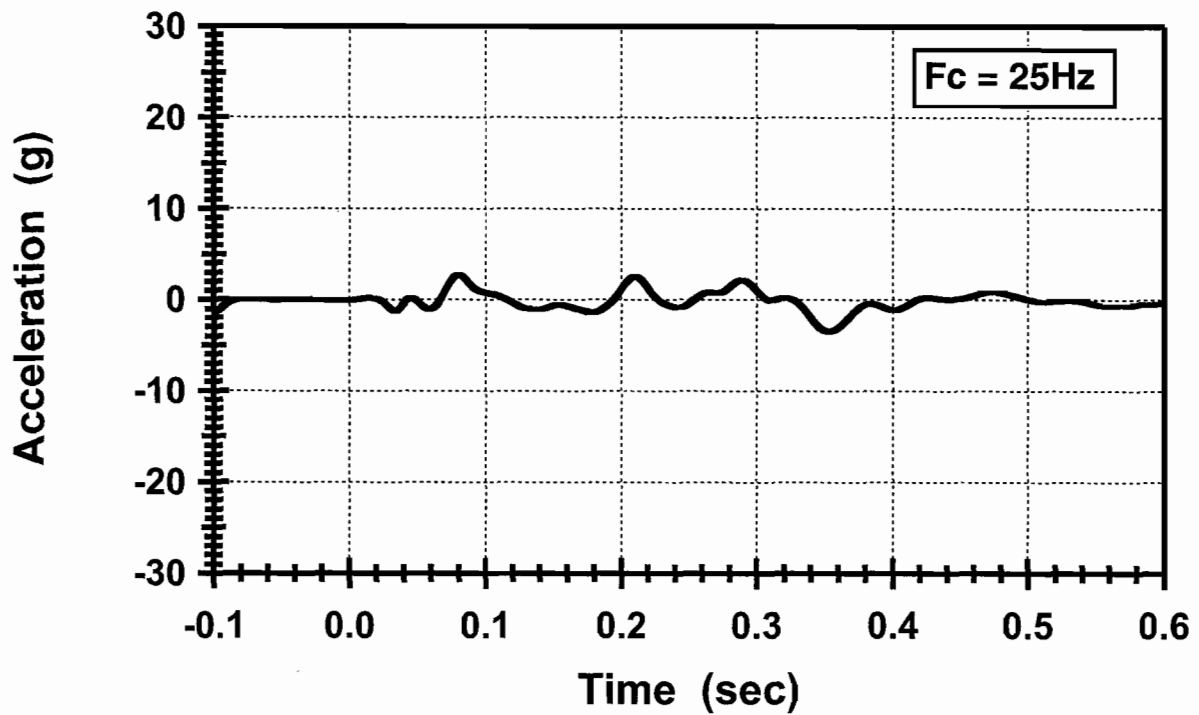


Figure E12. Accel., Lead Car, LS, Position 3, Y-Axis

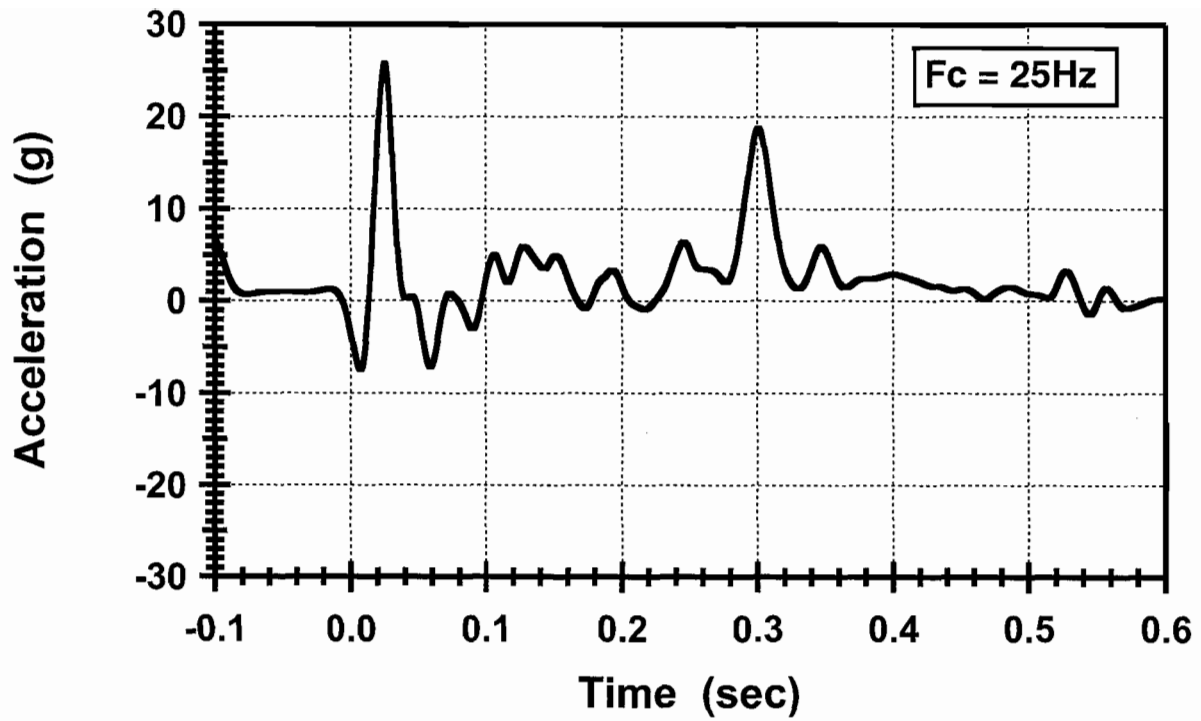


Figure E13. Accel., Lead Car, CS, Position 2, Z-Axis

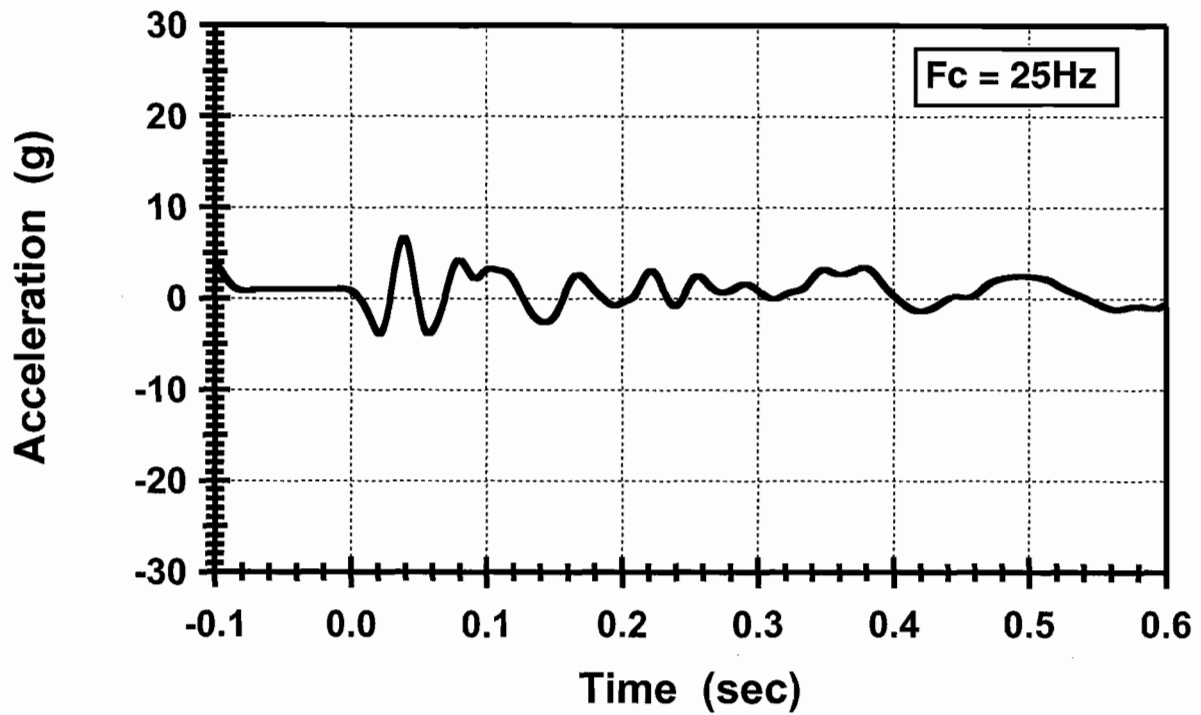


Figure E14. Accel., Lead Car, CS, Position 3, Z-Axis

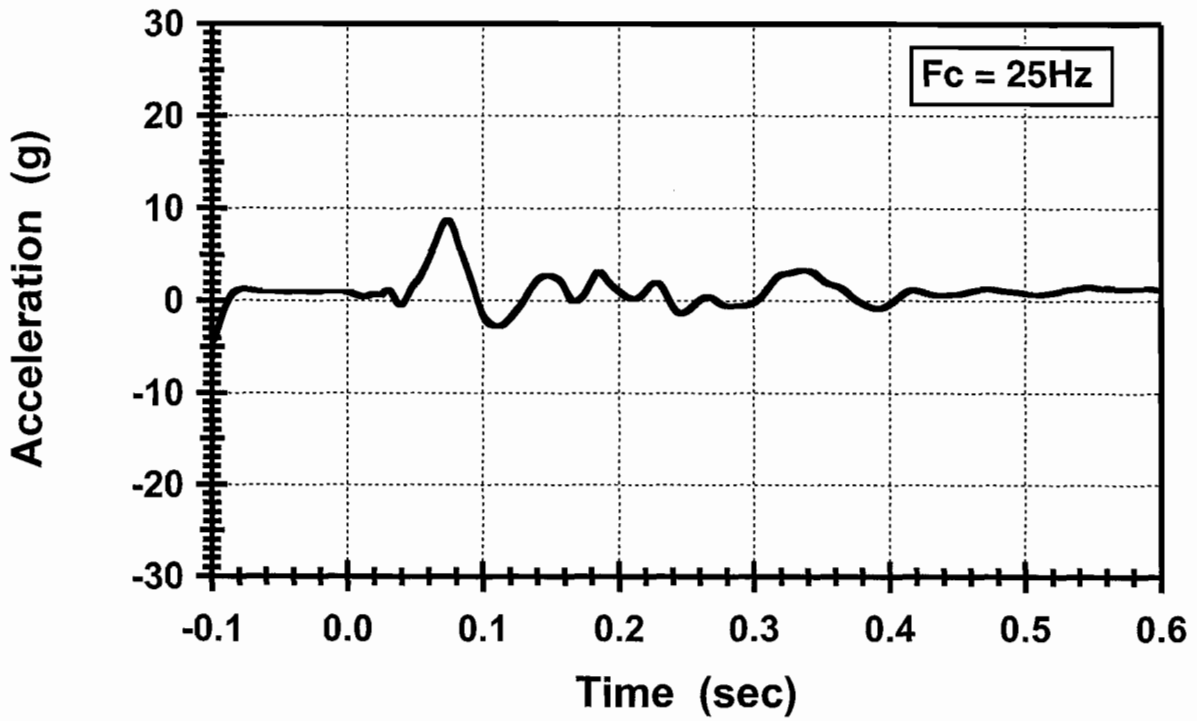


Figure E15. Accel., Lead Car, CS, Position 4, Z-Axis

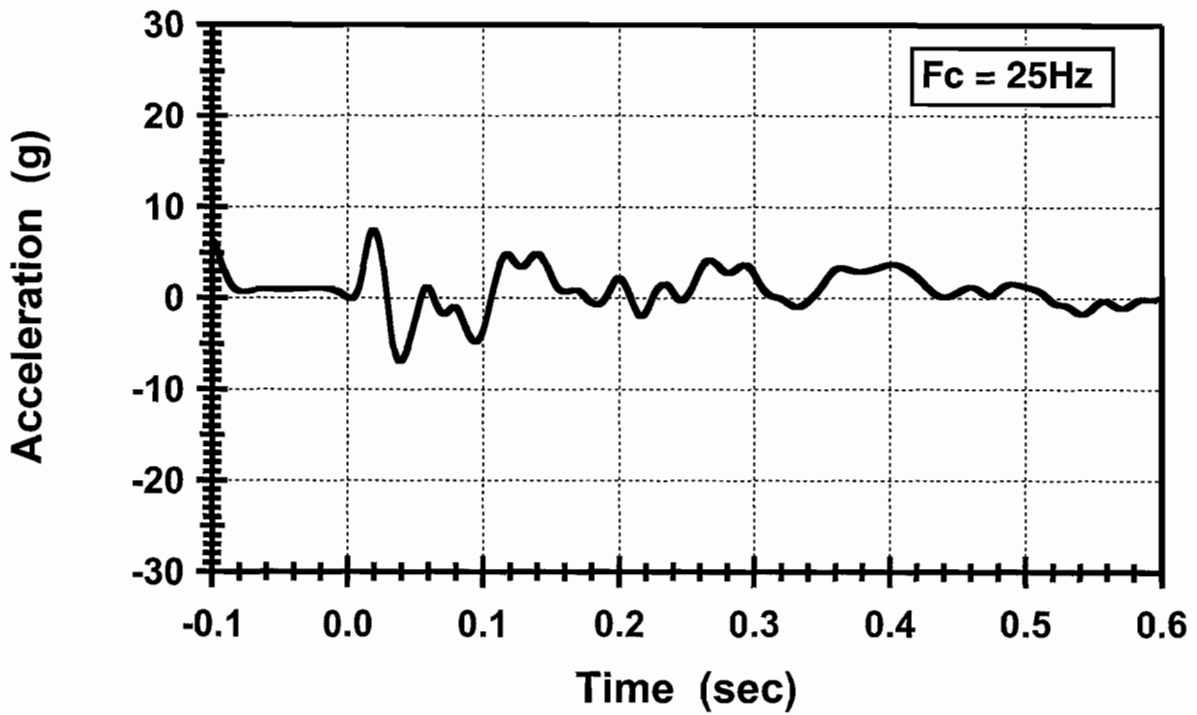


