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16. Abstract The purpose of this project was to investigate the behavior of fiber reinforced polymer (FRP) reinforcement in a concrete bridge rail when subjected to a vehicle collision. FRP reinforcement for a Texas Department of Transportation (TXDOT) T202 (MOD) bridge rail (now TXDOT T203 bridge rail) was designed, and the rail was subjected to two full-scale crash tests. Two design conditions were incorporated into the test article. One was based on strength immediately after construction, and the other was based on reduced strength after deterioration due to long-term exposure to the environment. In the first test, which was performed on the stronger section, structural performance of the rail was good, but the vehicle rolled and safety performance was unacceptable. For the second test, which was performed on the weaker section, the height of the rail was increased to 30 inches. Both structural and safety performance of the rail was good.					
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**PERFORMANCE OF THE
TxDOT T202 (MOD) BRIDGE RAIL
REINFORCED WITH FIBER REINFORCED POLYMER BARS**

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DISCLAIMER

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INTRODUCTION

Corrosion of reinforcing steel in structural concrete has been and continues to be a problem in many reinforced concrete structures such as highway bridges. Ways of addressing the problem have been pursued with varying degrees of success. Recently, non-metallic reinforcing bars have been offered and are being studied as a solution for eliminating corrosion. Researchers are studying various types of fibers in various types of resins. Some are rather expensive, and all have mechanical/chemical properties that are new to the reinforced concrete industry.

Fiber reinforced polymer bars have been proposed for use as reinforcing bars in structural concrete, and some are being manufactured on a limited basis. Common types of fiber reinforced polymer bars for concrete are:

- Glass Fiber Reinforced Polymer (GFRP) – Tensile Strength 70-150 ksi, Elastic Modulus 5.1-6.5 E6 psi
- Carbon Fiber Reinforced Polymer (CFRP) – Tensile Strength 87-420 ksi, Elastic Modulus 17.4-43.5 E6 psi
- Aramid Fiber Reinforced Polymer (AFRP) – Tensile Strength 145-203 ksi, Elastic Modulus 8.7-12.6 E6 psi.

The American Concrete Institute (ACI) Committee 440 published report ACI 440.1R-01, “Guide for the Design and Construction of Concrete Reinforced with FRP Bars” in May 2001 (*1*). The guide provides extensive information on properties of the various types of FRP bars, recommended design philosophy, and detailed design equations.

Significant properties of fiber reinforced polymer (FRP) bars, such as tensile strength, creep rupture, and fatigue endurance, are reduced by long-term exposure to the environment. The guide gives environmental reduction factors for various fibers and exposure conditions. The reduction factors, in the form of constant coefficients (C_E), are multiplied by the initial strength to obtain the expected strength after long-term exposure. Values of reduction factors are based on short-term exposure and accelerated environmental testing, and have been extrapolated to account for long-term exposure. ACI 440 guide states “Conservatism is advised in applying these results in design until additional long-term durability data are available.”

Specimens taken from the structures tested in the study reported herein and from the earlier study have been set aside in the ambient environment for future study of the remaining strength/moduli of the GFRP bars (*2*).

Another significant property of FRP bars is the brittle behavior exhibited when loaded to rupture. This behavior has been cause for concern on the part of those investigating the use of FRP bars in reinforced concrete. Concrete is a brittle material, and ductile reinforced concrete structures are obtained by proportioning members such that the ductile steel portion of a member reaches its load limit before the concrete in the

member reaches its load limit. This approach will not provide a ductile member/structure when FRP bars are used.

The approach being adopted is to over-reinforce members so that the concrete portion reaches its load limit before the FRP bars do because the concrete portion is the more ductile of the two materials. This approach will provide members with more ductility than those designed to fail by rupture of the GFRP reinforcement. However, concrete members reinforced with GFRP will be less ductile than those constructed with conventional steel reinforcement.

The T202 bridge rail was a TxDOT standard December 2001. A cross section showing the basic geometry of the T202 design is shown in [Figure 1](#). Full-scale vehicle crash tests showed that snagging of the vehicle wheel occurred on posts in that design (3). The cross section was then modified to provide more post setback as shown in [Figure 2](#). For a period of time, the modified design was referred to as the T202 (MOD). That design became a TxDOT standard and is designated the T203.

The cross sectional geometry of the T202 (MOD) (the T203), shown in [Figure 2](#), is the geometry of the rail addressed in the study reported herein.

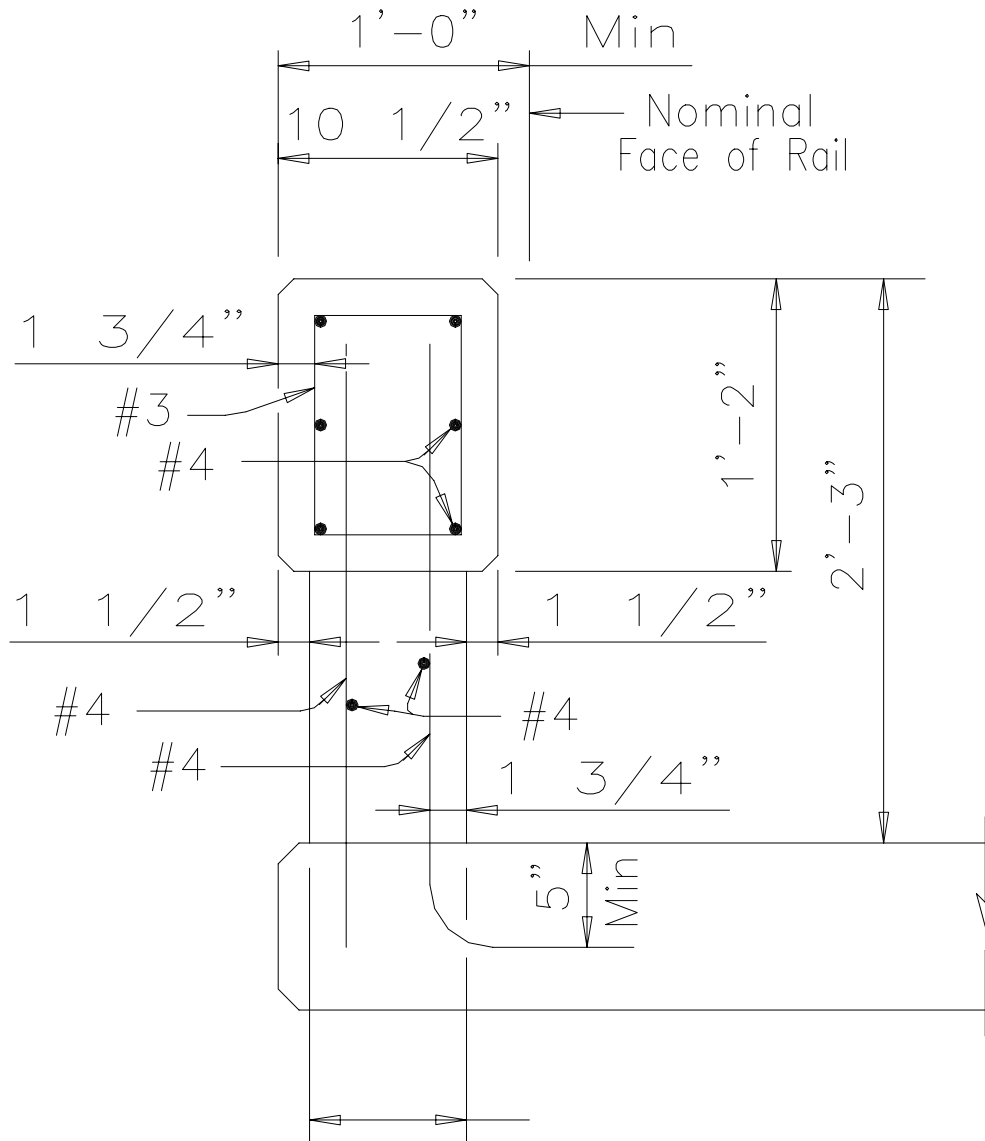


Figure 1. T202 Bridge Rail Cross Section.

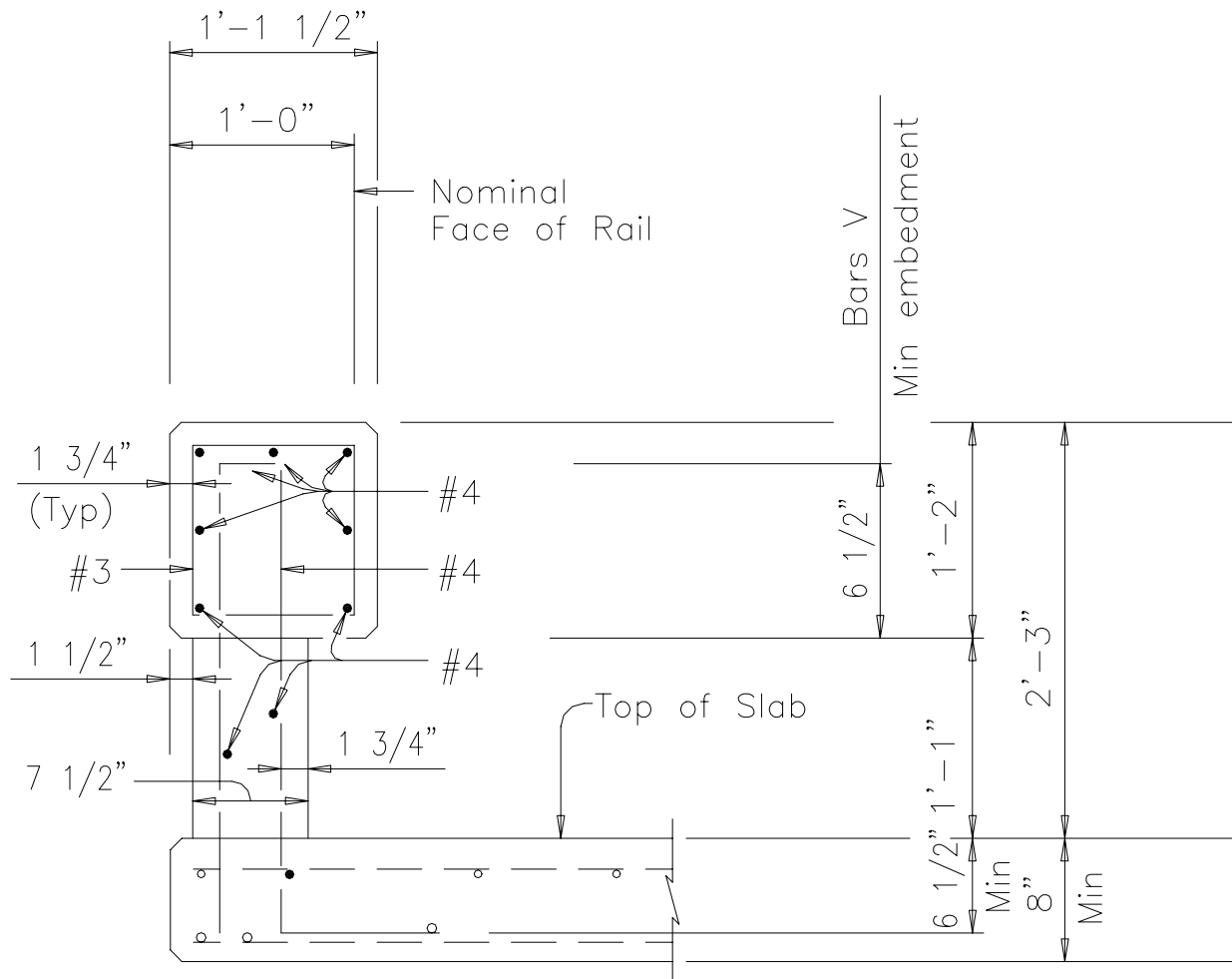


Figure 2. T202 (MOD) (Now T203) Bridge Rail Cross Section.

EXPERIMENTAL PROGRAM

Researchers selected the Aslan 100 Vinyl Resin with E-Glass Fiber Reinforced Polymer Bars as manufactured by Hughes Brothers Inc., Seward, Nebraska, for use in the TxDOT T202 (MOD) bridge rail to be subjected to full-scale vehicle crash tests. Researchers developed a detailed design of a prototype test installation. Physical properties of the FRP bars from a specific manufacturer were used in the design calculations.

At construction time, bars from that manufacturer were no longer available. Another supplier was selected, and the prototype railing was redesigned using physical properties of bars from that manufacturer.