Figure E16. Accel., Lead Car, RS, Position 1, Z-Axis

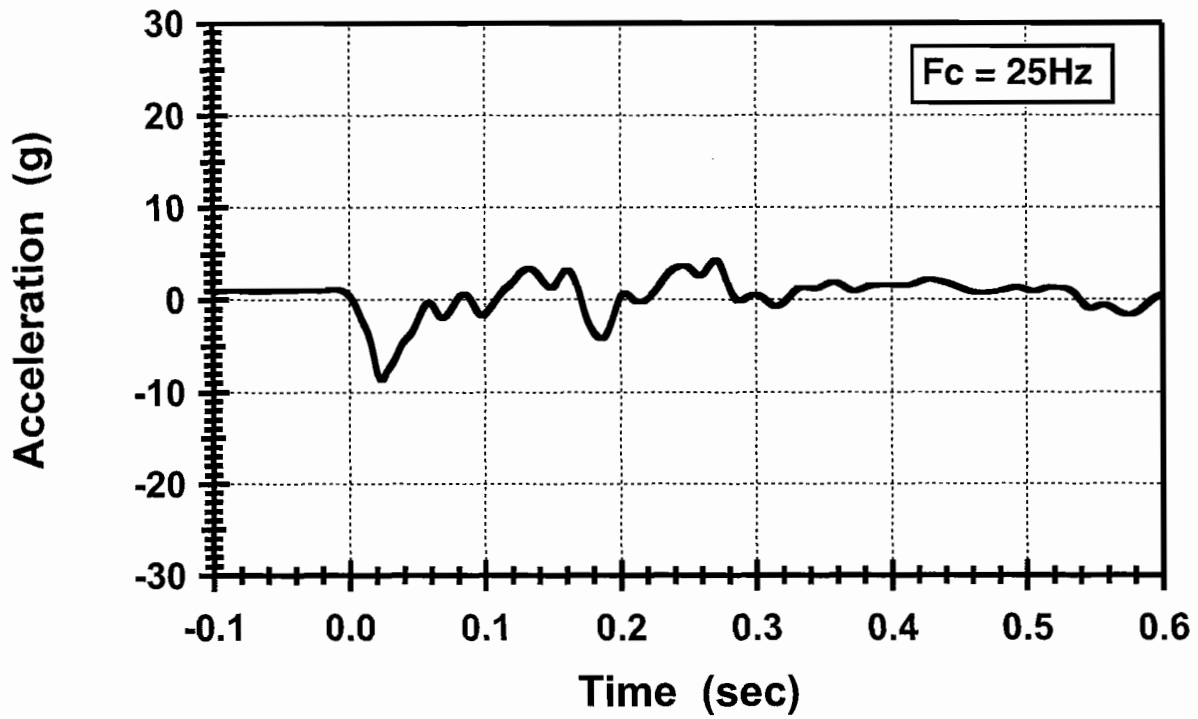


Figure E17. Accel., Lead Car, LS, Position 1, Z-Axis

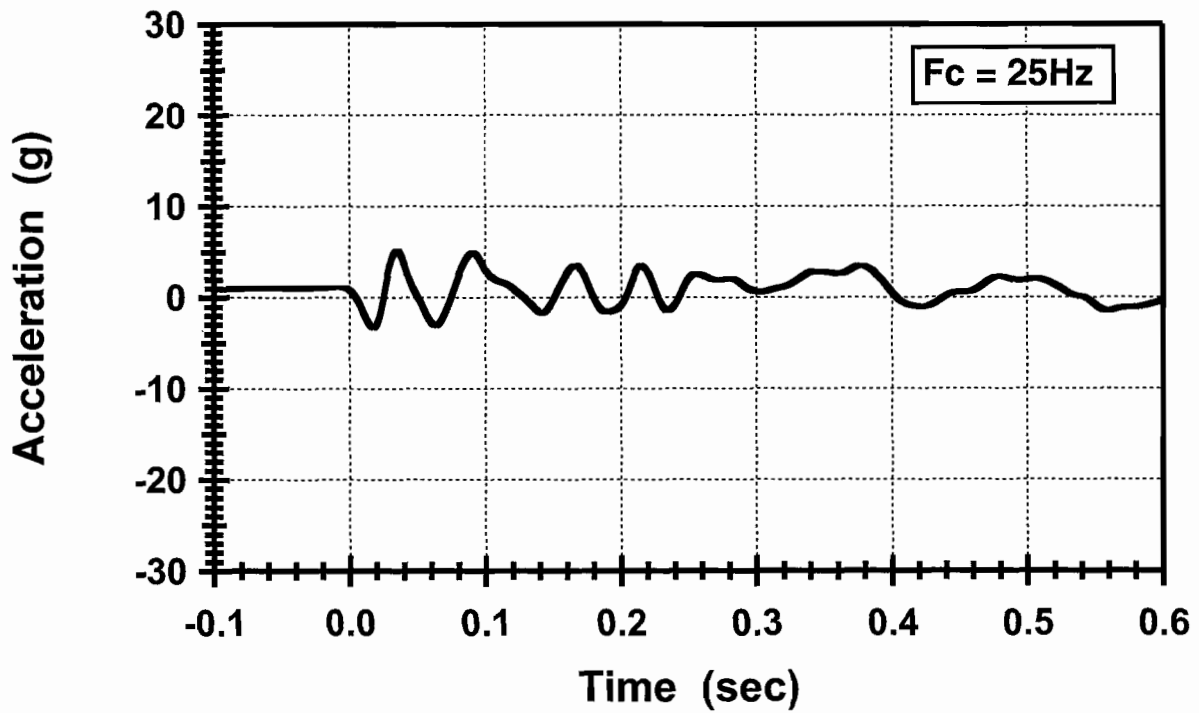


Figure E18. Accel., Lead Car, RS, Position 3, Z-Axis

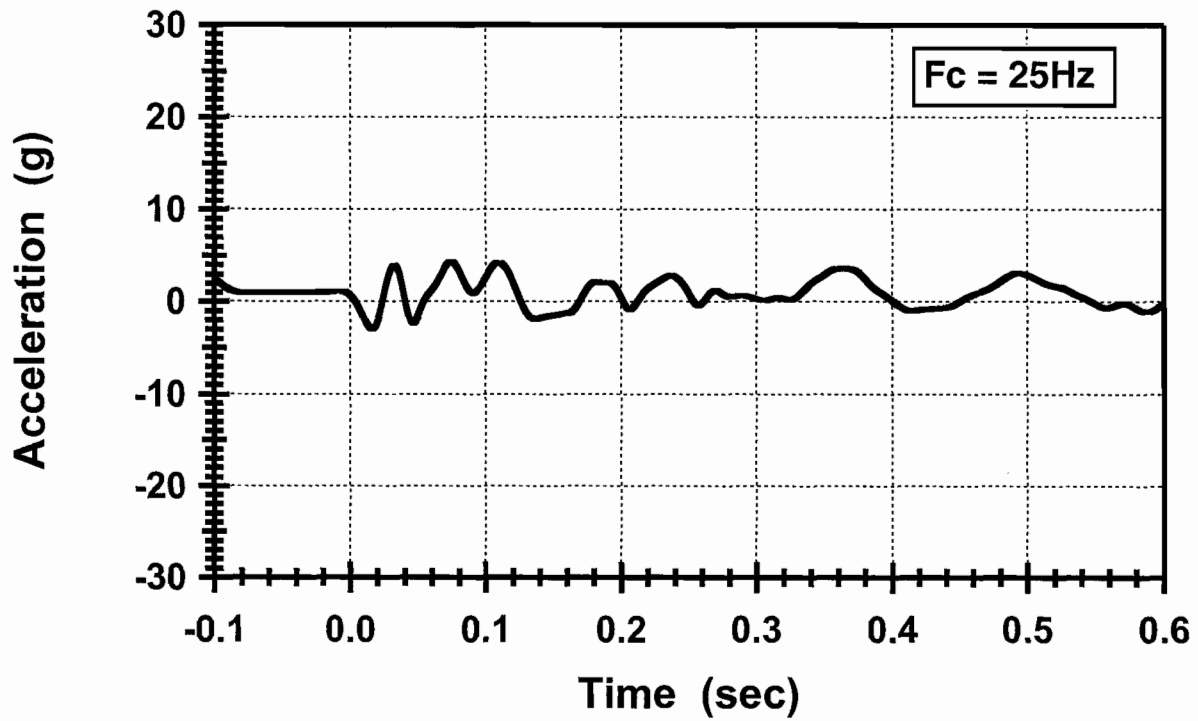


Figure E19. Accel., Lead Car, LS, Position 3, Z-Axis

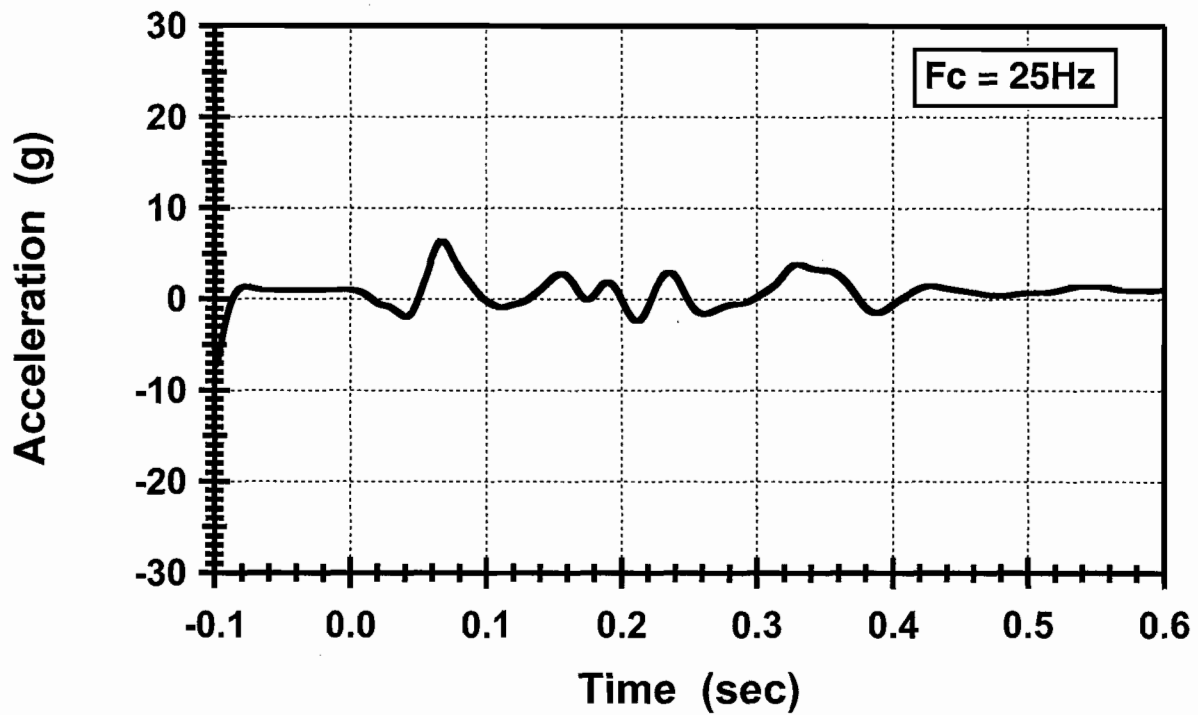


Figure E20. Accel., Lead Car, RS, Position 5, Z-Axis

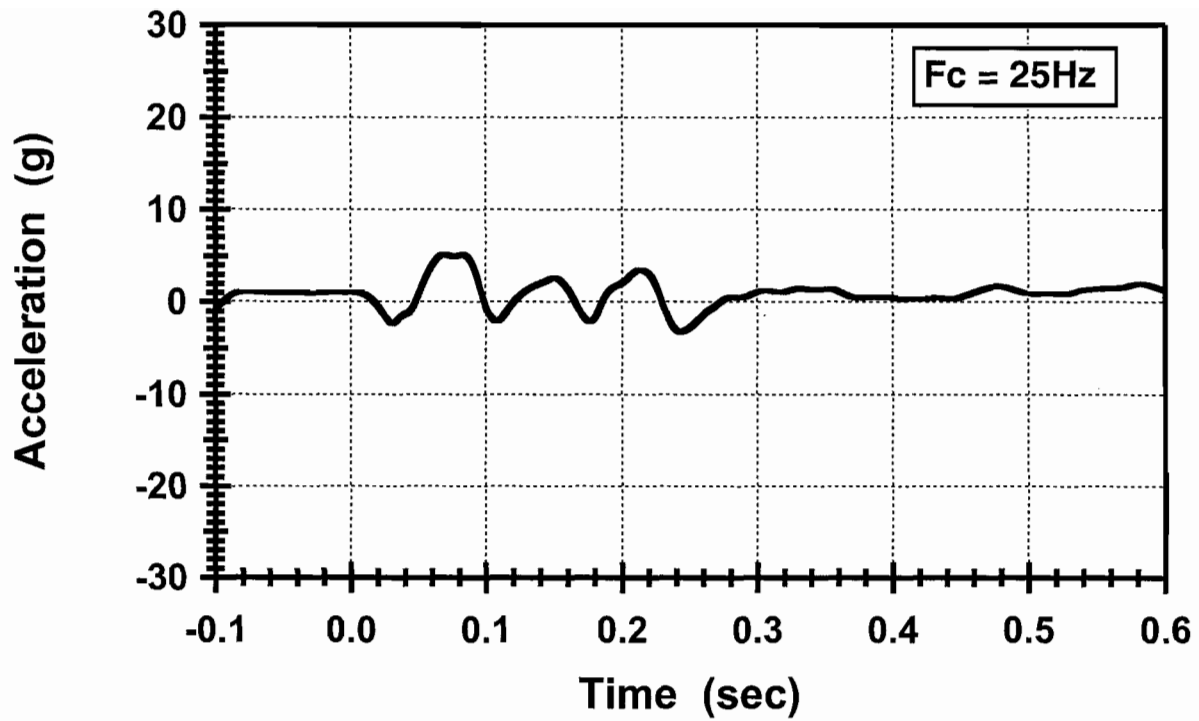


Figure E21. Accel., Lead Car, LS, Position 5, Z-Axis

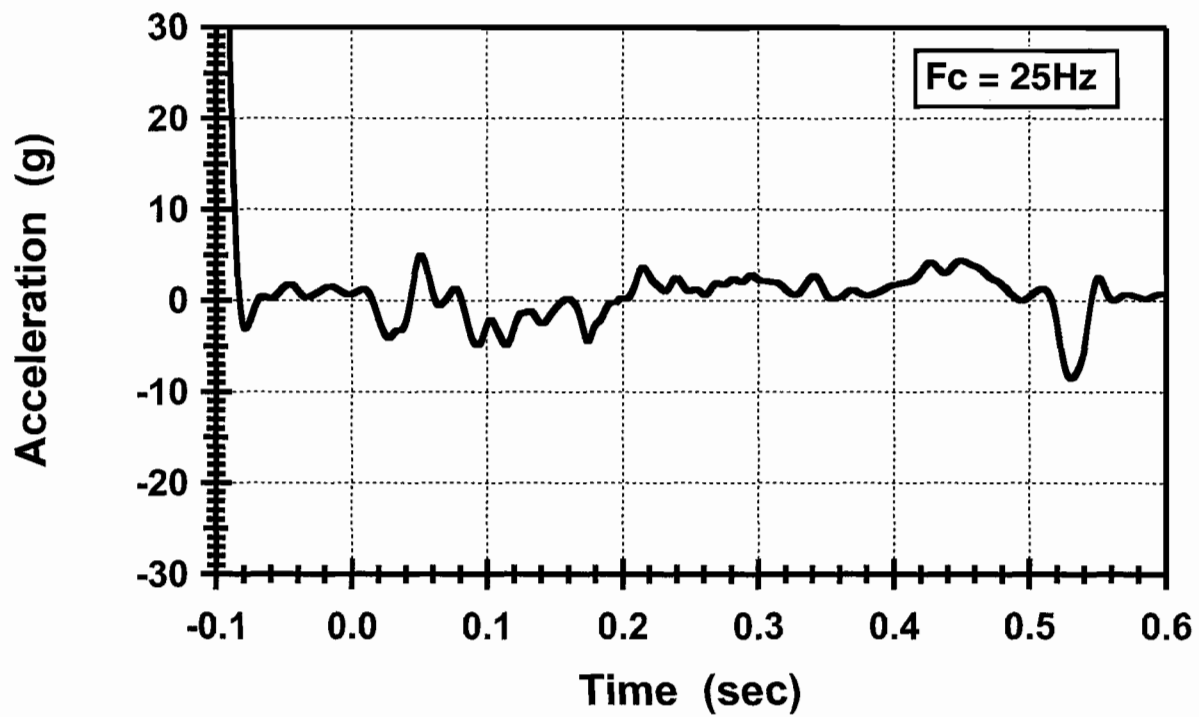


Figure E22. Accel., Lead Car, A End Bogie, Z-Axis

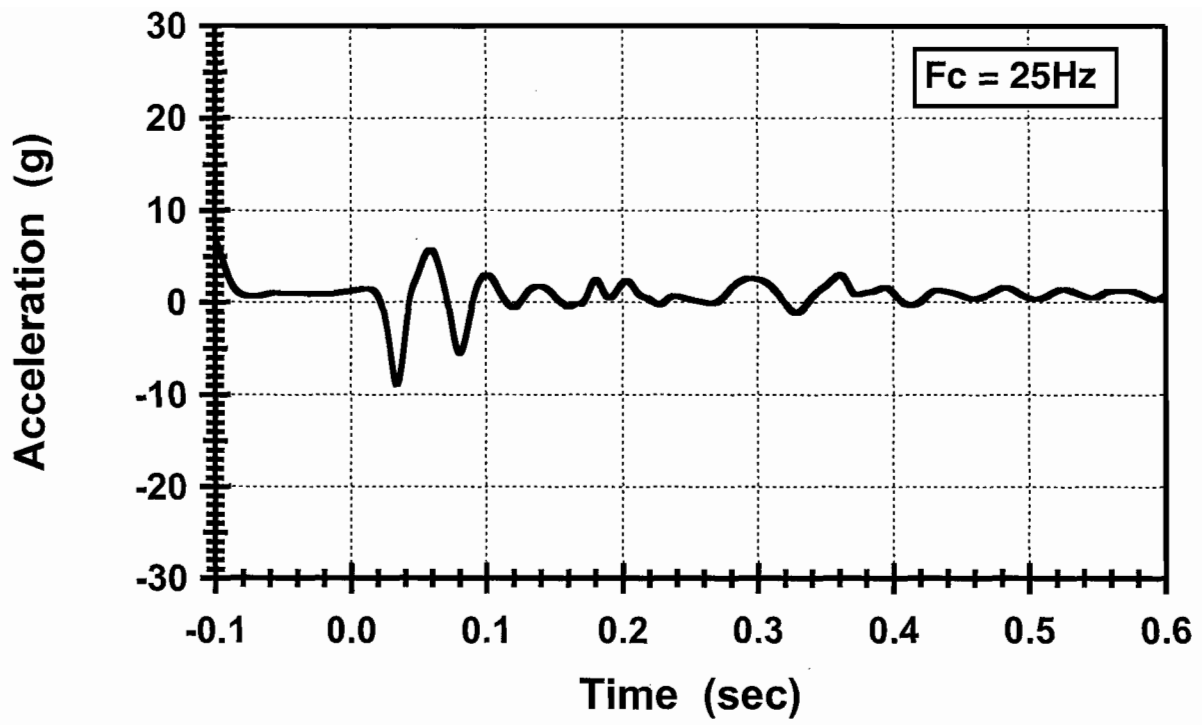


Figure E23. Accel., Lead Car, B End Bogie, Z-Axis

APPENDIX F
LOW PASS FILTERED ACCELERATIONS
FOR THE TRAILING CAR, $f_c = 25$ HZ

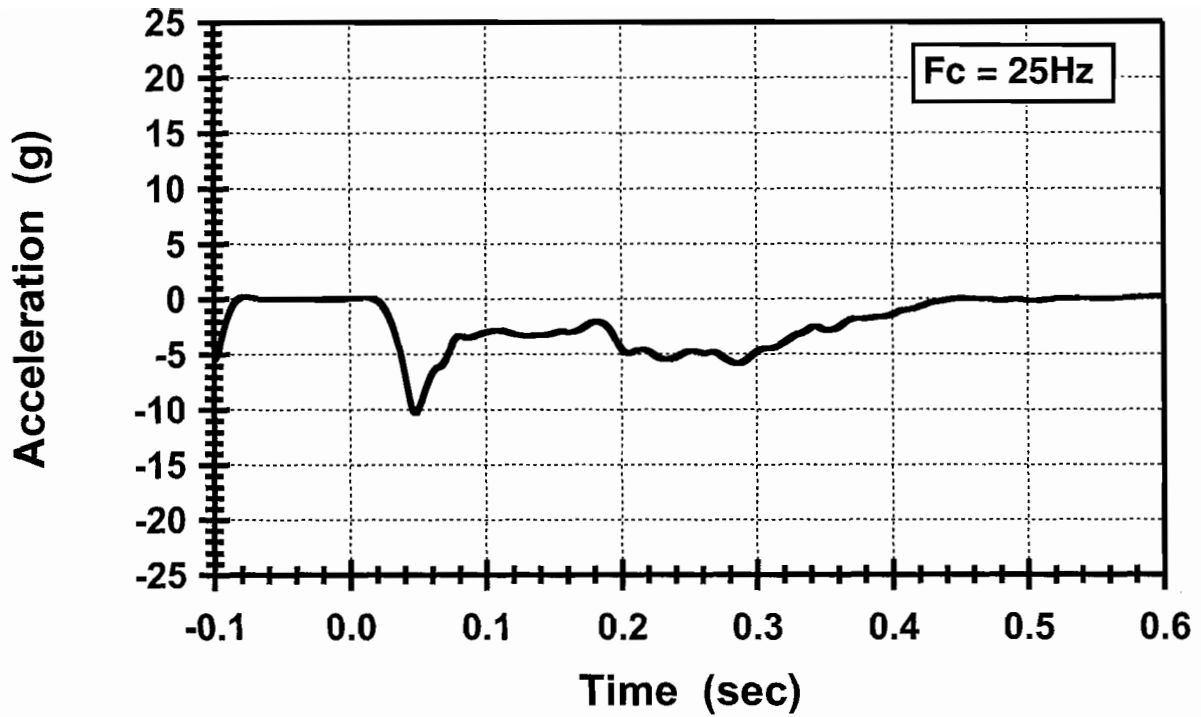


Figure F1. Accel., Trailing Car, CS, Position 1, X-Axis