A T202 (MOD) bridge rail was selected for investigation. The cross sectional dimensions were held, and glass fiber reinforced polymer reinforcement was designed to replace the steel reinforcement. Although it does not corrode like steel, GFRP reinforcement deteriorates with age. It loses strength, and the modulus of elasticity decreases. To account for this behavior, ACI 440 prescribes the use of an environment coefficient in design equations. A value of $C_E = 1.0$ would indicate no expected deterioration, and a value of $C_E = 0.7$ would account for the expected deterioration of GFRP during its life. In other words, a design made using a value of $C_E = 0.7$ would initially be stronger than required but would have adequate strength after losses due to deterioration. Portions of the test railing were designed for each of the two values of C_E .

The first crash test was performed on the portion of railing designed using $C_E = 0.7$. The railing demonstrated adequate structural capacity by containing and redirecting the vehicle with no structural distress. However, the vehicle rolled onto its side and did not pass the performance requirements of *National Cooperative Highway Research Program (NCHRP) Report 350 (4)*. [Appendix A](#) includes a detailed report of that test. Results of that test presented a dilemma because a railing with the same geometry performed acceptably in an earlier test. After much deliberation, TxDOT and Texas Transportation Institute (TTI) engineers decided to test the weaker ($C_E = 1.0$) portion of the railing with a structural steel tube added to the top to increase total height to 30 inches. Roll stability of the vehicle was much improved. In that test, the bridge rail demonstrated adequate structural capacity and met the requirements of *NCHRP Report 350*. [Appendix B](#) includes a detailed report of the second test.

SUMMARY AND CONCLUSIONS

A T202 (MOD) bridge rail constructed with GFRP reinforcement was designed and subjected to full-scale vehicle crash testing. In accordance with *NCHRP Report 350* test 3-11 for test level three, two full-scale tests were performed. Structural adequacy of the rail was demonstrated in both tests. There was no structural distress and no shortcomings attributable to the GFRP reinforcement.

In the first test, the vehicle rolled, and the safety performance was not acceptable. For the second test, the height of rail was increased by 3 inches to 30 inches. Rollover did not occur, and safety performance of the rail was acceptable.

Results of this testing indicate that bridge rails and deck overhangs constructed with GFRP reinforcing performed acceptably during impact loads from collisions by vehicles. Other appropriately designed bridge rails using GFRP reinforcement would be expected to perform acceptably.

Collision loads imposed on the bridge rail were readily resisted by the bridge rail. Structural distress did not occur in the bridge rail. Consequently, structural failure modes for the bridge rail with GFRP reinforcement were not identified in the full-scale crash tests.

In an earlier study of GFRP reinforcement, impact tests with a pendulum were performed on short lengths of TxDOT T2 bridge rail mounted on deck overhang (*B*). In those tests, two types of specimens were tested. Some had conventional steel reinforcement and others had GFRP for the top layer of reinforcement in the deck. Strength of the hybrid deck specimens (GFRP reinforcement in the top layer of the deck) was similar to strength of specimens using conventional steel reinforcement.

APPENDIX A: NCHRP REPORT 350 Test 3-11 OF THE TXDOT T202 (MOD) BRIDGE RAIL WITH GFRP REINFORCEMENT

CHAPTER 1. INTRODUCTION

PROBLEM

In some areas of the state, corrosion of reinforcing steel in concrete bridge structures, especially in deck slabs, continues to be a serious problem for the Texas Department of Transportation (TxDOT). One remedial measure for this problem might be the use of glass fiber reinforced polymer (GFRP) reinforcing bars. Physical properties of these reinforcing bars differ significantly from those of conventional reinforcing steel, and the behavior of concrete reinforced with GFRP is not completely defined and understood. GFRP reinforcement is typically much more brittle than conventional reinforcing steel, and its behavior under dynamic load from a vehicle collision is not known. This project addresses the behavior of a bridge slab/rail structure reinforced with glass fiber reinforced polymer when subjected to full-scale vehicle crash tests.

BACKGROUND

Use of GFRP reinforcement in decks, rails, and perhaps other elements of bridge structures has high potential for reducing the problem of deterioration of bridge structures as a result of corrosion of reinforcement. Glass fiber reinforced polymer reinforcement cannot be used as a direct replacement for steel because GFRP has significantly different mechanical properties. One major fundamental difference is that GFRP is a relatively brittle material while steel is ductile. Ductility of steel is the fundamental property that allows one to design reinforced concrete structures that behave in a ductile manner, although the (plain) concrete is brittle. This ductility is accomplished by providing ratios of steel reinforcement that cause the steel to yield before the concrete ruptures in a brittle manner. With the use of GFRP, the greatest amount of structural ductility is achieved by proportioning the materials such that the concrete ruptures first because it is the more ductile of the two materials. Thus, the expected result is a bridge structure that is somewhat more brittle than a structure with conventional steel reinforcement and, therefore, its behavior under dynamic loads needs to be evaluated. Sufficient ductility and/or reserve strength for adequate performance in service must exist.

OBJECTIVES/SCOPE OF RESEARCH

TxDOT Project 9-1520, "FRP Reinforcing Bars in Bridge Decks," was initiated in August 1999. This was a joint project involving the Texas Transportation Institute, the University of Texas at Arlington, and Texas Tech University. In that project, GFRP reinforcement was used on a trial basis in the top of a bridge deck in selected spans in a structure

in Potter County. Behavior of the GFRP was monitored during construction, and monitoring will continue while the bridge is in service. Also, extensive laboratory studies of the fundamental properties and behavior of concrete reinforced with GFRP were undertaken.

TTI researchers have performed full-scale vehicle crash tests on concrete bridge rails with conventional steel reinforcement that are now TxDOT standard bridge rails (3,6-19). In some instances, TTI researchers worked cooperatively with TxDOT engineers to develop the design details of the bridge rail. These bridge rails are now being used throughout the state with some of them being more popular in some areas. Several rail designs that are used more in the areas of the state where corrosion continues to be a major problem were considered for inclusion in this project. Should the project demonstrate that partial or full replacement of steel reinforcement with GFRP reinforcement is acceptable, those rail designs will be available and approved for use in areas of the state that need to address problems with corrosion.

TxDOT currently uses several standard concrete bridge rails. They include the T201, T202 (MOD), T4, and the T500 series. The TTI researchers met with TxDOT personnel to review usage of the various designs and selected the T202 (MOD) bridge rail design for testing and evaluation. Design details, including replacement of reinforcing steel with GFRP, were established in concert with TxDOT engineers.

TTI researchers performed calculations to determine the strength of the T202 (MOD) rail and posts using conventional steel reinforcement and details as shown on a TxDOT drawing entitled "Type T202 (MOD)" and dated September 1999. Using these calculated strengths, TTI researchers then performed calculations to determine the required GFRP reinforcement needed in the rail and posts using the American Concrete Institute (ACI) 440.1R-01 "Guide for the Design and Construction of Concrete Reinforced with FRP Bars" (1). GFRP reinforcement loses some strength with age. The guide accounts for the loss in strength by using an environmental reduction factor, C_E , for various fiber type and exposure conditions in design calculations. Two designs were used. The first used a factor of $C_E = 0.7$. This design would have the required strength after long-term exposure to the environment. The second design used a factor of $C_E = 1.0$, which resulted in a reduced amount of reinforcement that would, at the time of testing, represent the strength that would exist after aging. A full-scale test installation was then constructed using the required GFRP reinforcement for both designs. One-half of the rail was reinforced with the amount of reinforcement required by the guide, and the remaining one-half was reinforced with a reduced amount of reinforcement that would represent loss of strength with age. This report presents the results from one crash test performed on the maximum strength design case ($C_E = 0.7$).

The TxDOT T202 (MOD) bridge rail with GFRP reinforcement was subjected to National Cooperative Highway Research Program (NCHRP) *Report 350* test designation 3-11 (4). Test 3-11 is a strength test for Test Level 3 (TL-3) of *NCHRP Report 350* and involves a 4405-lb (2000 kg) pickup truck traveling at 62.1 mi/h (100 km/h) and impacting the railing at an approach angle of 25 degrees. Standard evaluation criteria of *NCHRP Report 350* for evaluating safety performance of the railing were used. Researchers evaluated the structural behavior of the railing and deck overhang in detail to determine behavior of the GFRP reinforcement.

CHAPTER 2. PROJECT APPROACH

TEST FACILITY

The test facilities at the Texas Transportation Institute's Proving Ground consist of an 2,000 acre (809-hectare) complex of research and training facilities situated 10 miles (16 km) northwest of the main campus of Texas A&M University. The site, formerly an air force base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for construction of the TxDOT T202 (MOD) bridge rail with GFRP is along a wide out-of-service apron/runway. The apron/runway consists of an unreinforced jointed concrete pavement in 12.5 ft by 15.0 ft (3.8 m by 4.6 m) blocks nominally 8 to 12 inches (203-305 mm) deep. The aprons and runways are about 50 years old, and the joints have some displacement, but are otherwise flat and level.

TEST ARTICLE

The bridge deck cantilever constructed for this project was 2 ft-4 3/8 inch (721 mm) in width and 8 inch (203 mm) thick. The bridge deck was constructed immediately adjacent to an existing concrete runway located at the TTI test facility. The concrete deck was anchored into the existing runway with #5 (#16) steel reinforcement in the bottom layer in the deck overhang. The transverse reinforcement in the top and bottom layers of reinforcing in the deck cantilever consisted of #6 (#19) GFRP bars spaced 5 1/2 inches (140 mm) apart. The longitudinal reinforcement in the top of the deck cantilever consisted of #5 (#16) GFRP bars spaced 9 inches (229 mm) apart. The longitudinal reinforcement in the bottom of the deck consisted of two #5 (#16) bars on the field side of the deck spaced 3 inches (75 mm) apart with the next adjacent # 5 (#16) bar spaced 12 inches (305 mm) toward the traffic face. Transit Mix Concrete and Materials, Bryan, Texas, provided the concrete used for this project. TxDOT Class "S" concrete was used to construct the deck cantilever. The average compressive strength of the Class "S" concrete exceeded the required strength of 4000 psi (28 MPa) at the time the test was performed.

The T202 (MOD) bridge rail consists of a 1 ft-1 1/2 inches \times 1 ft-2 inches (343 mm \times 356 mm) concrete bridge rail supported by 7 1/2 inches \times 5 ft-0 inch (191 mm \times 1524 mm) concrete posts spaced 5 ft-0 inch (1524 mm) apart. The total height of the T202 (MOD) bridge rail was 2 ft-3 inches (686 mm). Two separate designs were constructed within this test installation. The details of the maximum strength design ($C_E = 0.7$) are reported herein. For details of both designs, please refer to the drawings shown as [Figure A-1](#) in this report. For the maximum strength design, vertical reinforcement in each post consisted of 17 #6 (#19) "L" shaped GFRP bars equally spaced on the front face (traffic side) and nine straight #5 (#16) GFRP bars equally spaced on the back face (field side). Longitudinal reinforcement in each post consisted of a #4 (#13) GFRP bar located on the front and back faces. Reinforcement in the rail consisted of four longitudinal #5 GFRP bars equally spaced on both the front and back faces of the rail (eight