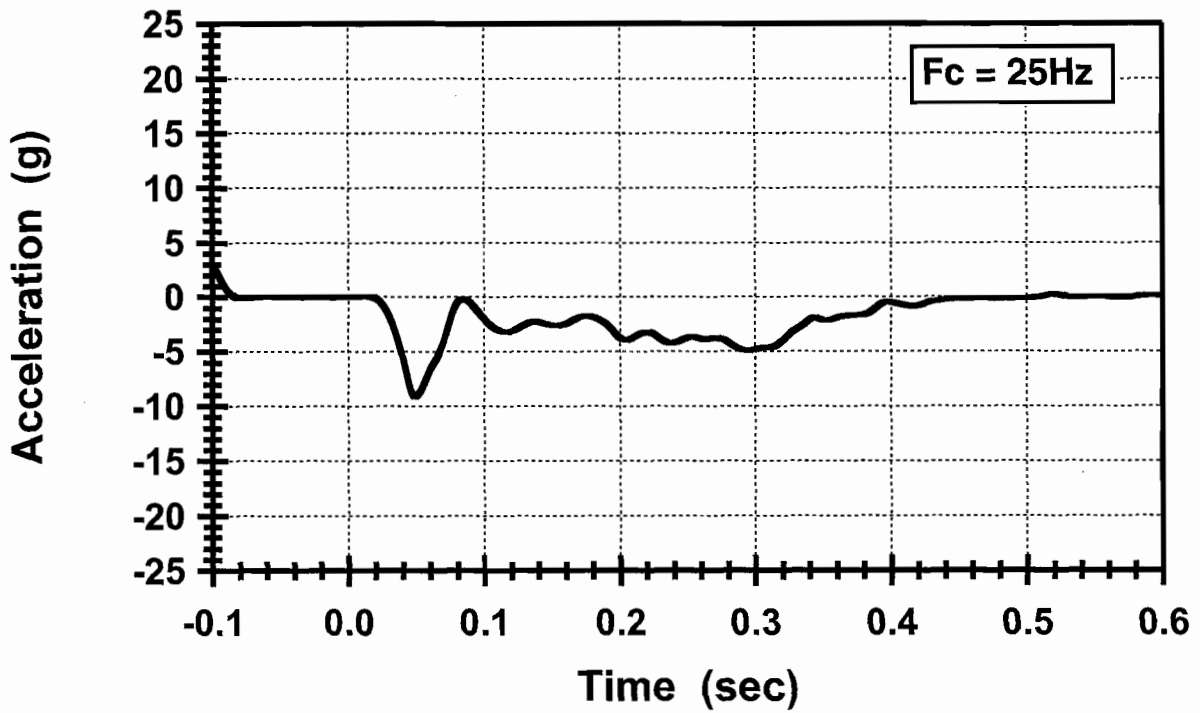


Figure F2. Accel., Trailing Car, CS, Position 2, X-Axis

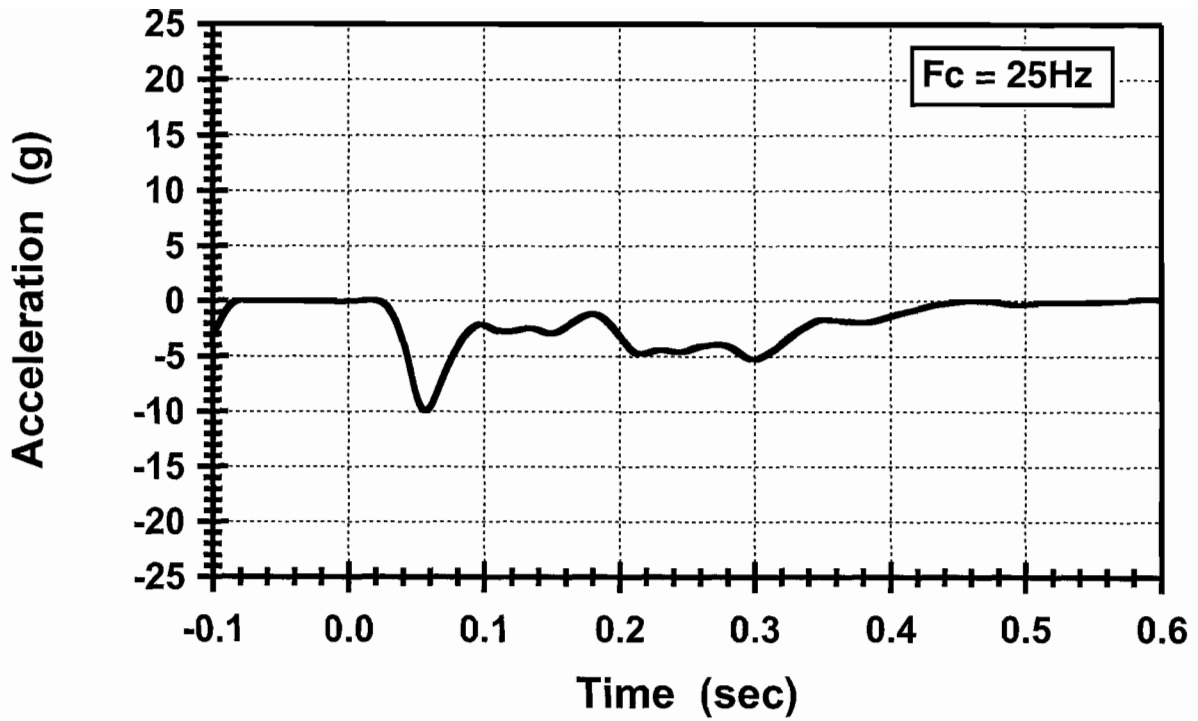


Figure F3. Accel., Trailing Car, CS, Position 3, X-Axis

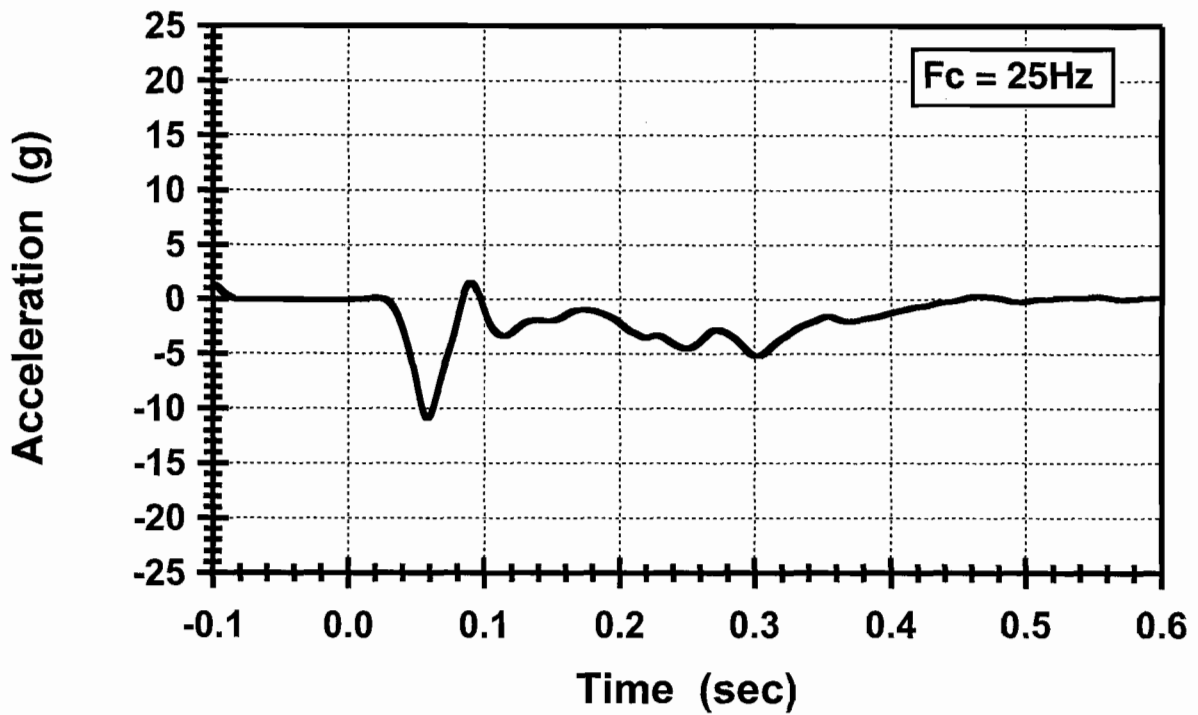


Figure F4. Accel., Trailing Car, CS, Position 4, X-Axis

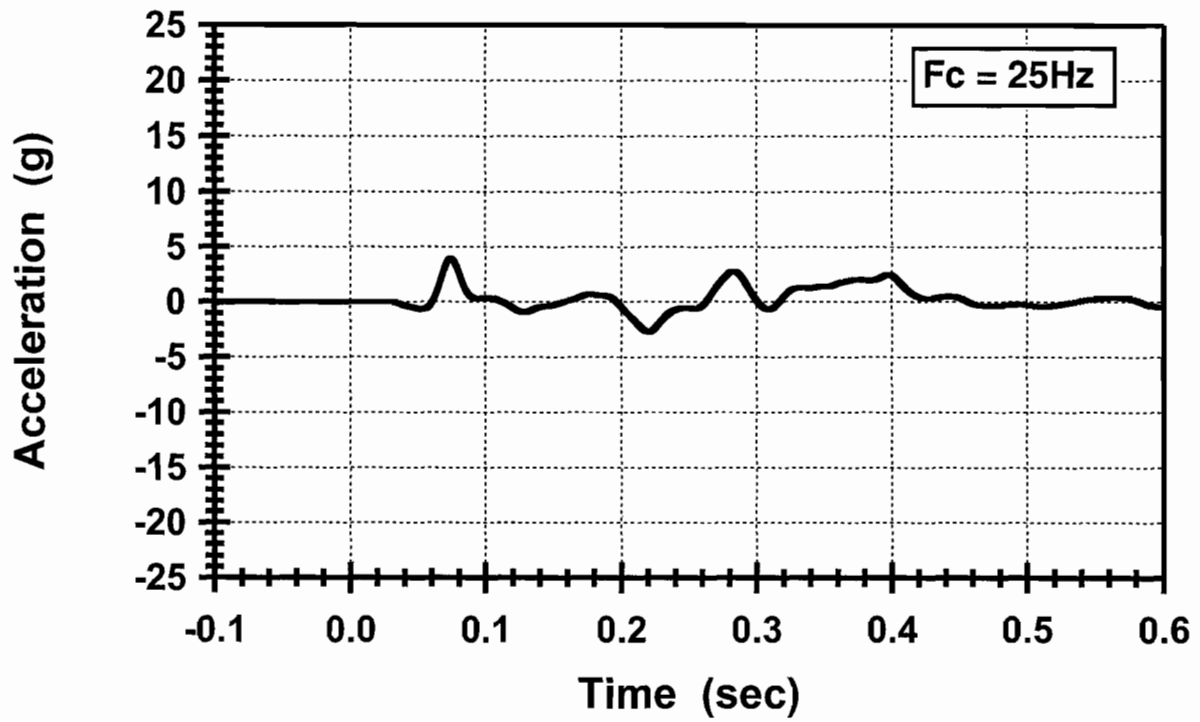


Figure F5. Accel., Trailing Car, CS, Position 2, Y-Axis

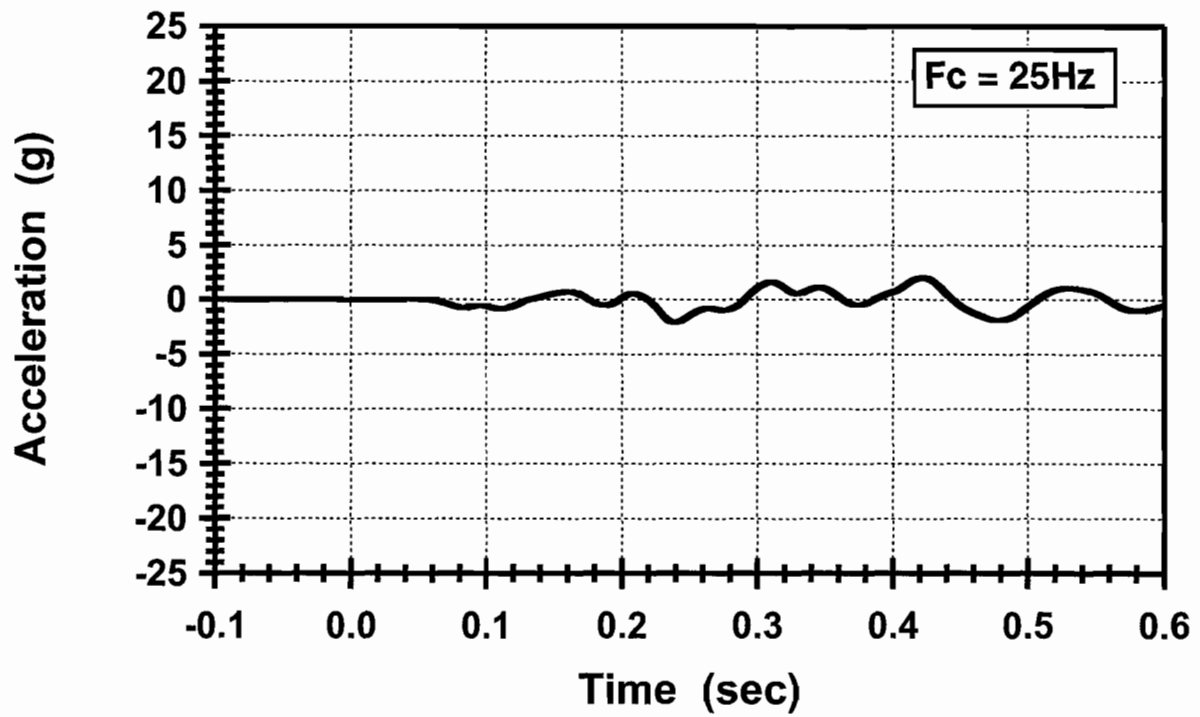