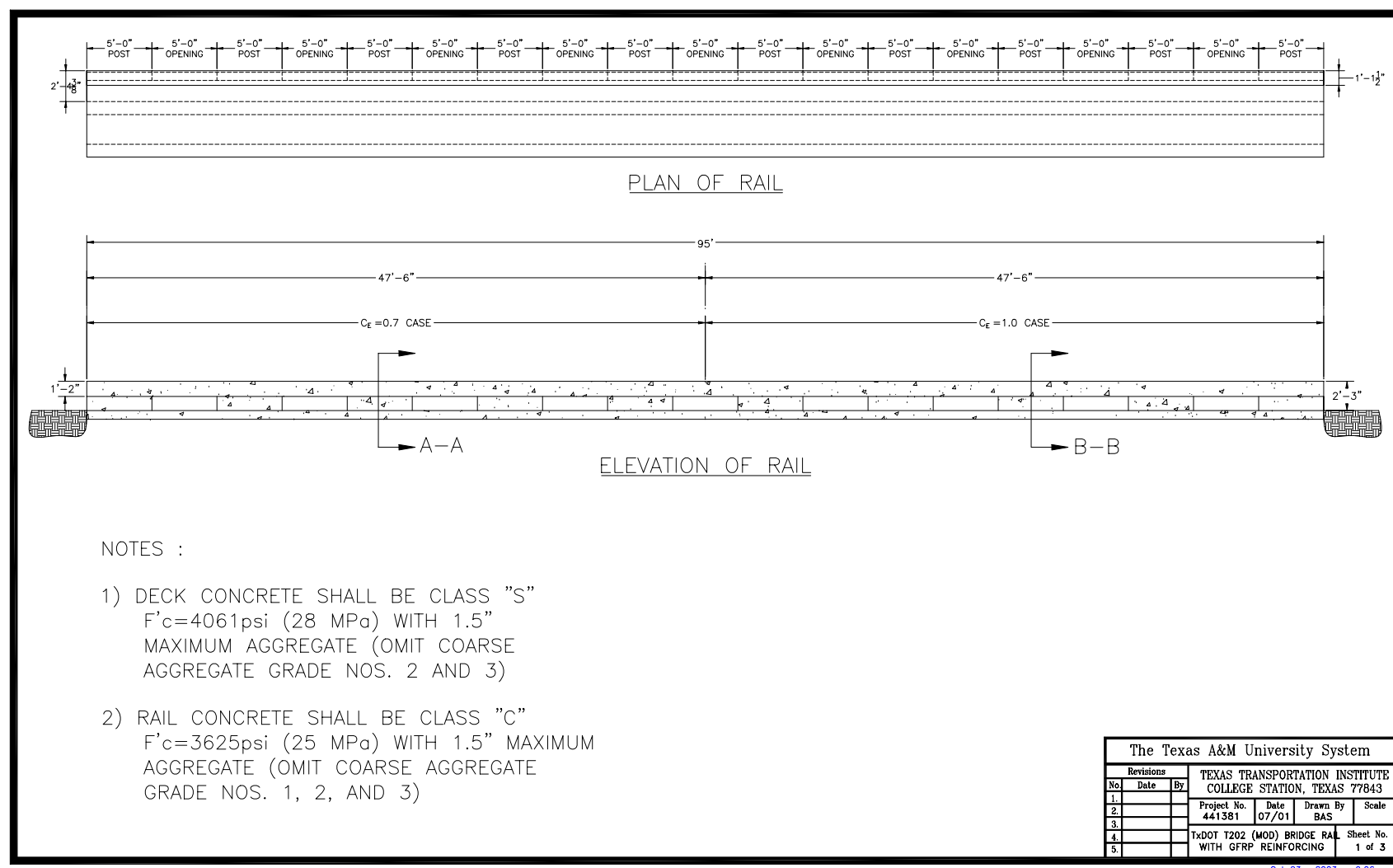
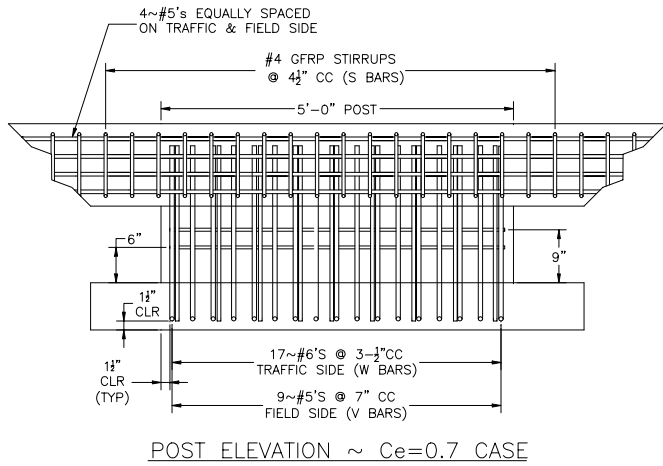
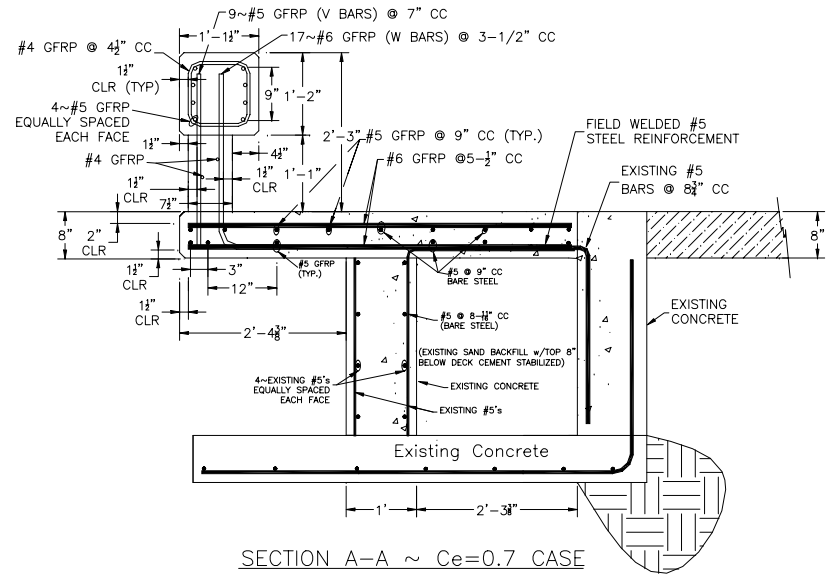


Figure A-1. Details of the TxDOT T202 (MOD) Bridge Rail with GFRP.



POST ELEVATION ~ Ce=0.7 CASE



SECTION A-A ~ Ce=0.7 CASE

The Texas A&M University System				
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TxDOT T202 (MOD) BRIDGE RAIL WITH GFRP REINFORCING	Sheet No.
	2 of 3

Figure A-1. Details of the TxDOT T202 (MOD) Bridge Rail with GFRP (Continued).

total). This longitudinal reinforcement was enclosed by #4 (#13) GFRP stirrups spaced 4 1/2 inches (114 mm) apart. Each stirrup was constructed using two “U” shaped bars that were lapped together on the vertical faces of the rail. Hughes Brothers in Seward, Nebraska, provided all the GFRP reinforcement used for this project. TxDOT Class “C” concrete was used to construct the bridge rail. The average compressive strength of the Class “C” concrete exceeded the required strength of 3600 psi (25 MPa) at the time the test was performed. Please refer to [Figure A-1](#) for additional details. [Figure A-2](#) shows photographs of the completed installation.

CRASH TEST CONDITIONS

NCHRP Report 350 recommends two tests for Test Level 3 evaluation of longitudinal barriers, such as the T202 (MOD) with GFRP reinforcement:

NCHRP Report 350 test designation 3-10: This test involves a 1806-lb (820 kg) passenger car impacting the critical impact point (CIP) in the length of need (LON) of the longitudinal barrier at a nominal speed and angle of 62 mi/h (100 km/h) and 20 degrees. The purpose of this test is to evaluate the overall performance of the LON section in general and occupant risks in particular.

NCHRP Report 350 test designation 3-11: This test involves a 4405-lb (2000 kg) pickup truck impacting the CIP in the LON of the longitudinal barrier at a nominal speed and angle of 62 mi/h (100 km/h) and 25 degrees. The test is intended to evaluate the strength of the section for containing and redirecting the pickup truck.

This report documents the results of test 441382-1, which corresponds to *NCHRP Report 350* test designation 3-11.

The crash test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. [Appendix C](#) presents brief descriptions of these procedures.

EVALUATION CRITERIA

The crash test performed was evaluated in accordance with *NCHRP Report 350*. As stated in *NCHRP Report 350*, “Safety performance of a highway appurtenance cannot be measured directly but can be judged on the basis of three factors: structural adequacy, occupant risk, and vehicle trajectory after collision.” Accordingly, researchers used the safety evaluation criteria from Table 5.1 of *NCHRP Report 350* to evaluate the crash test reported herein.

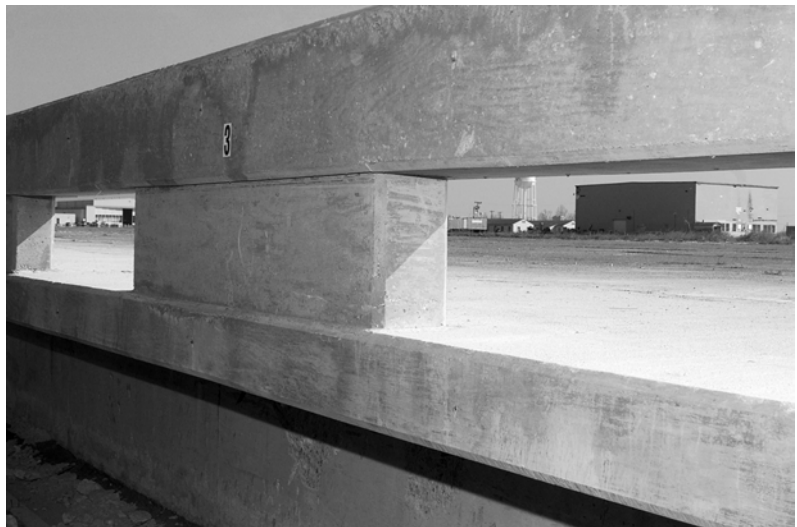


Figure A-2. Test Article/Installation before Test 441382-1.

CHAPTER 3. CRASH TEST RESULTS

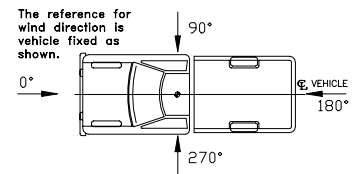
TEST NO. 441382-1 (NCHRP Report 350 TEST NO. 3-11)

Test Vehicle

Figures A-3 and A-4 show a 1998 Chevrolet 2500 pickup truck used for the crash test. Test inertia weight of the vehicle was 4498 lb (2042 kg), and its gross static weight was 4498 lb (2042 kg). The height to the lower edge of the vehicle bumper was 17.1 inches (435 mm), and it was 25.8 inches (655 mm) to the upper edge of the bumper. Figure A-5 shows additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

Weather Conditions

The test was performed on the morning of March 12, 2002. Weather conditions at the time of testing were as follows: Wind speed: 5 mi/h (8 km/h); Wind direction: 0 degrees with respect to the vehicle (vehicle was traveling in a northeasterly direction); Temperature: 52 °F (11 °C); Relative humidity: 70 percent.



Test Description

The 4498-lb (2042 kg) pickup truck traveling at 62.8 mi/h (101.0 km/h) impacted the TxDOT T202 (MOD) bridge rail with GFRP 63.0 inches (1600 mm) upstream of leading edge of post 3 at an impact angle of 26.1 degrees. At approximately 0.037 s after impact, the driver's side door (impact side) opened slightly, and at 0.039 s the vehicle began to redirect. The right front tire lost contact with the ground at 0.088 s, followed by the right rear tire at 0.124 s, and the left front tire at 0.207 s. At 0.238 s the vehicle became parallel with the bridge rail and was traveling at a speed of 44.5 mi/h (71.7 km/h). The vehicle lost contact with the bridge rail at 0.521 s while traveling at a speed of 42.5 mi/h (68.4 km/h) and an exit angle of 18.9 degrees. As the vehicle exited the rail, it came down on the left front quarter panel and rolled onto its left side. The vehicle subsequently came to rest on the left side, 172.5 ft (52.6 m) downstream of impact and 31.2 ft (9.5 m) forward of the traffic face of the rail. Figures A-6 and A-7 show sequential photographs of the test period.



Figure A-3. Vehicle/Installation Geometrics for Test 441382-1.



Figure A-4. Vehicle before Test 441382-1.

DATE: 03/12/02 TEST NO.: 441382-1 VIN NO.: 1GCGC24R4WZ169775
 YEAR: 1998 MAKE: Chevrolet MODEL: 2500 Pickup
 TIRE INFLATION PRESSURE: _____ ODOMETER: 179551 TIRE SIZE: LT245 75R16

MASS DISTRIBUTION (kg) LF 576 RF 575 LR 448 RR 443

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:

● Denotes accelerometer location.

NOTES: _____

ENGINE TYPE: 8 CYL
 ENGINE CID: 5.7 L
 TRANSMISSION TYPE:
 AUTO
 MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:
 TYPE: _____
 MASS: _____
 SEAT POSITION: _____

GEOMETRY - (mm)

A	<u>1870</u>	E	<u>1310</u>	J	<u>1090</u>	N	<u>1595</u>	R	<u>720</u>
B	<u>820</u>	F	<u>5480</u>	K	<u>655</u>	O	<u>1620</u>	S	<u>920</u>
C	<u>3350</u>	G	<u>1461.7</u>	L	<u>70</u>	P	<u>760</u>	T	<u>1460</u>
D	<u>1870</u>	H	_____	M	<u>435</u>	Q	<u>445</u>	U	<u>3420</u>

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M ₁	<u>1243</u>	<u>1151</u>	<u>1151</u>
M ₂	<u>890</u>	<u>891</u>	<u>891</u>
M _T	<u>2133</u>	<u>2042</u>	<u>2042</u>

Figure A-5. Vehicle Properties for Test 441382-1.



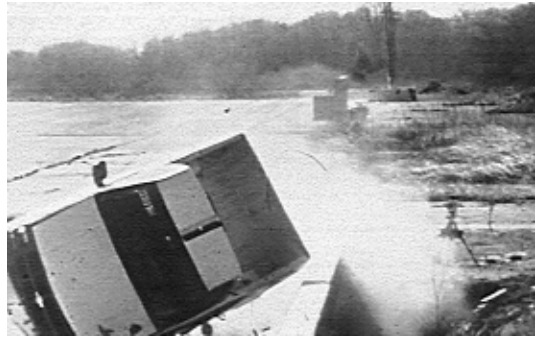
0.000 s



0.365 s



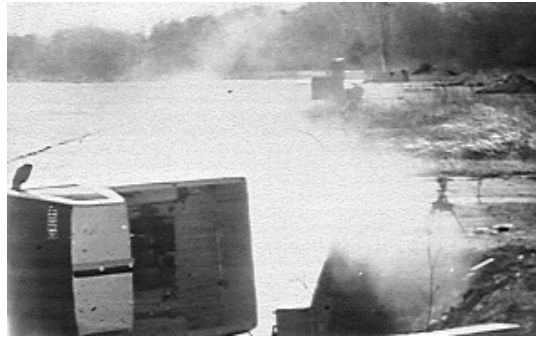
0.049 s



0.730 s



1.097 s



1.095 s



0.195 s



2.190 s

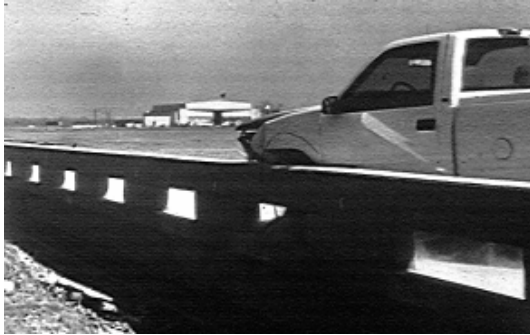
Figure A-6. Sequential Photographs for Test 441382-1 (Frontal View).



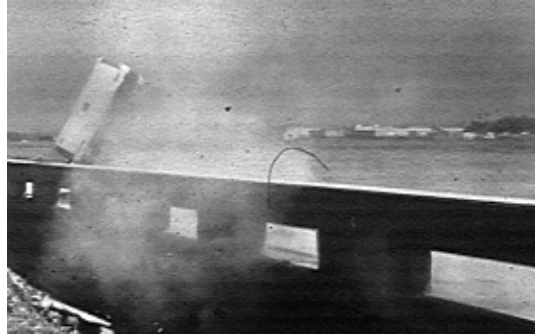
0.000 s



0.365 s



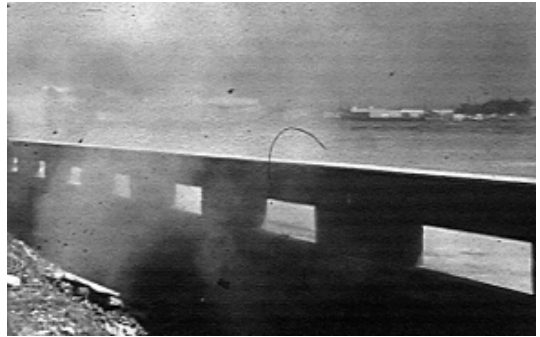
0.049 s



0.730 s



0.097 s



1.095 s



0.195 s



2.190 s

Figure A-7. Sequential Photographs for Test 441382-1 (Rear View).

Damage to Test Installation

Pieces of concrete were chipped out of the lower edge of the beam rail where the vehicle's tire/wheel contacted it. Hairline cracks in the deck radiated from both sides of post 3. The vehicle was in contact with the bridge rail for a distance of 13.85 ft (4.22 m). Figures A-8 and A-9 show photographs of the damage to the bridge rail. There was no indication of significant structural damage to the rail or the deck. There was no indication that the GFRP exhibited any undesirable traits.

Vehicle Damage

Figure A-10 shows damage to the vehicle. Structural damage was imparted to the stabilizer bar, left upper and lower A-arms, left rod ends, left front frame member, firewall, and floor pan. Also damaged were the front bumper, hood, radiator, fan, left front tire and wheel rim, left front quarter panel, left door and window glass, and left rear exterior bed. The windshield broke during vehicle rollover. Maximum exterior crush to the exterior of the vehicle was 22.8 inches (580 mm) in the front plane at the left front corner near bumper height. Maximum occupant compartment deformation was 5.0 inches (128 mm) in the floor pan to instrument panel on the left side near the driver's feet. Figure A-11 shows photographs of the interior of the vehicle. Tables A-1 and A-2 show exterior vehicle crush and occupant compartment measurements.

Occupant Risk Factors

Data from the triaxial accelerometer, located at the vehicle center of gravity, were digitized to compute occupant impact velocity and ridedown accelerations. Only the longitudinal occupant impact velocity and ridedown accelerations are required for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 20.3 ft/s (6.2 m/s) at 0.099 s, maximum 0.010-s ridedown acceleration was -5.3 g's from 0.209 to 0.219 s, and the maximum 0.050-s average was -10.3 g's between 0.024 and 0.074 s. Figure A-12 presents data and other information pertinent to the test. Figures A-13 through A-19 show vehicle angular displacements and accelerations versus time traces.



Figure A-8. After Impact Trajectory for Test 441382-1.



Figure A-9. Installation after Test 441382-1.



Figure A-10. Vehicle after Test 441382-1.



Before Test



After Test



Figure A-11. Interior of Vehicle for Test 441382-1.

Table A-1. Exterior Crush Measurements for Test 441382-1.

VEHICLE CRUSH MEASUREMENT SHEET¹

Complete When Applicable	
End Damage	Side Damage
Undeformed end width _____ Corner shift: A1 _____ A2 _____ End shift at frame (CDC) (check one) < 4 inches _____ ≥ 4 inches _____	Bowing: B1 _____ X1 _____ B2 _____ X2 _____ Bowing constant $\frac{X1 + X2}{2} = \underline{\hspace{2cm}}$

Note: Measure C₁ to C₆ from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	±D
		Width** (CDC)	Max*** Crush								
1	Front bumper	800	580	960	580	400	180	80	50	0	-160
2	750 mm above ground	800	510	1110	50	130	150	Wheel Well		510	+1250

¹Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

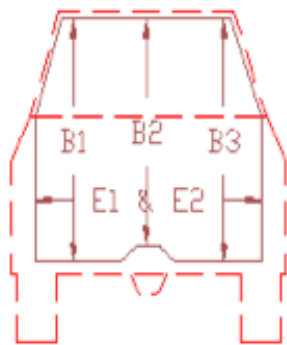
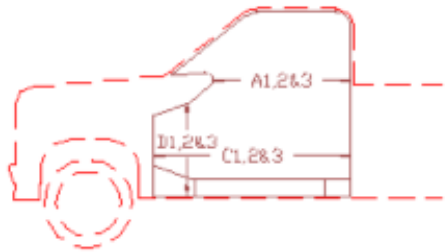
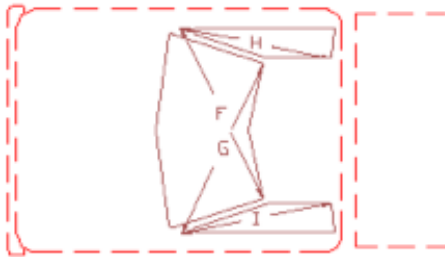
***Measure and document on the vehicle diagram the location of the maximum crush.

Note: Use as many lines/columns as necessary to describe each damage profile.

Table A-2. Occupant Compartment Measurements for Test 441382-1.

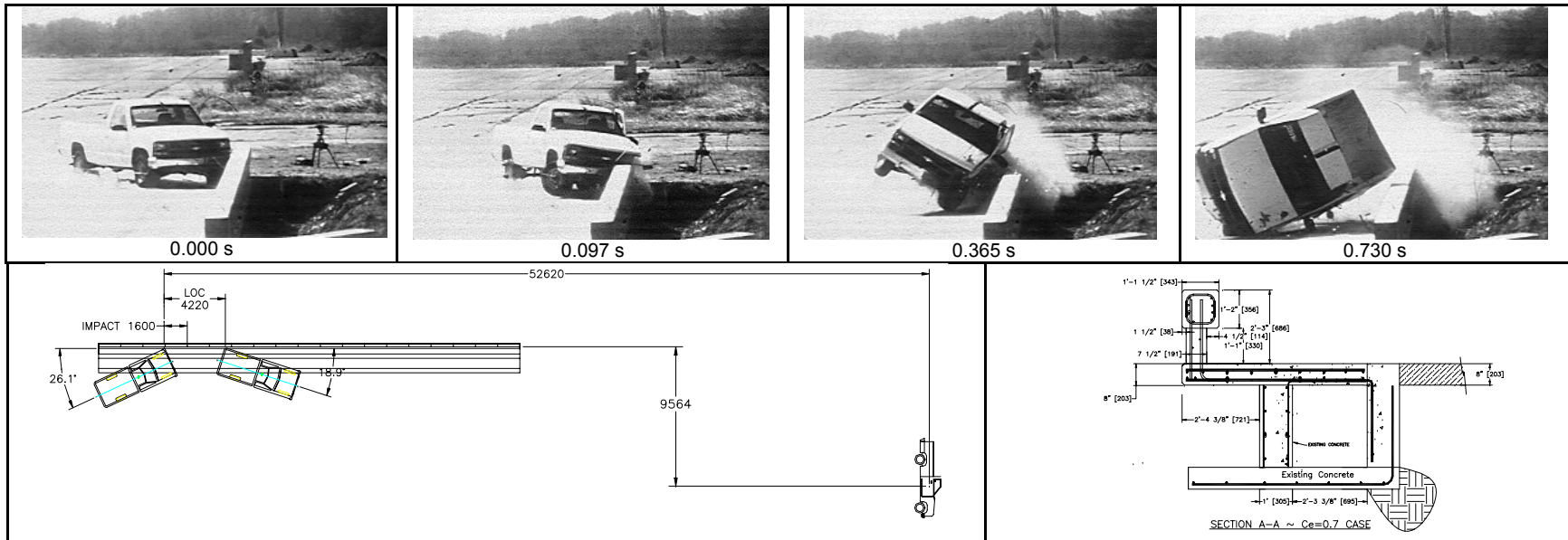
T r u c k

Occupant Compartment Deformation



	BEFORE (mm)	AFTER (mm)
A1	866	842
A2	927	935
A3	907	915
B1	1075	980
B2	1037	1072
B3	1070	1072
C1	1375	1333
C2	530	530
C3	1372	1372
D1	313	185
D2	158	166
D3	311	333
E1	1580	1557
E2	1593	1590
F	1460	1455
G	1460	1455
H	900	900
I	900	895
J*	1522	1402

*J = measurement laterally across occupant compartment from kickpanel to kickpanel.



A-22

General Information

Test Agency Texas Transportation Institute
 Test No. 441382-1
 Date 03/12/02

Test Article

Type Bridge Rail
 Name T202 (MOD) Bridge Rail With GFRP
 Installation Length (ft) 95 (28.96 m)
 Material or Key Elements T202 (MOD) Concrete Bridge Rail With GFRP Reinforcement

Soil Type and Condition Concrete Footing

Test Vehicle

Type Production
 Designation 2000P
 Model 1998 Chevrolet 2500 Pickup
 Mass (lbs)
 Curb 4697 (2133 kg)
 Test Inertial 4498 (2042 kg)
 Dummy N/A
 Gross Static 4498 (2042 kg)

Impact Conditions

Speed (mi/h) 62.8 (101 km/h)
 Angle (deg) 26.1

Exit Conditions

Speed (mi/h) 42.5 (68.4 km/h)
 Angle (deg) 18.9

Occupant Risk Values

Impact Velocity (ft/s)
 x-direction 20.3 (6.2 m/s)
 y-direction 23.0 (7.0 m/s)
 THIV (mi/h) 20.7 (33.3 km/h)
 Ridedown Accelerations (g's)
 x-direction -5.3
 y-direction 7.4
 PHD (g's) 7.7
 ASI 1.49
 Max. 0.050-s Average (g's)
 x-direction -10.3
 y-direction 11.2
 z-direction -4.1

Test Article Deflections (ft)

Dynamic None
 Permanent None
 Working Width 1.72 (0.52 m)

Vehicle Damage

Exterior
 VDS 11FL3
 CDC 11FFAO3
 Maximum Exterior
 Vehicle Crush (in) 22.6 (580 mm)
 Interior
 OCDI LF0115000
 Max. Occ. Compart.
 Deformation (in) 5.0 (128 mm)

Post-Impact Behavior

(during 1.0 s after impact)
 Max. Yaw Angle (deg) 80.6
 Max. Pitch Angle (deg) -5.9
 Max. Roll Angle (deg) -89.9

Figure A-12. Summary of Results for Test 441382-1, NCHRP Report 350 Test 3-11.