Figure F6. Accel., Trailing Car, CS, Position 3, Y-Axis

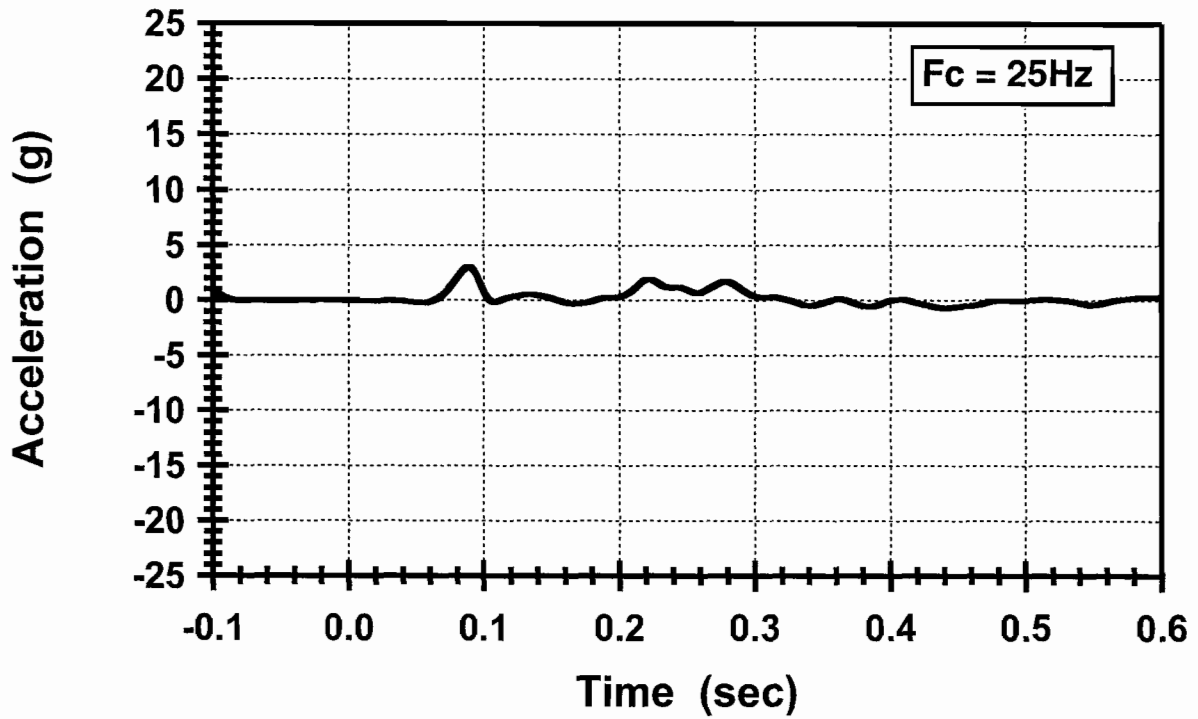


Figure F7. Accel., Trailing Car, CS, Position 4, Y-Axis

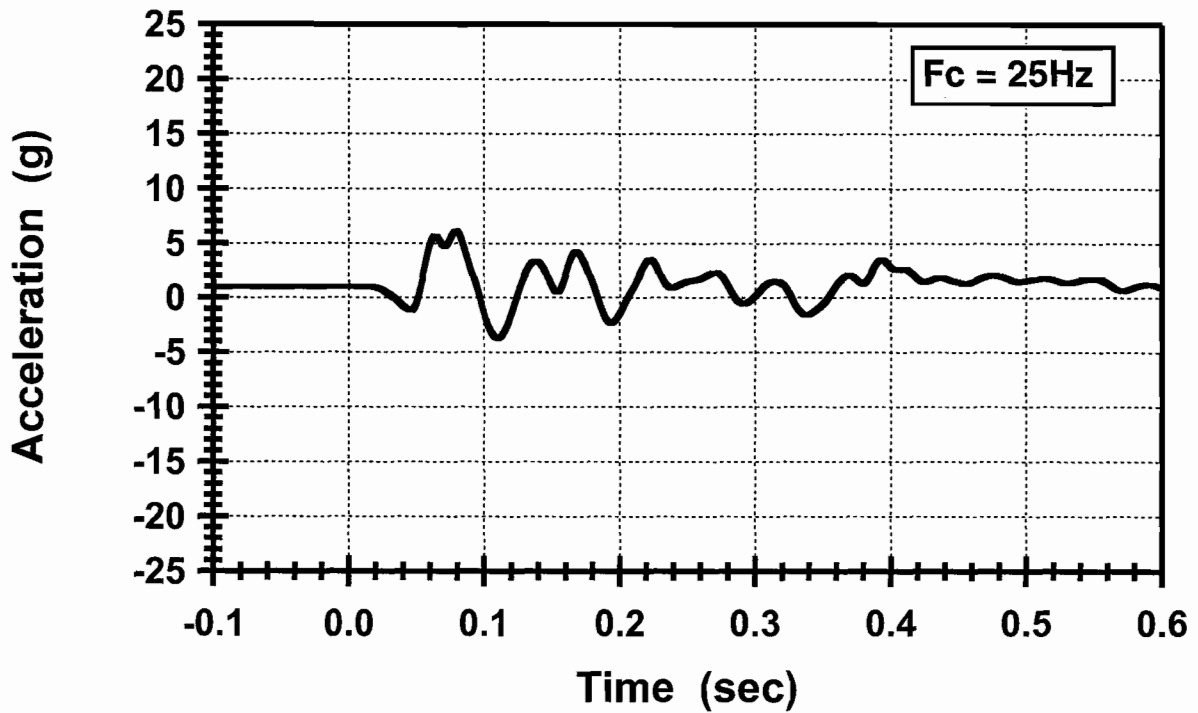


Figure F8. Accel., Trailing Car, CS, Position 2, Z-Axis

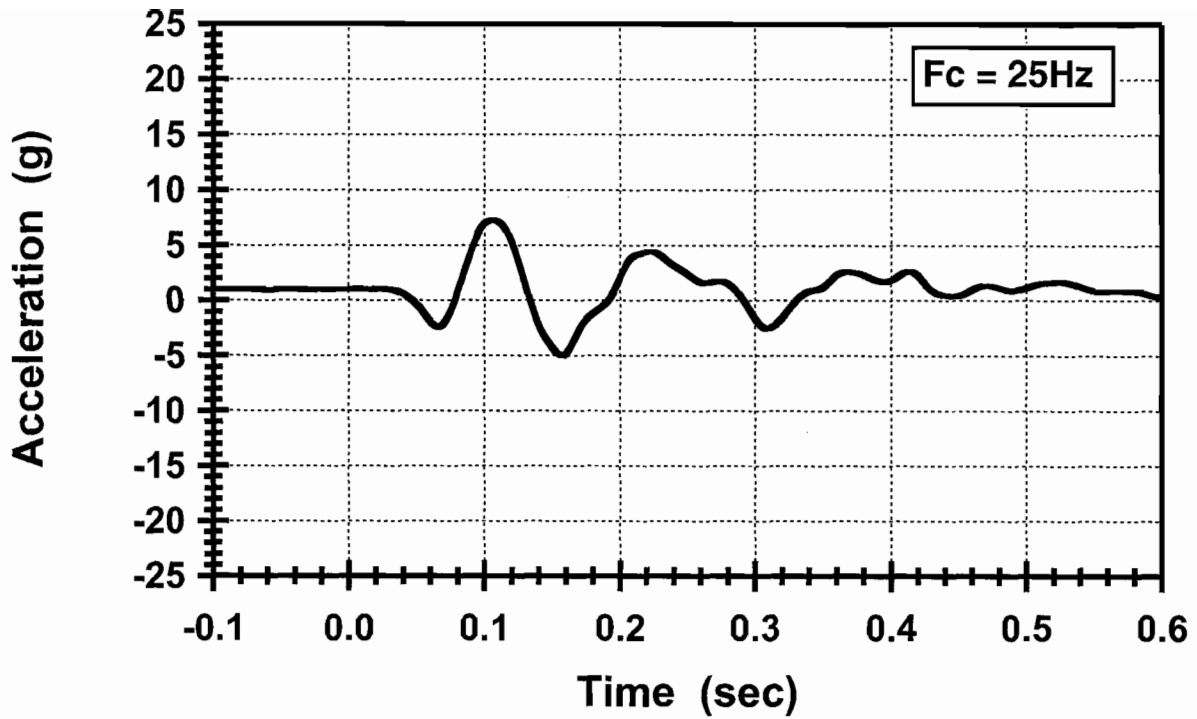


Figure F9. Accel., Trailing Car, CS, Position 3, Z-Axis

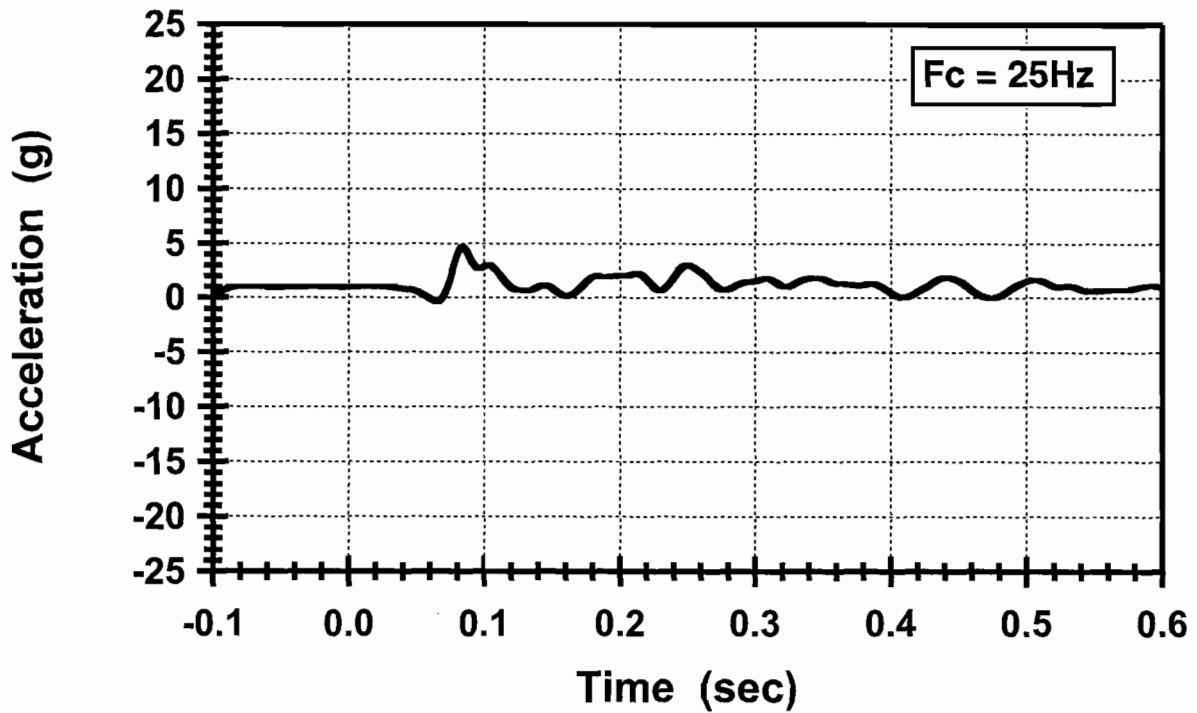


Figure F10. Accel., Trailing Car, CS, Position 4, Z-Axis