Roll, Pitch and Yaw Angles

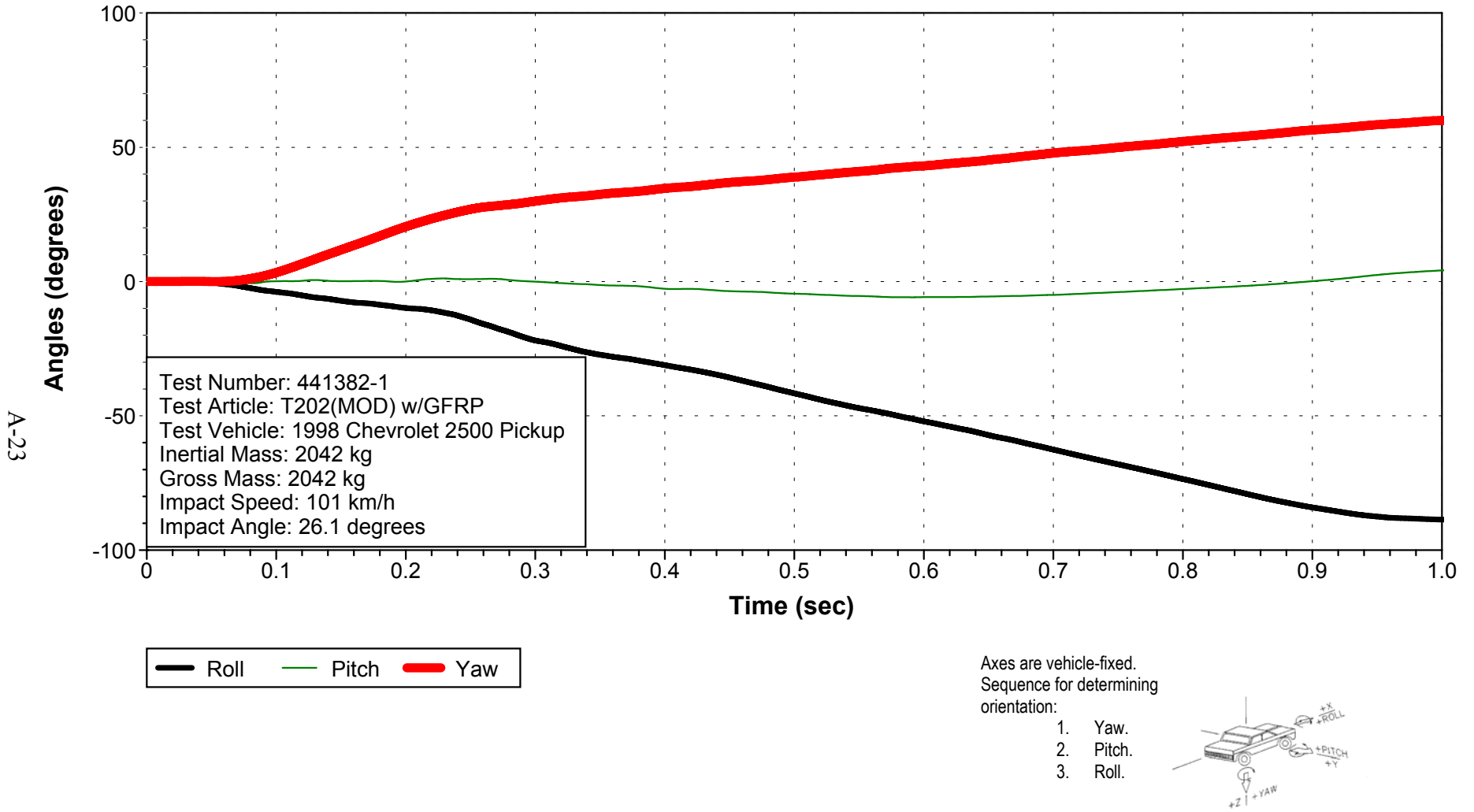
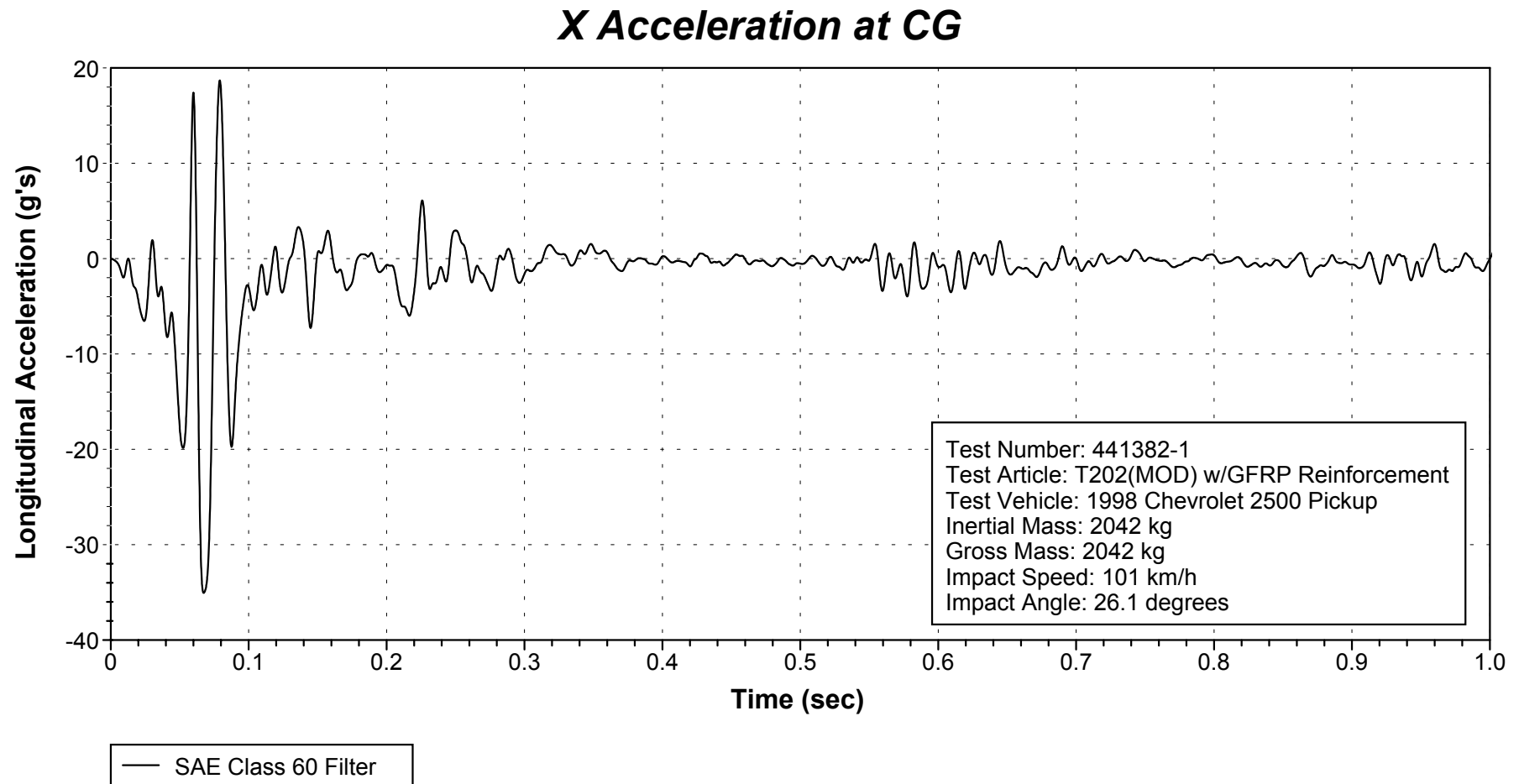


Figure A-13. Vehicular Angular Displacements for Test 441382-1.



**Figure A-14. Vehicle Longitudinal Accelerometer Trace for Test 441382-1
(Accelerometer Located at Center of Gravity).**

Y Acceleration at CG

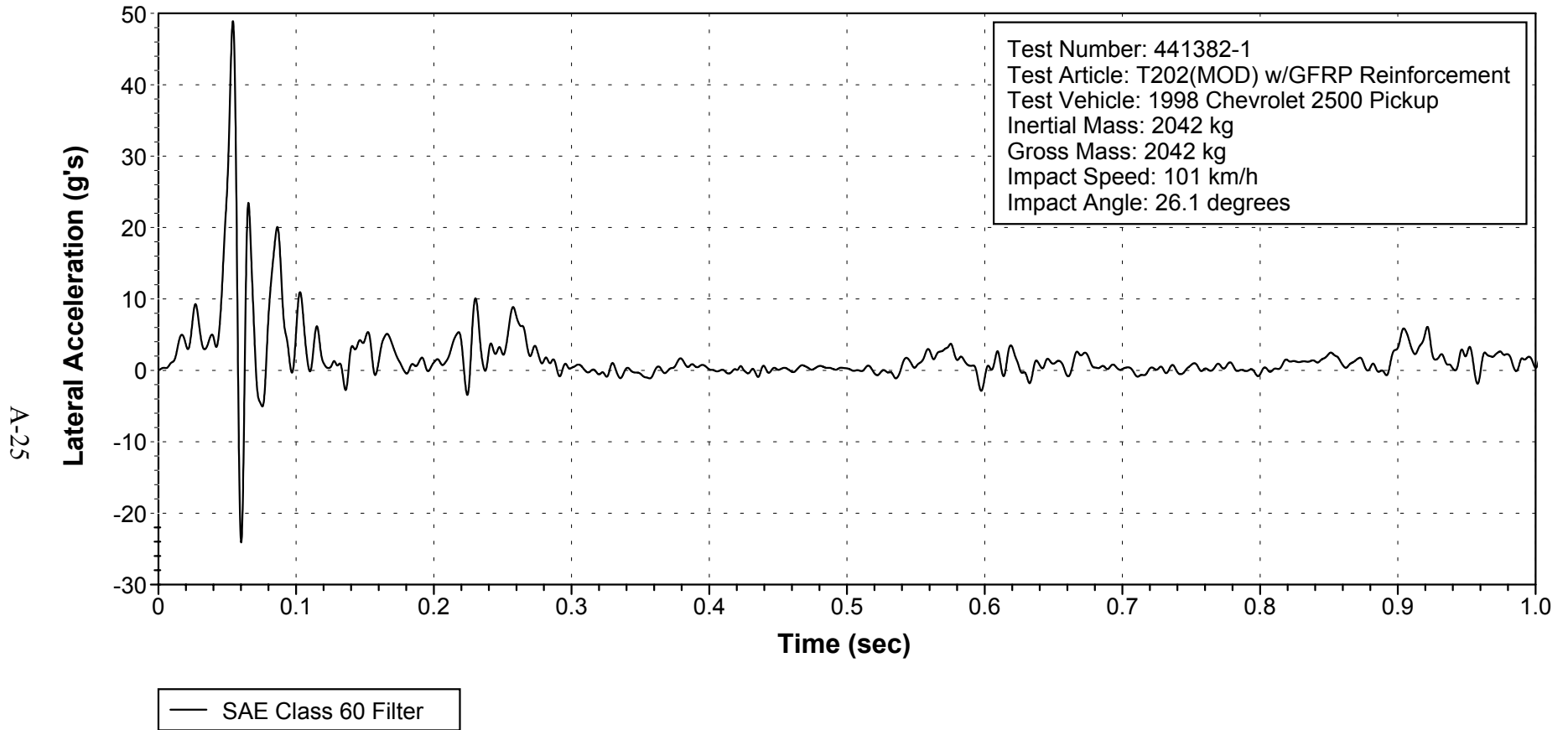
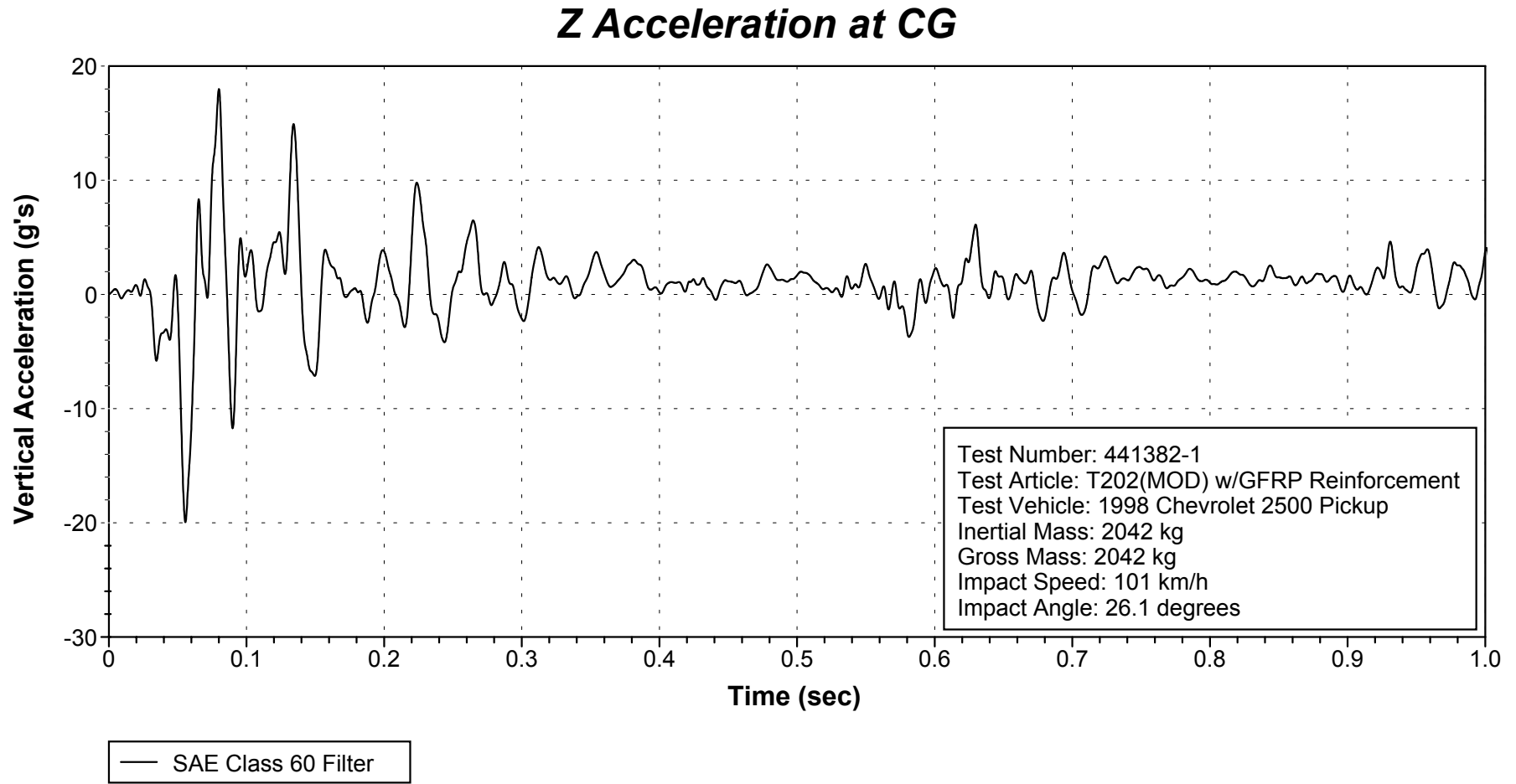


Figure A-15. Vehicle Lateral Accelerometer Trace for Test 441382-1
(Accelerometer Located at Center of Gravity).

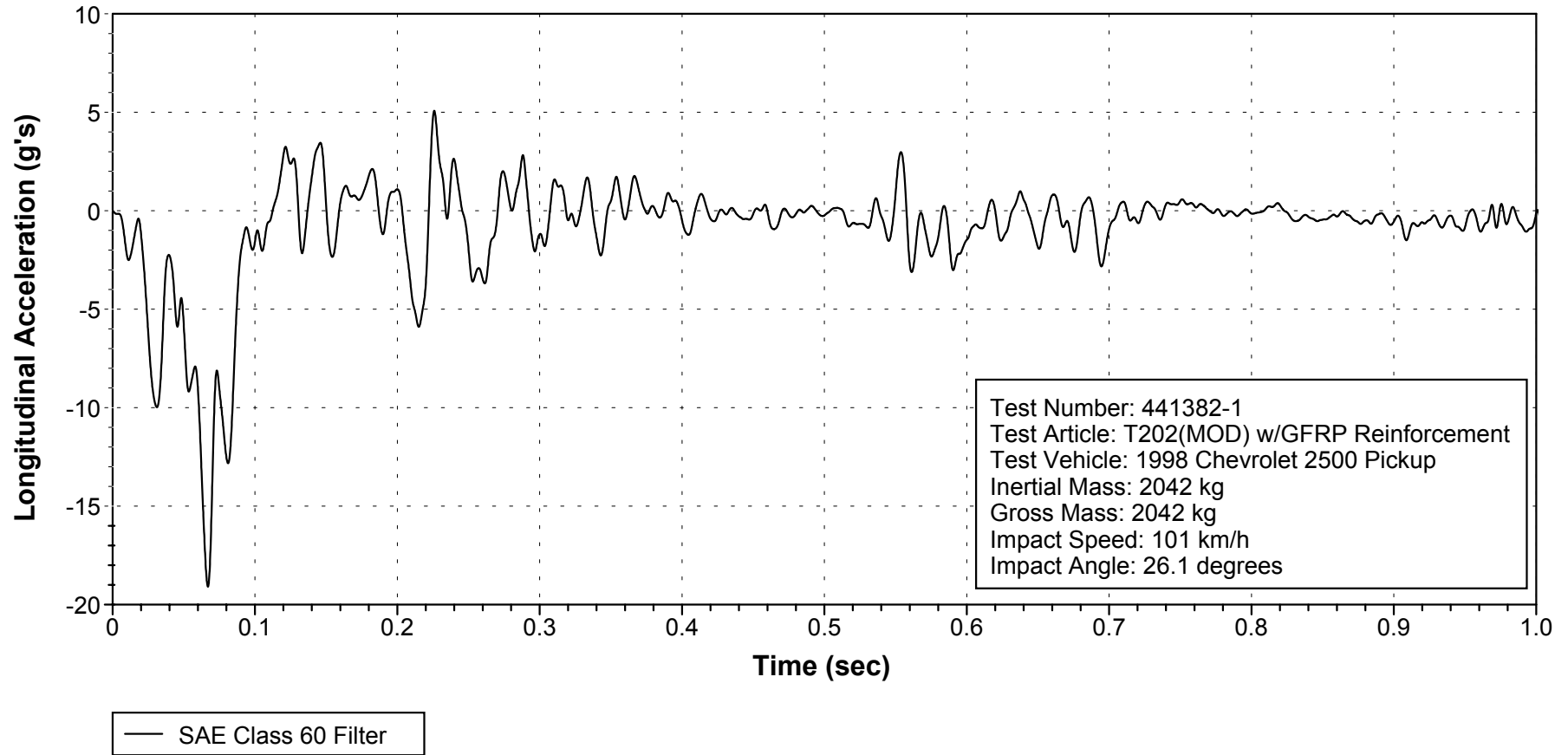
A-26



**Figure A-16. Vehicle Vertical Accelerometer Trace for Test 441382-1
(Accelerometer Located at Center of Gravity).**

A-27

X Acceleration Over Rear Axle



**Figure A-17. Vehicle Longitudinal Accelerometer Trace for Test 441382-1
(Accelerometer Located over Rear Axle).**

Y Acceleration Over Rear Axle

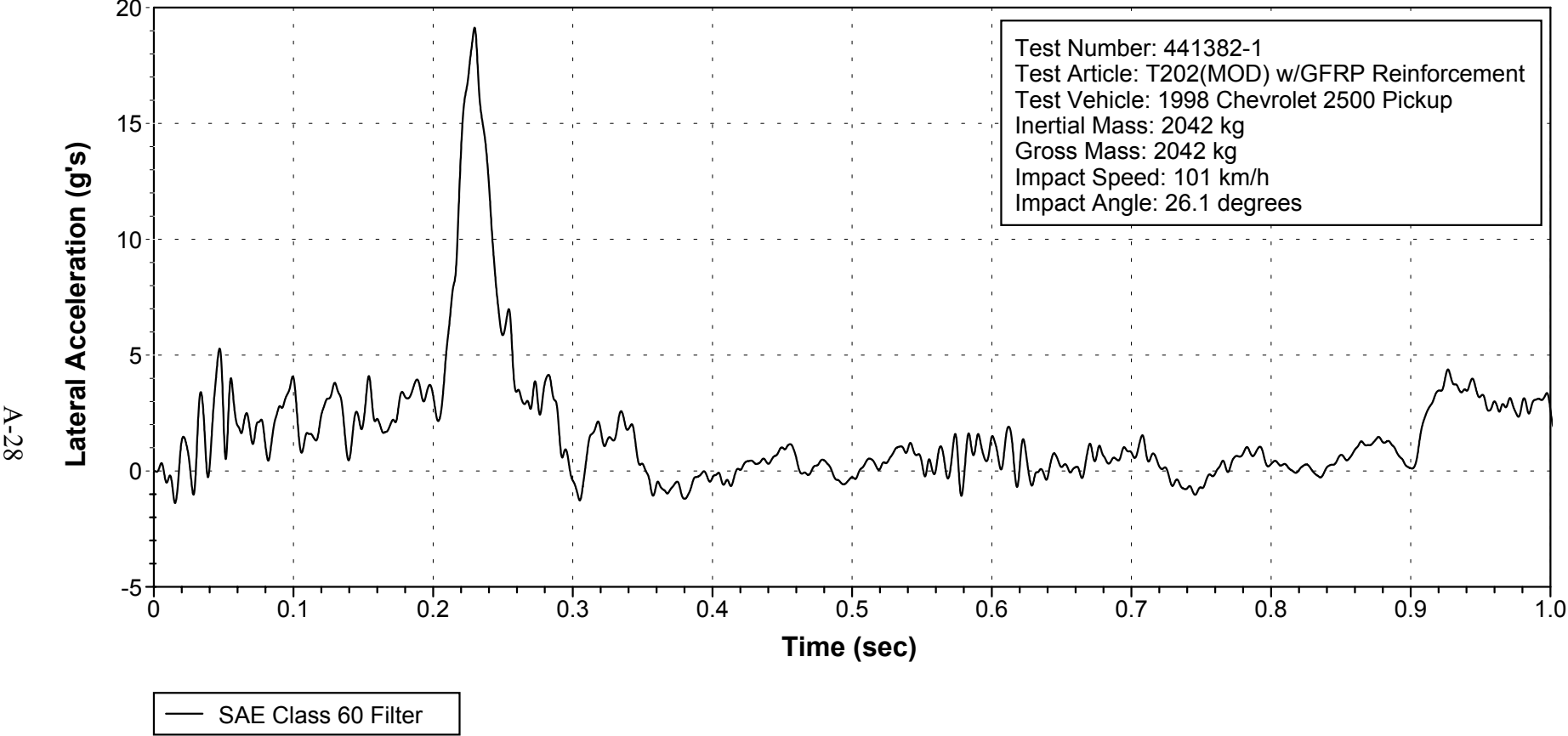
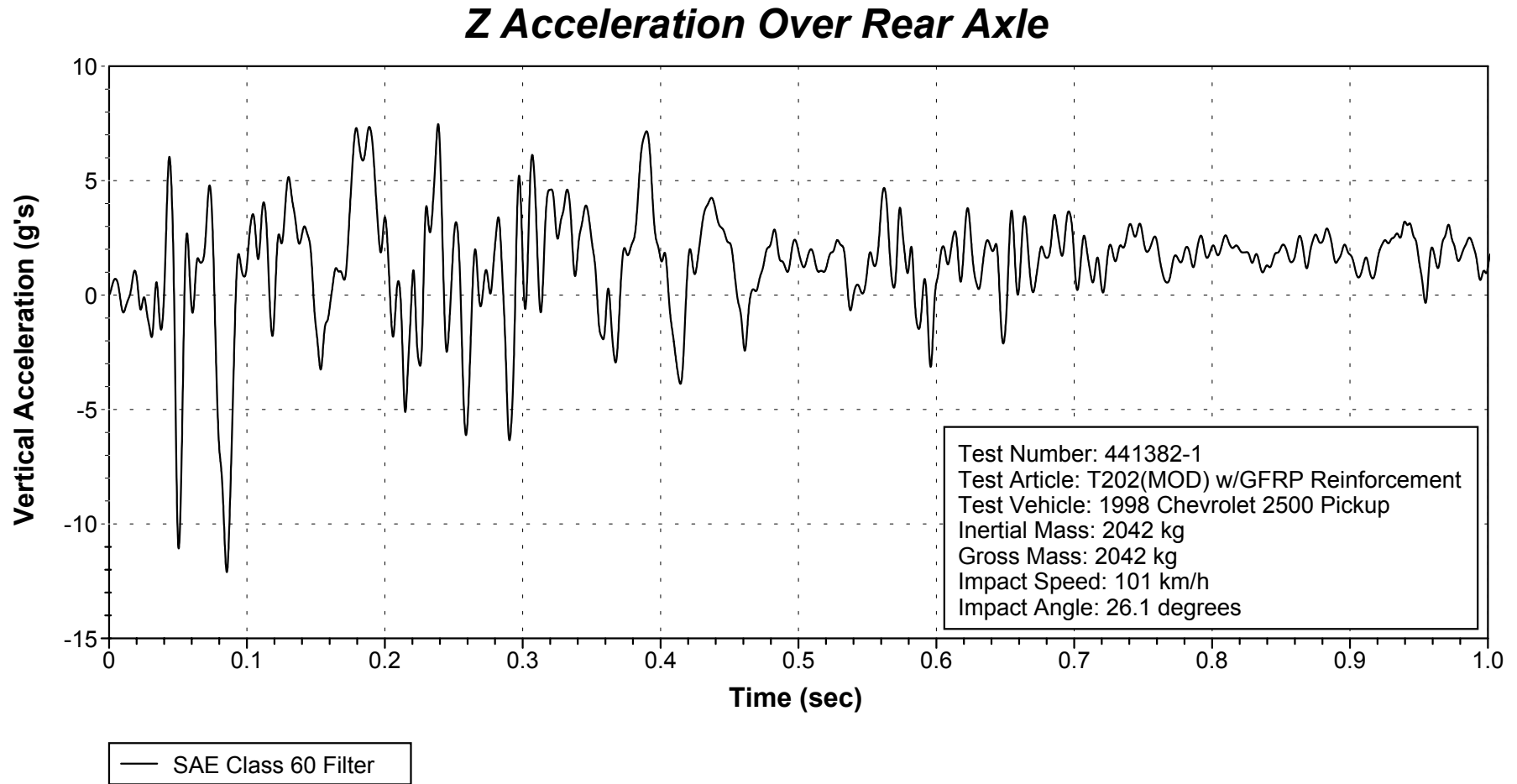