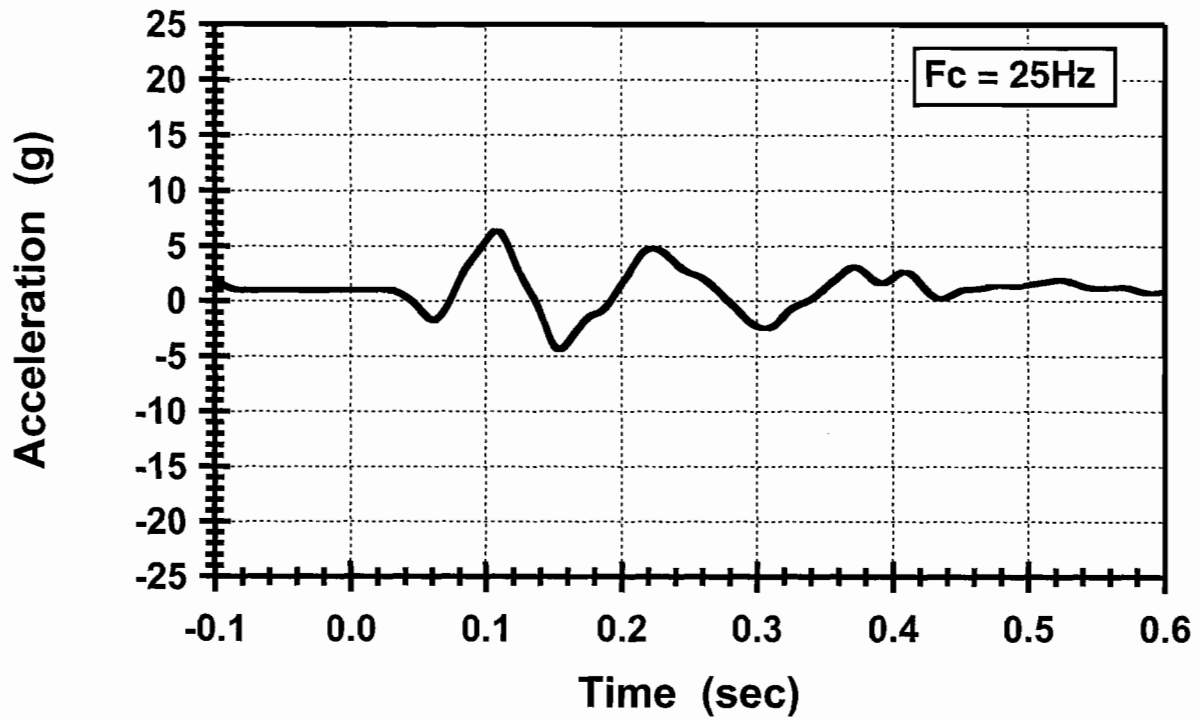


Figure F11. Accel., Trailing Car, RS, Position 3, Z-Axis

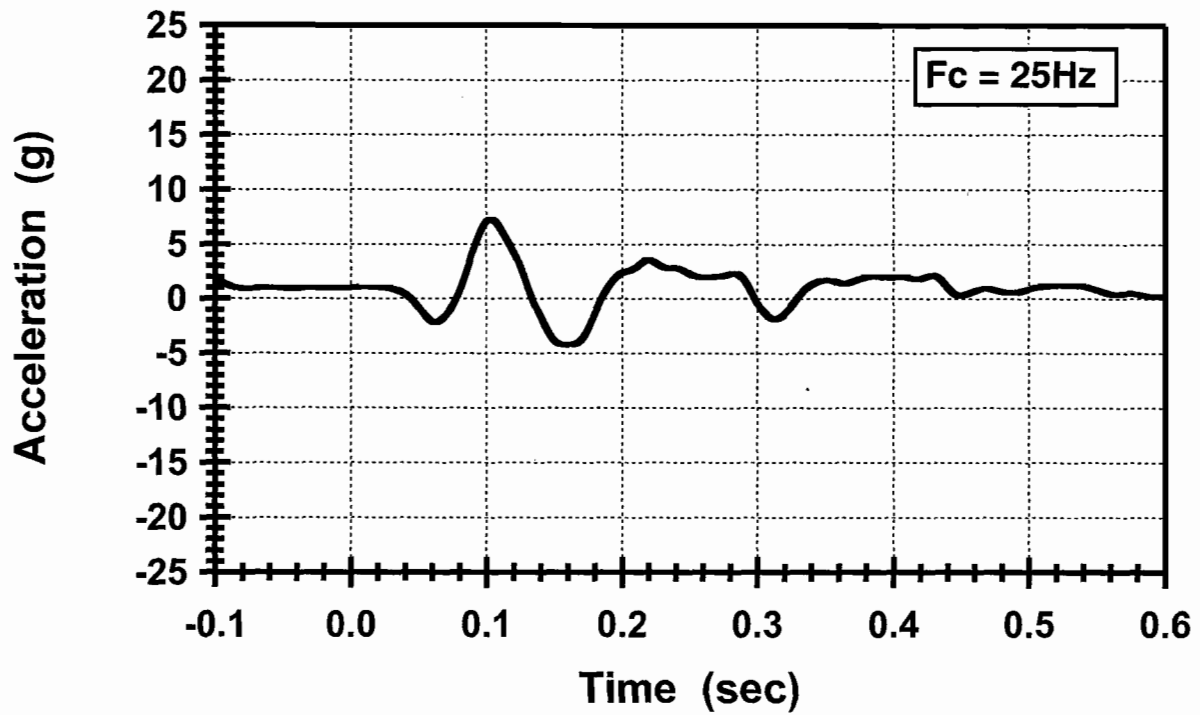


Figure F12. Accel., Trailing Car, LS, Position 3, Z-Axis

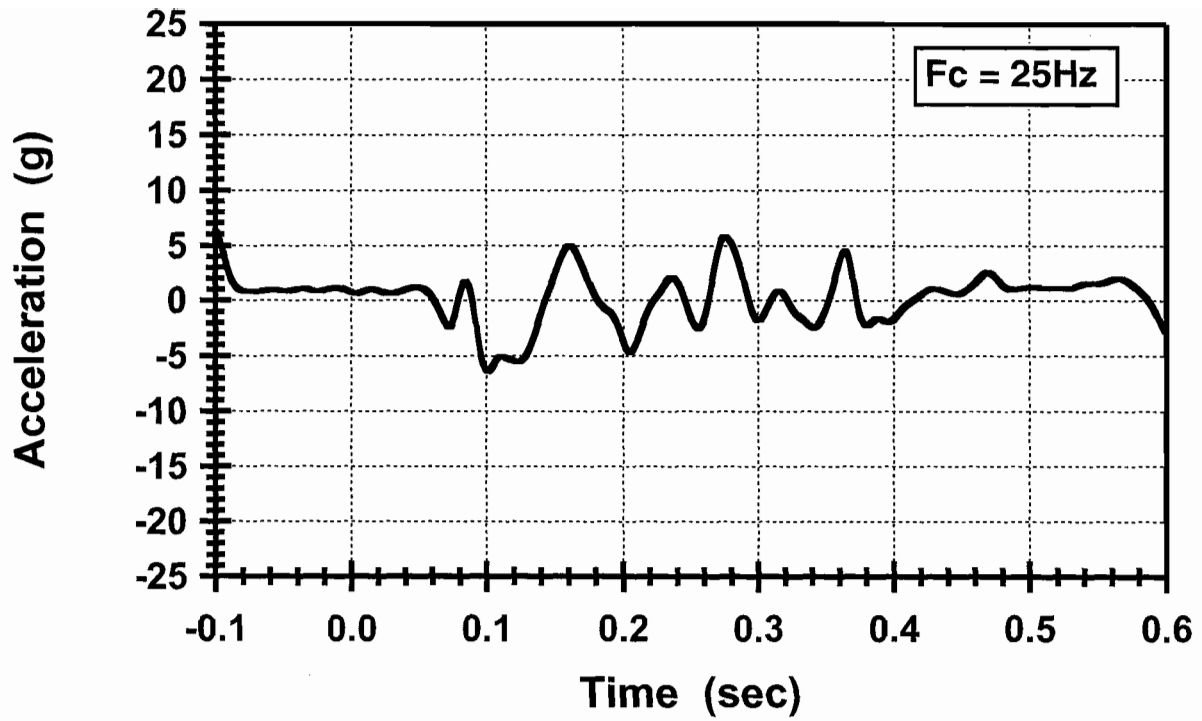


Figure F13. Accel., Trailing Car, A End Bogie, Z-Axis

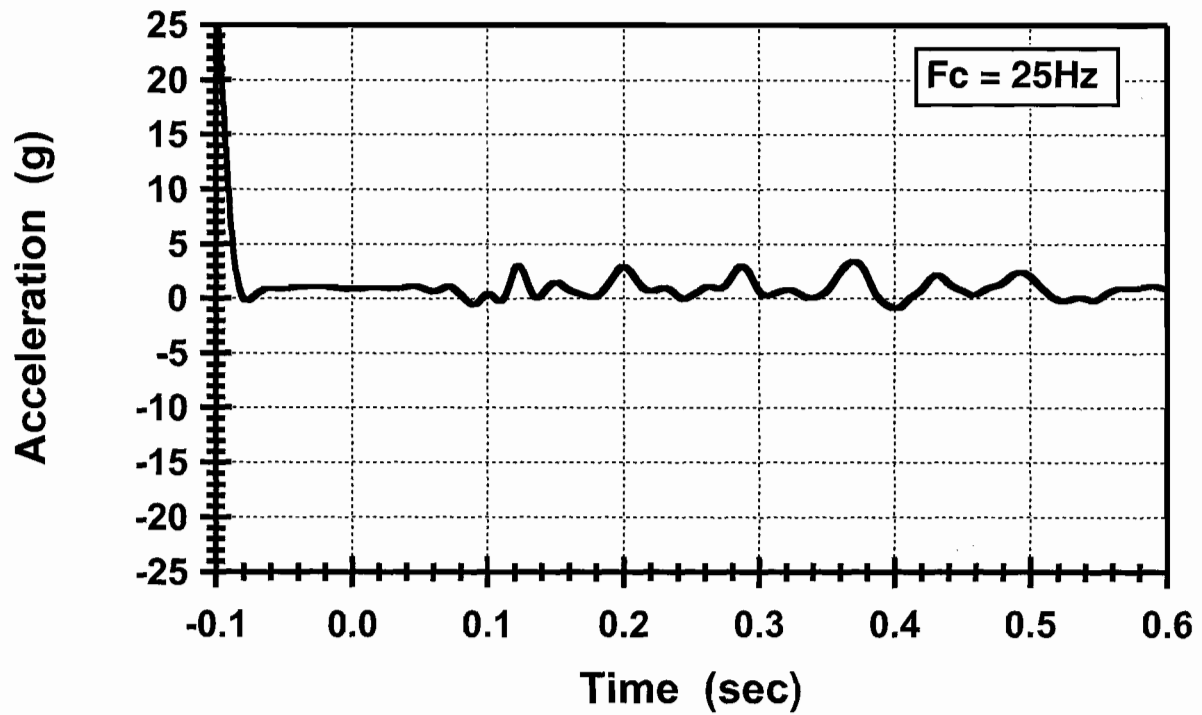
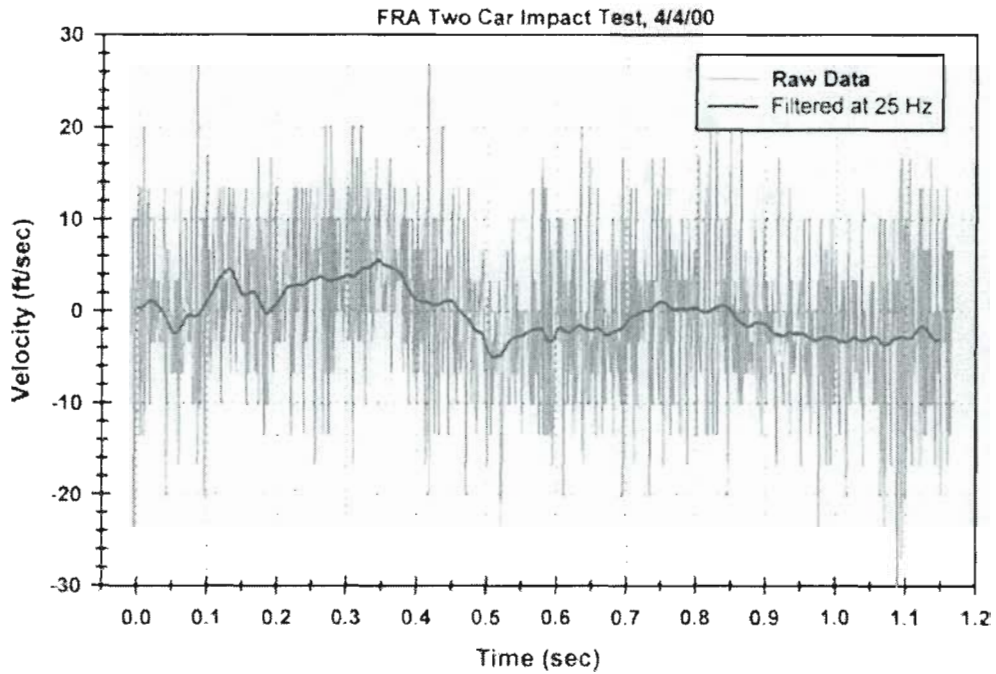
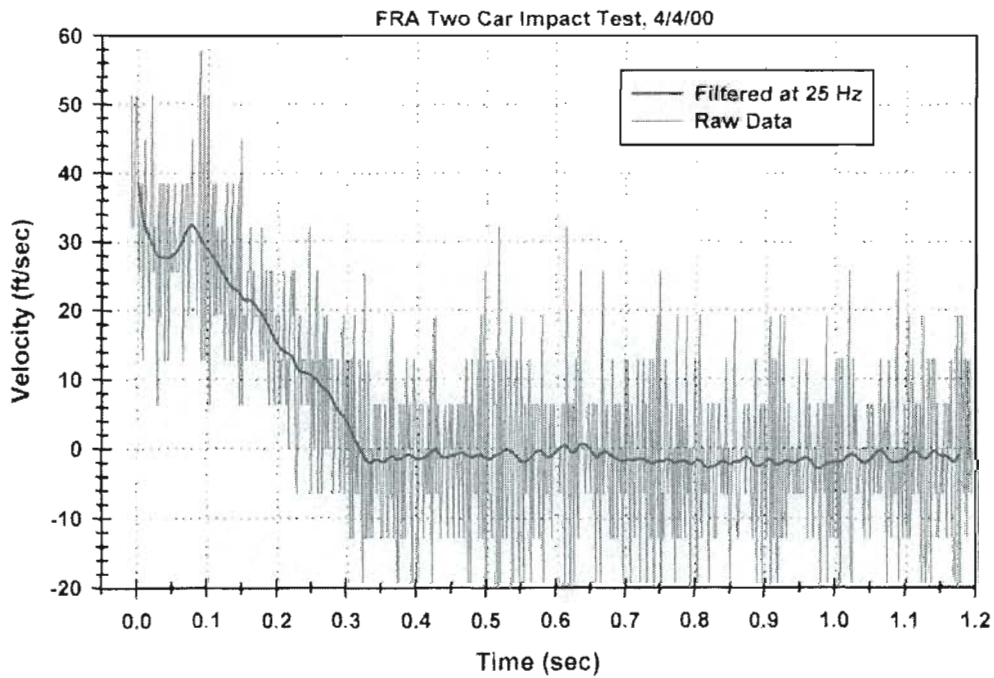