Figure A-18. Vehicle Lateral Accelerometer Trace for Test 441382-1 (Accelerometer Located over Rear Axle).



**Figure A-19. Vehicle Vertical Accelerometer Trace for Test 441382-1
(Accelerometer Located over Rear axle).**

CHAPTER 4. SUMMARY AND CONCLUSIONS

ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria is provided below (4).

Structural Adequacy

A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.

Results: The TxDOT T202 (MOD) with GFRP reinforcement contained and redirected the 4498-lb (2042 kg) pickup truck. The vehicle did not penetrate, underride, or override the bridge rail. No measurable deflection was noted.

Occupant Risk

D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.

Results: No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 5.0 inches (128 mm) in the floor pan to instrument panel on the left side near the driver's feet.

F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.

Results: The 4498-lb (2042 kg) pickup truck rolled onto its left side after exiting the installation.

Vehicle Trajectory

K. After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.

Results: The vehicle subsequently came to rest on the left side, 172.5 ft (52.6 m) downstream of impact and 31.2 ft (9.5 m) forward of the traffic face of the rail.

L. *The occupant impact velocity in the longitudinal direction should not exceed 12 m/s, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.*

Results: Longitudinal occupant impact velocity was 20.3 ft/s (6.2 m/s), and longitudinal occupant ridedown acceleration was -5.3 g's.

M. *The exit angle from the test article preferably should be less than 60 percent of the test impact angle, measured at time of vehicle loss of contact with the test device.*

Results: Exit angle at loss of contact was 18.9 degrees, which was 72 percent of the impact angle.

The following supplemental evaluation factors and terminology, as presented in the FHWA memo entitled "Action: Identifying Acceptable Highway Safety Features," were used for visual assessment of test results (20):

Passenger Compartment Intrusion

- | | |
|---|---|
| 1. <i>Windshield Intrusion</i> | |
| a. <i>No windshield contact (broke on roll)</i> | e. <i>Complete intrusion into passenger compartment</i> |
| b. <i>Windshield contact, no damage</i> | f. <i>Partial intrusion into passenger compartment</i> |
| c. <i>Windshield contact, no intrusion</i> | |
| d. <i>Device embedded in windshield, no significant intrusion</i> | |
| 2. <i>Body Panel Intrusion</i> | <u>yes</u> or no |

Loss of Vehicle Control

- | | |
|---|--|
| 1. <u><i>Physical loss of control</i></u> | 3. <i>Perceived threat to other vehicles</i> |
| 2. <i>Loss of windshield visibility</i> | 4. <i>Debris on pavement</i> |

Physical Threat to Workers or Other Vehicles

1. *Harmful debris that could injure workers or others in the area*
 2. *Harmful debris that could injure occupants in other vehicles*
- No debris was present

Vehicle and Device Condition

- | | |
|--|--|
| 1. <i>Vehicle Damage</i> | |
| a. <i>None</i> | d. <i>Major dents to grill and body panels</i> |
| b. <i>Minor scrapes, scratches, or dents</i> | e. <u><i>Major structural damage</i></u> |
| c. <i>Significant cosmetic dents</i> | |

2. *Windshield Damage*
 - a. *None*
 - b. *Minor chip or crack*
 - c. *Broken, no interference with visibility*
 - d. *Broken or shattered, visibility restricted but remained intact*
 - e. *Shattered, remained intact but partially dislodged*
 - f. *Large portion removed*
 - g. *Completely removed*
3. *Device Damage*
 - a. *None*
 - b. *Superficial*
 - c. *Substantial, but can be straightened*
 - d. *Substantial, replacement parts needed for repair*
 - e. *Cannot be repaired*

CONCLUSIONS

The TxDOT T202 (MOD) bridge rail with GFRP reinforcement contained and redirected the 4498-lb (2042 kg) pickup truck. The vehicle did not penetrate, underride, or override the bridge rail. No measurable deflection was noted. No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 5.0 inches (128 mm) in the floor pan to instrument panel on the left side near the driver's feet. The 4498-lb (2042 kg) pickup truck rolled onto its left side after exiting the installation. The vehicle subsequently came to rest on the left side, 172.5 ft (52.6 m) downstream of impact and 31.2 ft (9.5 m) forward of the traffic face of the rail. Longitudinal occupant impact velocity was 20.3 ft/s (6.2 m/s) and longitudinal occupant ridedown acceleration was -5.3 g's. Exit angle at loss of contact was 18.9 degrees, which was 72 percent of the impact angle.

As seen in [Table A-3](#), the TxDOT T202 (MOD) bridge rail with GFRP reinforcement did not pass the required specifications for occupant risk during *NCHRP Report 350* Test 3-11 due to rollover.

No significant structural damage occurred to the rail or the deck. There was no indication that the GFRP exhibited any undesirable traits.

IMPLEMENTATION STATEMENT

No implementation is indicated at this time.

Table A-3. Performance Evaluation Summary for Test 441382-1, NCHRP Report 350 Test 3-11.

Test Agency: Texas Transportation Institute		Test No.: 441382-1	Test Date: 03/12/2002
NCHRP Report 350 Test 3-11 Evaluation Criteria		Test Results	Assessment
Structural Adequacy			
A.	<i>Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</i>	The TxDOT T202 (MOD) with GFRP reinforcement contained and redirected the 4498-lb (2042 kg) pickup truck. The vehicle did not penetrate, underride, or override the bridge rail. No measurable deflection was noted.	Pass
Occupant Risk			
D.	<i>Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i>	No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 5.0 inches (128 mm) in the floor pan to instrument panel on the left side near the driver's feet.	Pass
F.	<i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i>	The 4498-lb (2042 kg) pickup truck rolled onto its left side after exiting the installation.	Fail
Vehicle Trajectory			
K.	<i>After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i>	The vehicle subsequently came to rest on the left side, 52.6 m downstream of impact and 9.5 m forward of the traffic face of the rail.	Fail*
L.	<i>The occupant impact velocity in the longitudinal direction should not exceed 12 m/s, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.</i>	Longitudinal occupant impact velocity was 20.3 ft/s (6.2 m/s), and longitudinal occupant ridedown acceleration was -5.3 g's.	Pass
M.	<i>The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.</i>	Exit angle at loss of contact was 18.9 degrees, which was 72 percent of the impact angle.	Fail*

*Criteria K and M are preferable, not required.

APPENDIX B: NCHRP REPORT 350 TEST 3-11 OF THE TXDOT T202 (MOD) BRIDGE RAIL WITH GFRP REINFORCEMENT AND METAL RAIL

CHAPTER 1. INTRODUCTION

PROBLEM

In some areas of the state, corrosion of reinforcing steel in concrete bridge structures, especially in deck slabs, continues to be a serious problem for the Texas Department of Transportation (TxDOT). One remedial measure for this problem might be the use of glass fiber reinforced polymer (GFRP) reinforcing bars. Physical properties of these reinforcing bars differ significantly from those of conventional reinforcing steel, and the behavior of concrete reinforced with GFRP is not completely defined and understood. GFRP reinforcement is typically much more brittle than conventional reinforcing steel, and its behavior under dynamic load from a vehicle collision is not known. This project addresses the behavior of a bridge slab/rail structure reinforced with glass fiber reinforced polymer when subjected to full-scale vehicle crash tests.

BACKGROUND

Use of GFRP reinforcement in decks, rails, and perhaps other elements of bridge structures has high potential for reducing the problem of deterioration of bridge structures as a result of corrosion of reinforcement. Glass fiber reinforced polymer reinforcement cannot be used as a direct replacement for steel because GFRP has significantly different mechanical properties. One major fundamental difference is that GFRP is a relatively brittle material while steel is ductile. Ductility of steel is the fundamental property that allows one to design reinforced concrete structures that behave in a ductile manner, although the (plain) concrete is brittle. This ductility is accomplished by providing ratios of steel reinforcement that cause the steel to yield before the concrete ruptures in a brittle manner. With the use of GFRP, the greatest amount of structural ductility is achieved by proportioning the materials such that the concrete ruptures first because it is the more ductile of the two materials. This is expected to result in a bridge structure that is somewhat more brittle than a structure with conventional steel reinforcement and, therefore, its behavior under dynamic loads needs to be evaluated. Sufficient ductility and/or reserve strength for adequate performance in service must exist.

OBJECTIVES/SCOPE OF RESEARCH

TxDOT Project 9-1520, "FRP Reinforcing Bars in Bridge Decks" was initiated in August 1999. This was a joint project involving the Texas Transportation Institute, the University of Texas at Arlington, and Texas Tech University. In that project, GFRP reinforcement was used on a trial basis in the top of a bridge deck in selected spans in a structure in Potter County. Behavior of the GFRP was monitored during construction, and monitoring will continue while

the bridge is in service. Also, extensive laboratory studies of the fundamental properties and behavior of concrete reinforced with GFRP were undertaken.

TTI researchers have performed full-scale vehicle crash tests on concrete bridge rails with conventional steel reinforcement that are now TxDOT standard bridge rails (3, 6-19). In some instances, TTI researchers worked cooperatively with TxDOT engineers to develop the design details of the bridge rail. These bridge rails are now being used throughout the state with some of them being more popular in some areas. Several rail designs that are used more in the areas of the state where corrosion continues to be a major problem were considered for inclusion in this project. Should the project demonstrate that partial or full replacement of steel reinforcement with GFRP reinforcement is acceptable, those rail designs will be available and approved for use in areas of the state that need to address problems with corrosion.

TxDOT currently uses several standard concrete bridge rails. They include the T201, T202 (MOD), T4, and the T500 series. The TTI researchers met with TxDOT personnel to review usage of the various designs and selected the T202 (MOD) bridge rail design for testing and evaluation. Design details, including replacement of reinforcing steel with GFRP, were established in concert with TxDOT engineers.

TTI researchers performed calculations to determine the strength of the T202 (MOD) rail and posts using conventional steel reinforcement and details as shown on a TxDOT drawing entitled "Type T202 (MOD)" and dated September 1999. Using these calculated strengths, TTI researchers then performed calculations to determine the required GFRP reinforcement needed in the rail and posts using the American Concrete Institute (ACI) 440.1R-01 "Guide for the Design and Construction of Concrete Reinforced with FRP Bars" (1). GFRP reinforcement loses some strength with age. The guide accounts for the loss in strength by using an environmental reduction factor, C_E , for various fiber type and exposure conditions in design calculations. Two designs were used. The first used a factor of $C_E = 0.7$. This design would have the required strength after long-term exposure to the environment. The second design used a factor of $C_E = 1.0$. This design resulted in a reduced amount of reinforcement that would, at the time of testing, represent the strength that would exist after aging. A full-scale test installation was then constructed using the required GFRP reinforcement for both designs. One-half of the rail was reinforced with the amount of reinforcement required by the guide and the remaining one-half was reinforced with a reduced amount of reinforcement that would represent loss of strength with age.