Figure F14. Accel., Trailing Car, B End Bogie, Z-Axis

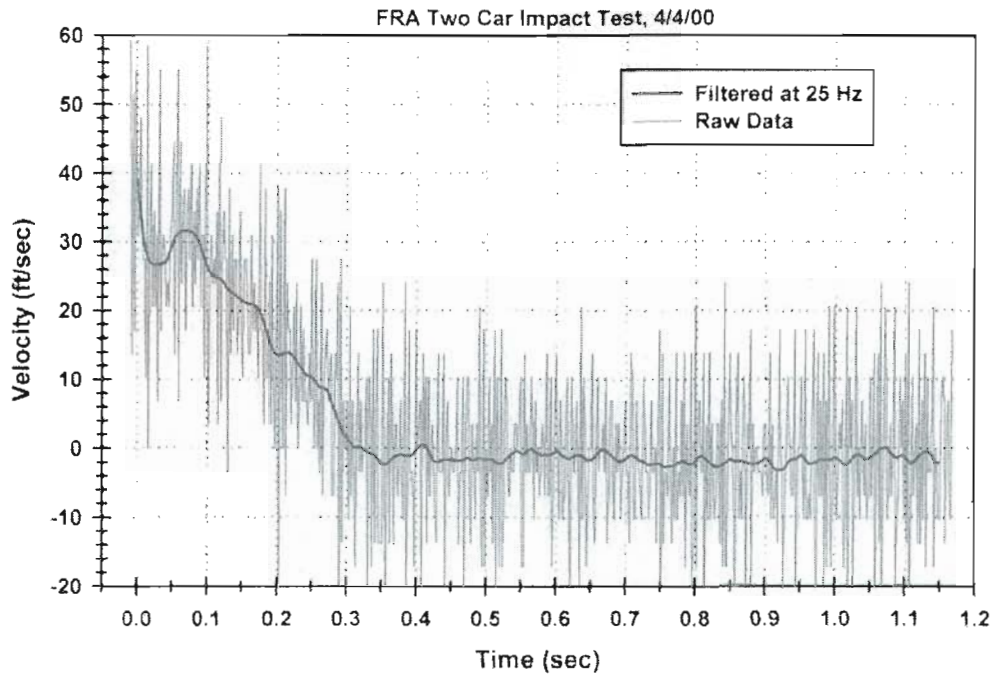
APPENDIX G
RAW VELOCITY DATA



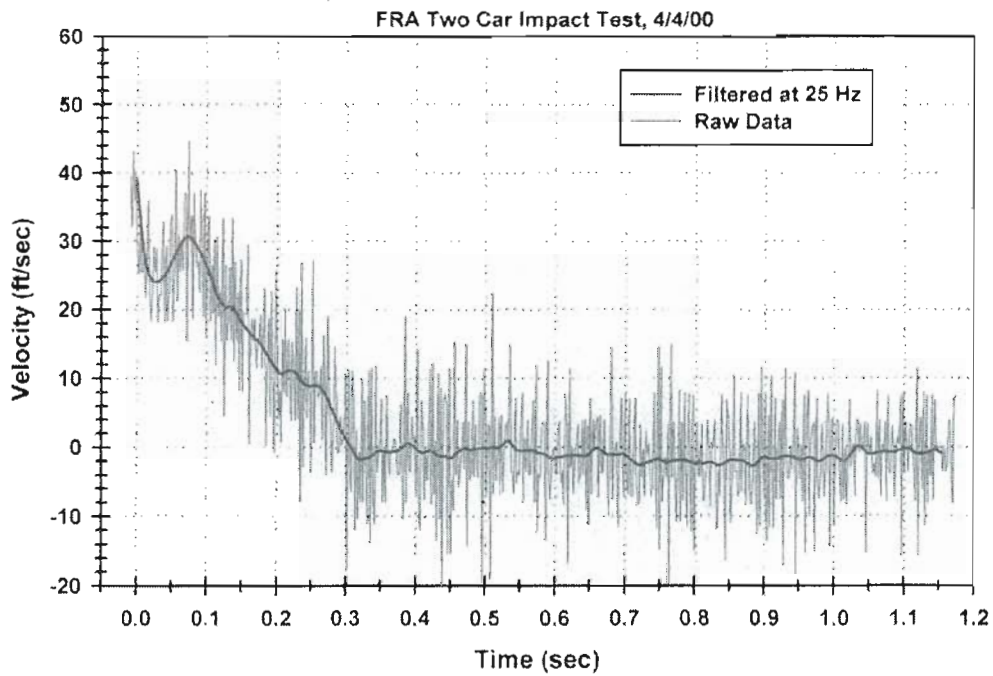
**Figure G1. Coupler View Side Camera
Vertical Velocity Trailing Car Relative to Leading Car**



**Figure G2. Barrier View Side Camera
Leading Car Impact End Longitudinal Velocity**

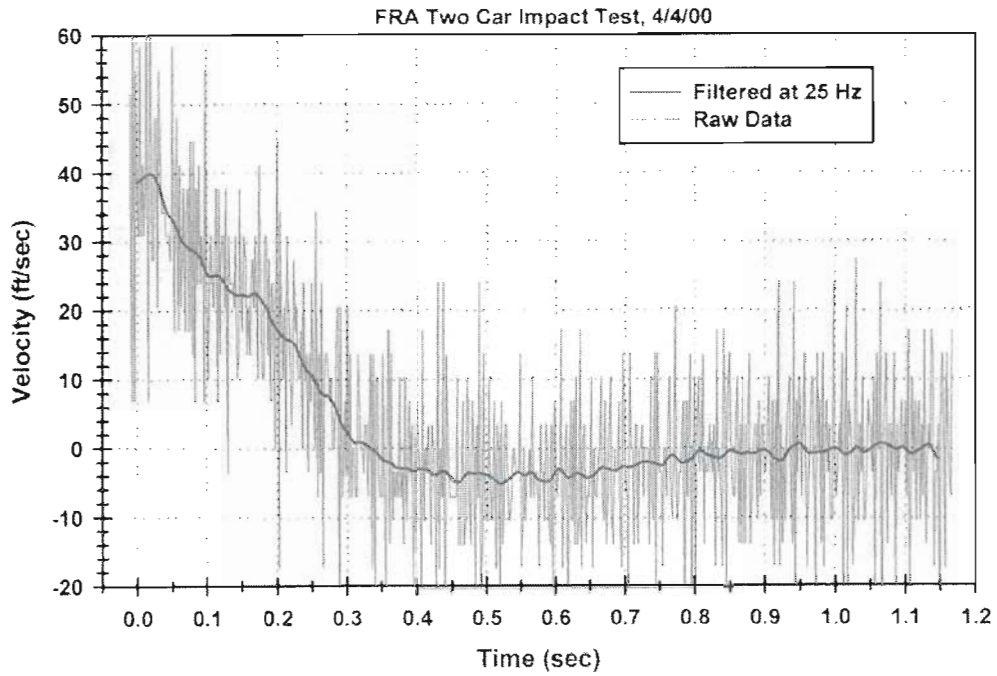


**Figure G3. Coupler View Side Camera
Leading Car Trailing End Longitudinal Velocity**

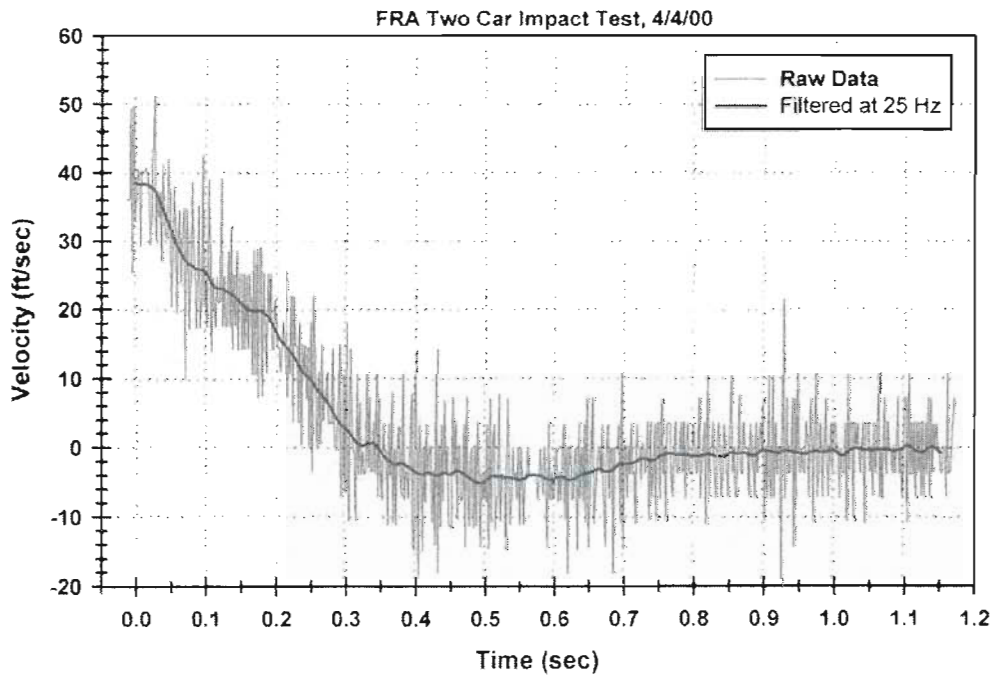


**Figure G4. Coupler View Overhead Camera
Leading Car Trailing End Longitudinal Velocity**

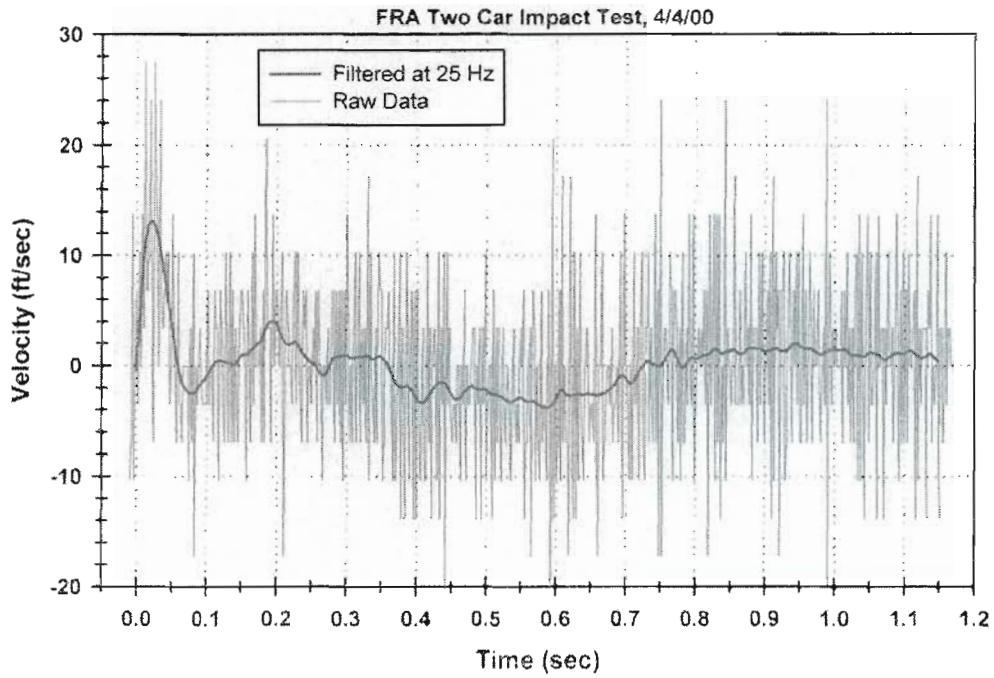
175



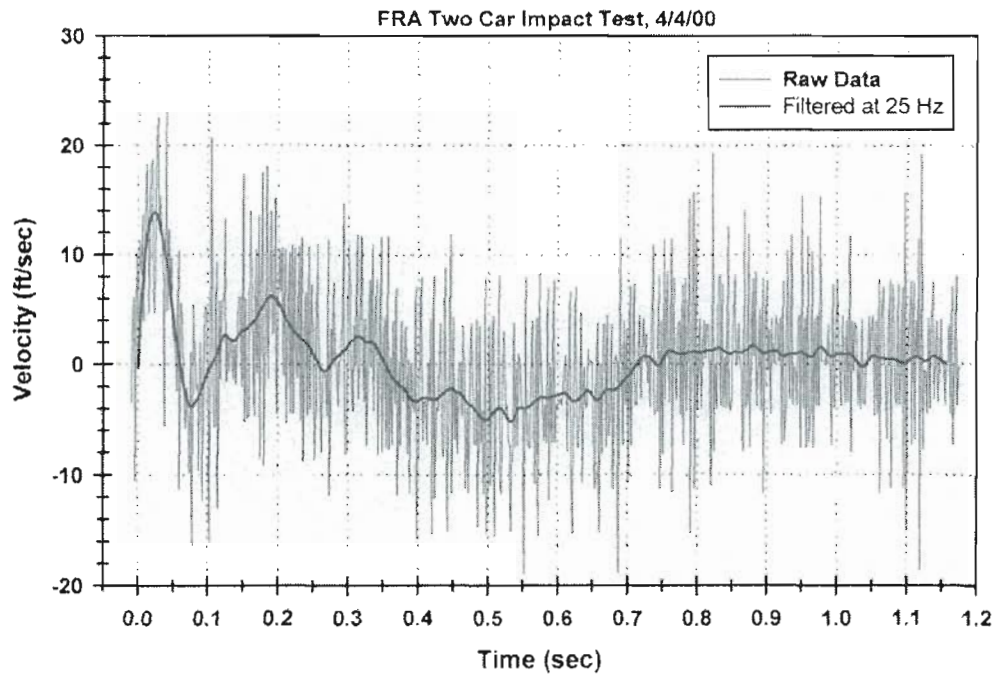
**Figure G5. Coupler View Side Camera
Trailing Car Leading End Longitudinal Velocity**



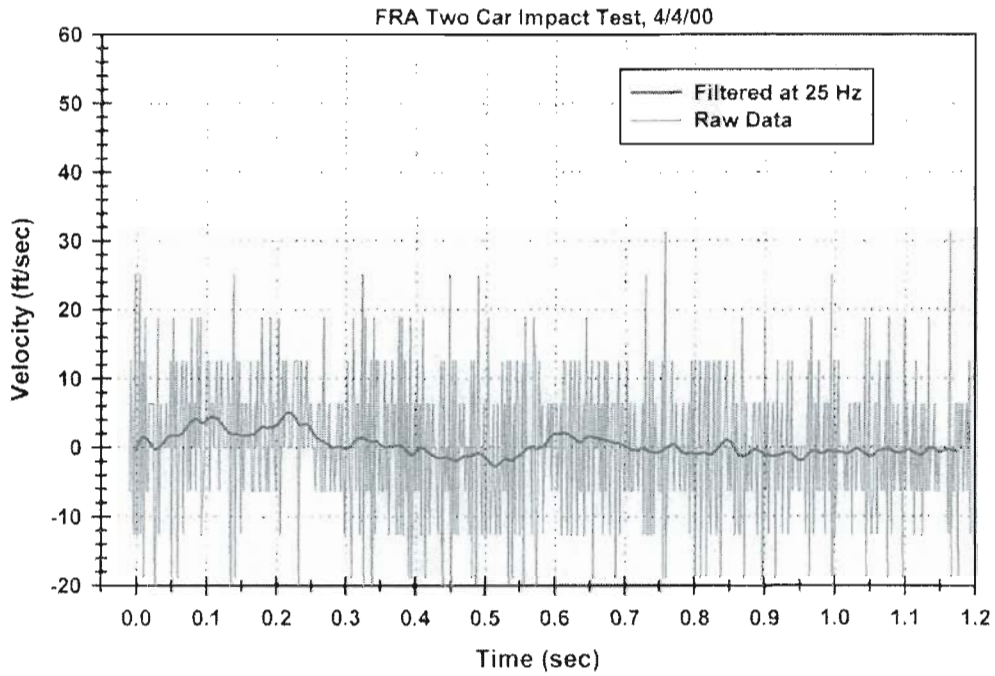
**Figure G6. Coupler View Overhead Camera
Trailing Car Leading End Longitudinal Velocity**



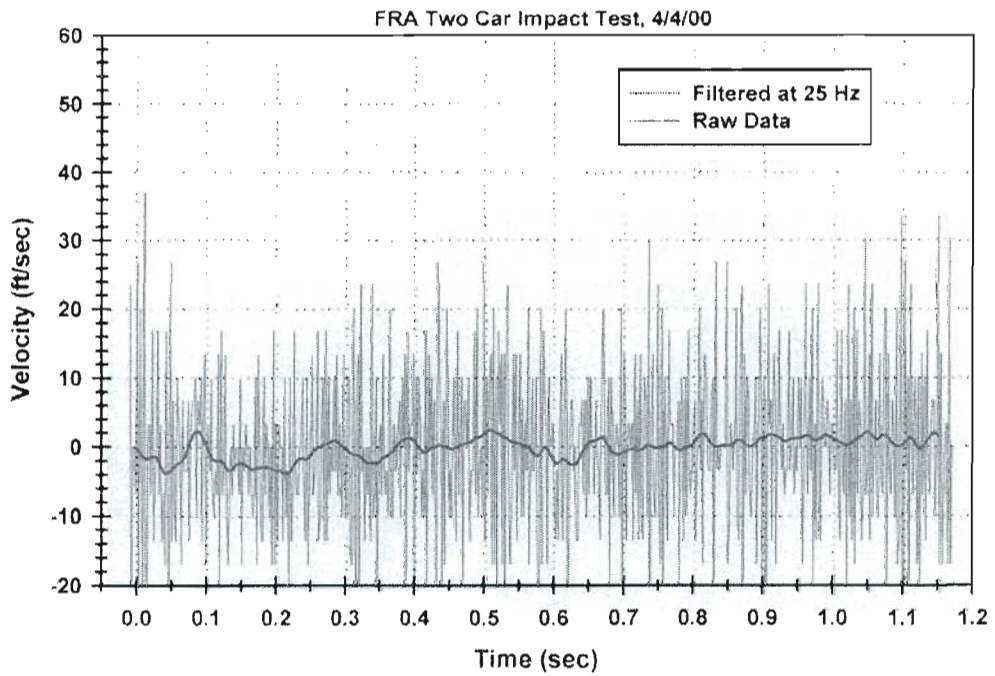
**Figure G7. Coupler View Side Camera
Longitudinal Velocity Trailing Car Relative to Leading Car**



**Figure G8. Coupler View Overhead Camera
Longitudinal Velocity Trailing Car Relative to Leading Car**

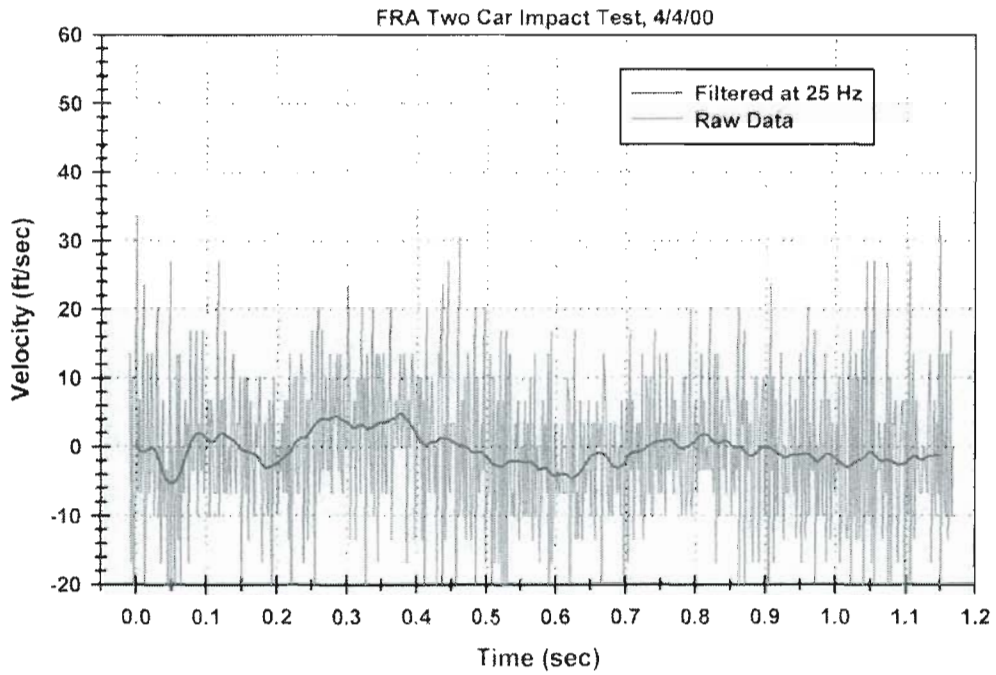


**Figure G9. Barrier View Side Camera
Leading Car Impact End Vertical Velocity**

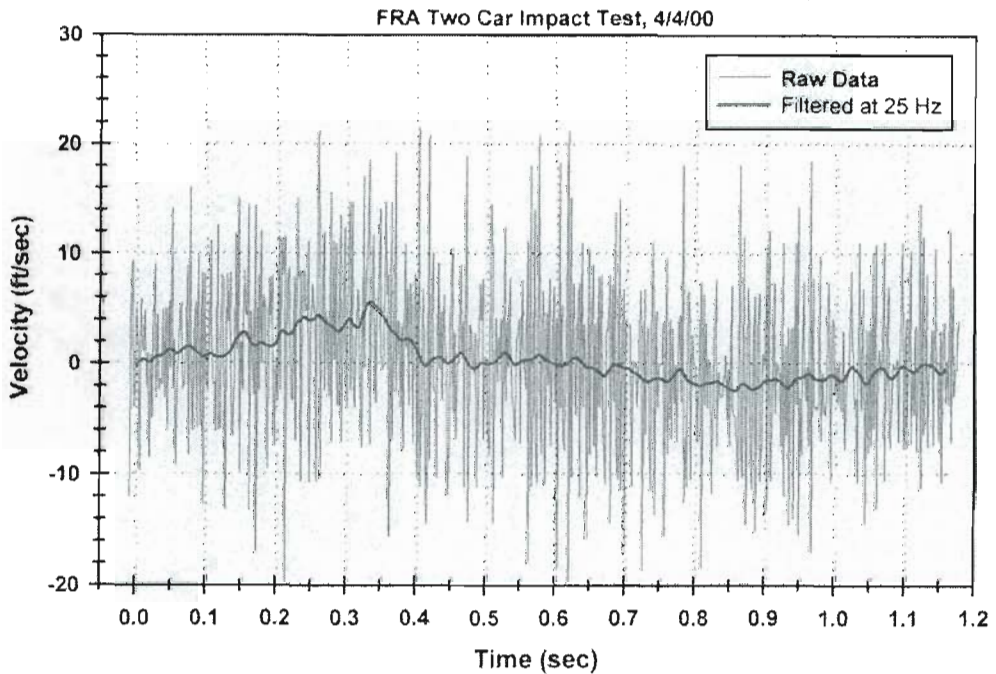


**Figure G10. Coupler View Side Camera
Leading Car Trailing End Vertical Velocity**

175



**Figure G11. Coupler View Side Camera
Trailing Car Leading End Vertical Velocity**



**Figure G12. Coupler View Overhead Camera
Leading Car Trailing End Lateral Velocity**

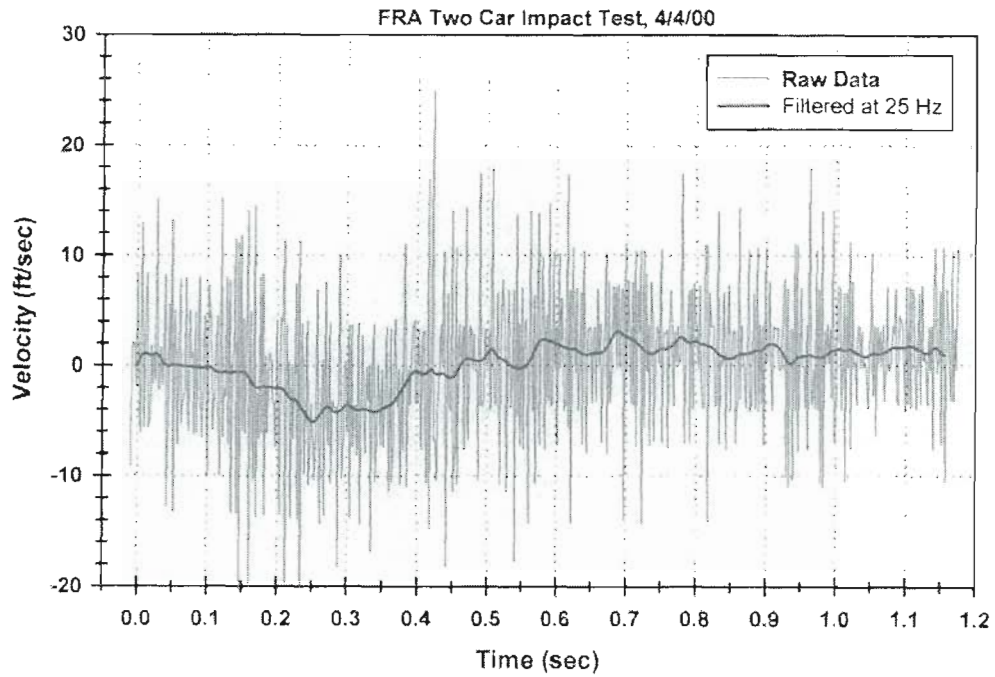


Figure G13. Coupler View Overhead Camera Trailing Car Leading End Lateral Velocity

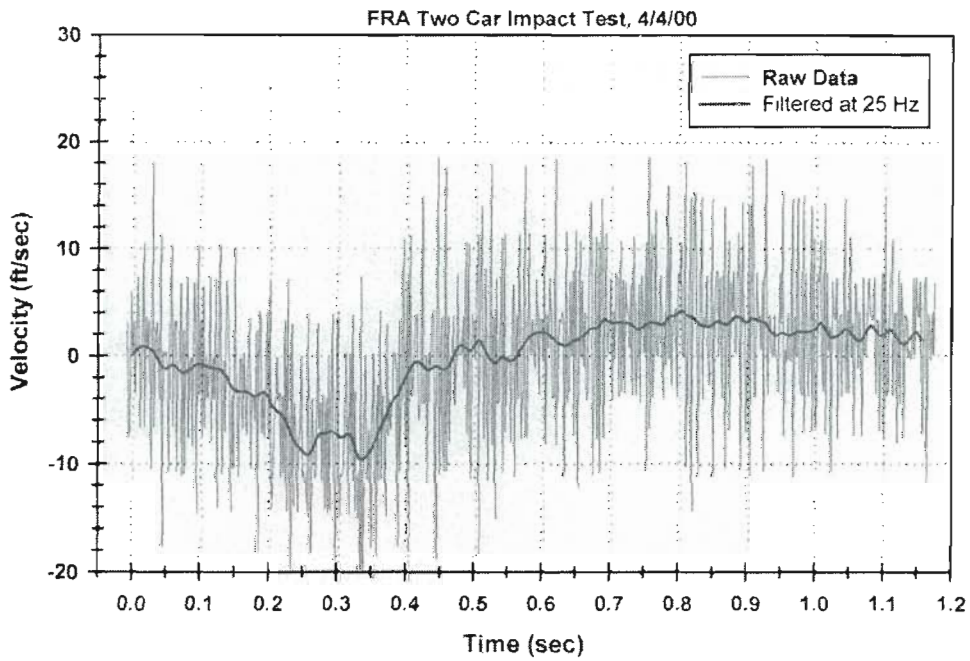


Figure G14. Coupler View Overhead Camera Lateral Velocity Trailing Car Relative to Leading Car

180 ALL