Researchers performed a full-scale vehicle crash test on the maximum strength design case ($C_E = 0.7$). In that test, the vehicle rolled onto its side and thus failed the safety requirements of National Cooperative Highway Research Program (*NCHRP Report 350*) (4). However, structural behavior of the bridge rail (with GFRP reinforcement) was entirely acceptable. An earlier report presented the results of that test (21).

This outcome presented a dilemma because the Type T202 (MOD) bridge rail had acceptable safety performance in two previous tests (test 3-11 of *NCHRP Report 350*) (2,3). There was some indication that the 27-inches (686 mm) height of the rail was marginal and was the cause of the rollover.

After deliberations, it was decided that the need to test the railing with reduced amount of reinforcement ($C_E = 1.0$) was still valid. Height of the rail was increased 3 inches (76 mm) by adding a TS6×3×1/4 inch (TS152×76×6) member on top of the existing test article. This test article was then subjected to *NCHRP Report 350* test designation 3-11. Test 3-11 is a strength test for Test Level 3 (TL-3) of *NCHRP Report 350* and involves a 4405-lb (2000 kg) pickup truck traveling at 62.1 mi/h (100 km/h) and impacting the railing at an approach angle of 25 degrees. Researchers used standard evaluation criteria of *NCHRP Report 350* for evaluating safety performance of the railing. Next they evaluated the structural behavior of the railing and deck overhang in detail to determine behavior of the GFRP reinforcement.

CHAPTER 2. PROJECT APPROACH

TEST FACILITY

The test facilities at the Texas Transportation Institute's Proving Ground consist of an 2,000 acre (809-hectare) complex of research and training facilities situated 10 miles (16 km) northwest of the main campus of Texas A&M University. The site, formerly an air force base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and safety evaluation of roadside safety hardware. The site selected for construction of the TxDOT T202 (MOD) bridge rail with GFRP is along a wide out-of-service apron/runway. The apron/runway consists of an unreinforced jointed concrete pavement in 12.5 ft by 15.0 ft (3.8 m by 4.6 m) blocks nominally 8 to 12 inches (203 to 305 mm) deep. The aprons and runways are about 50 years old, and the joints have some displacement, but are otherwise flat and level.

TEST ARTICLE

The bridge deck cantilever constructed for this project was 2 ft-4 3/8 inches (721 mm) in width and 8 inches (203 mm) thick. The bridge deck was constructed immediately adjacent to an existing concrete runway located at the TTI test facility. The concrete deck was anchored into the existing runway with #5 (#16) steel reinforcement in the bottom layer in the deck overhang. The transverse reinforcement in the top and bottom layers of reinforcing in the deck cantilever consisted of #6 (#19) GFRP bars spaced 5½ inches (140 mm) apart. The longitudinal reinforcement in the top of the deck cantilever consisted of #5 (#16) GFRP bars spaced 9 inches (229 mm) apart. The longitudinal reinforcement in the bottom of the deck consisted of two #5 (#16) bars on the field side of the deck spaced 3 inches (75 mm) apart with the next adjacent #5 (#16) bar spaced 12 inches (305 mm) toward the traffic face. Transit Mix Concrete and Materials, Bryan, Texas, provided the concrete used for this project. TxDOT Class "S" concrete was used to construct the deck cantilever. The average compressive strength of the Class "S" concrete exceeded the required strength of 4000 psi (28 MPa) at the time the test was performed.

The T202 (MOD) bridge rail consists of a 1 ft-1½ inches × 1 ft-2 inches (343 mm × 356 mm) concrete bridge rail supported by 7½ inches × 5 ft-0 inch (191 mm × 1524 mm) concrete posts spaced 5 ft-0 inch (1524 mm) apart. The total height of the T202 (MOD) bridge rail was 2 ft-3 inches (686 mm). Researchers constructed two separate designs within this test installation. The details of the reduced strength design ($C_E = 1.0$) are reported herein. For details of both designs, please refer to the drawings shown as [Figure B-1](#) in this report. For the reduced strength design, vertical reinforcement in each post consisted of 13 #6 (#19) "L" shaped GFRP bars equally spaced on the front face (traffic side) and nine straight #5 (#16) GFRP bars equally spaced on the back face (field side). Longitudinal reinforcement in each post consisted of a #4 (#13) GFRP bar located on the front and back faces. Reinforcement in the rail consisted of four longitudinal #4 GFRP bars equally spaced on both the front and back faces of the rail

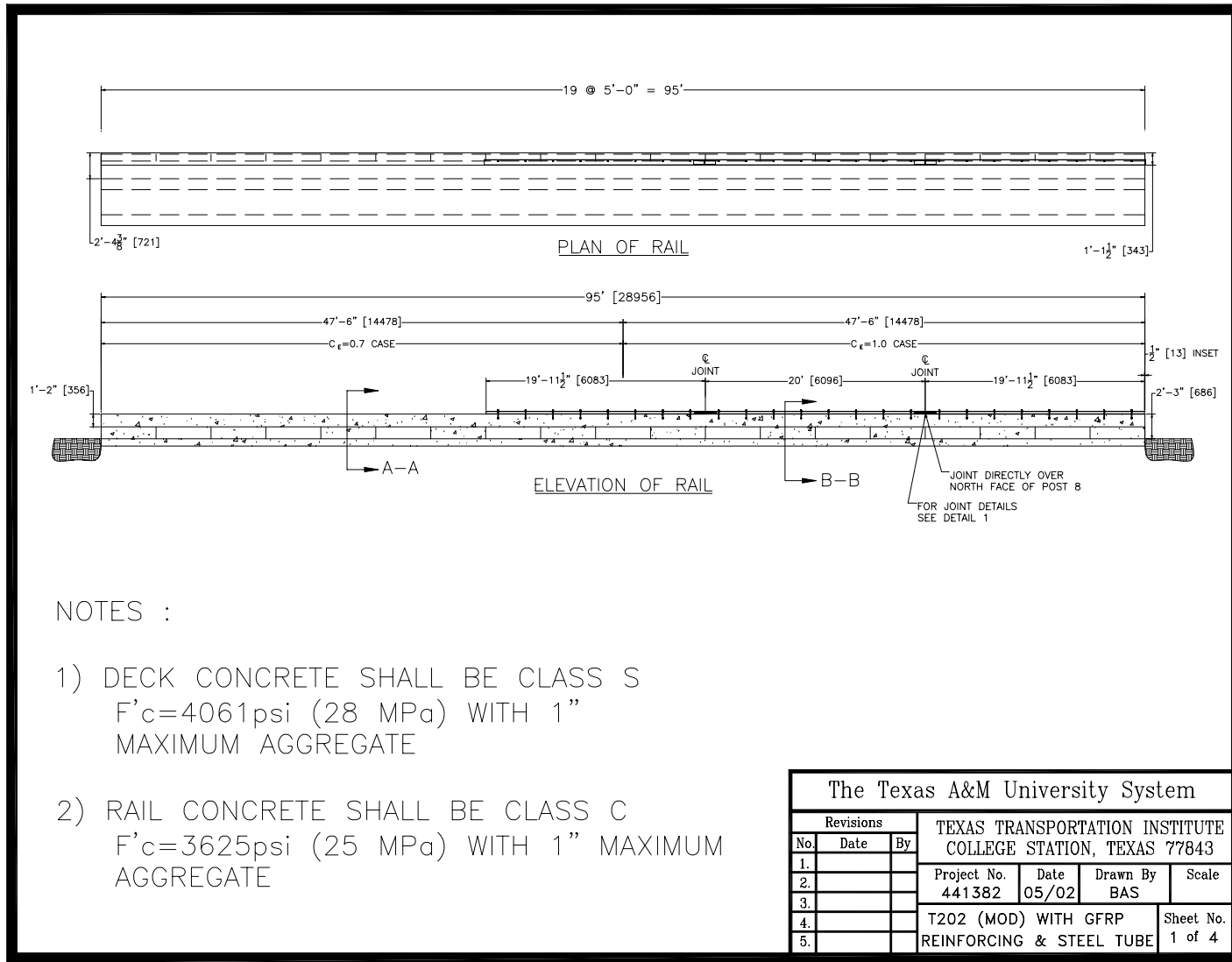


Figure B-1. Details of the TxDOT T202 (MOD) Bridge Rail with GFRP and Metal Rail.

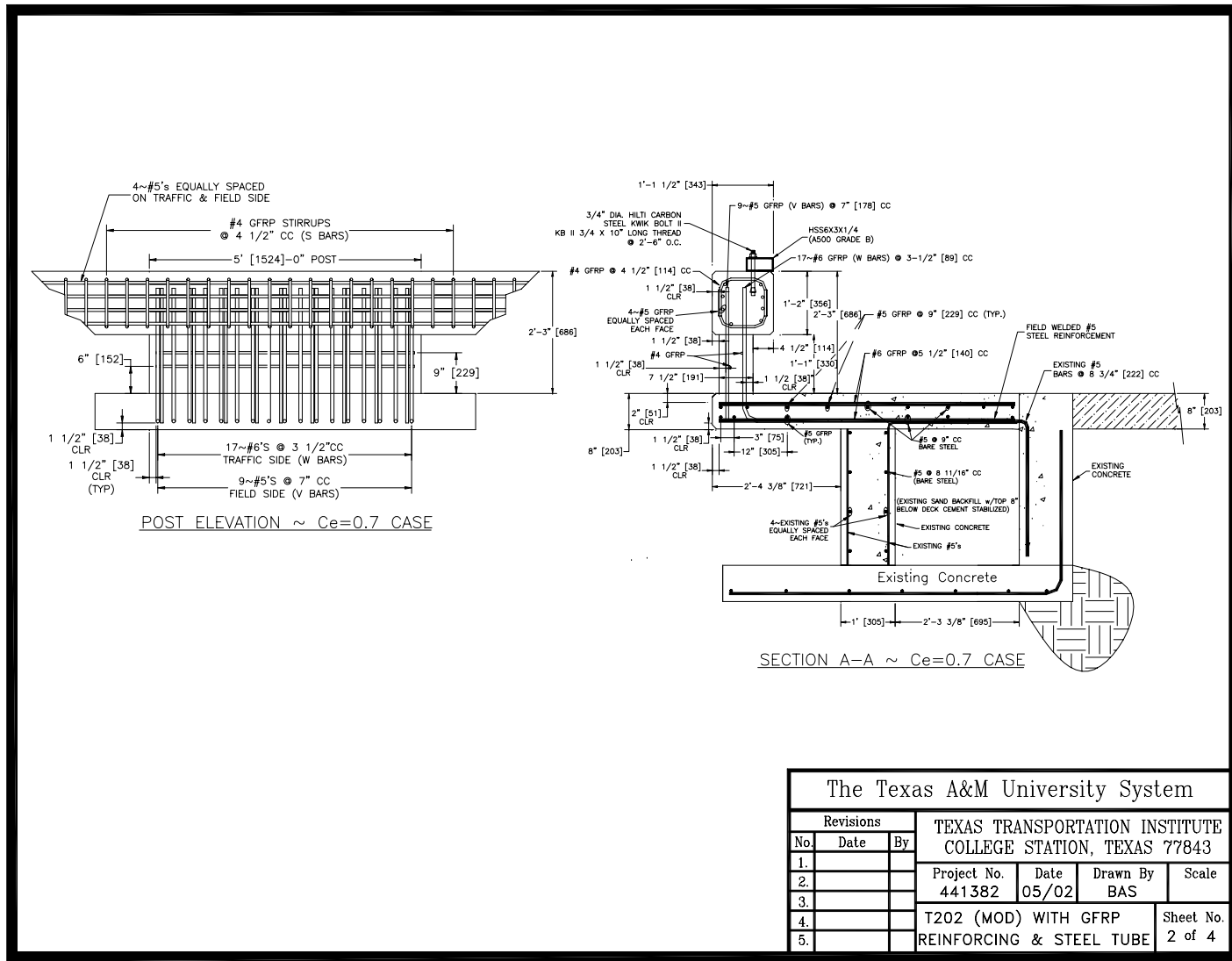


Figure B-1. Details of the TxDOT T202 (MOD) Bridge Rail with GFRP and Metal Rail (Continued).

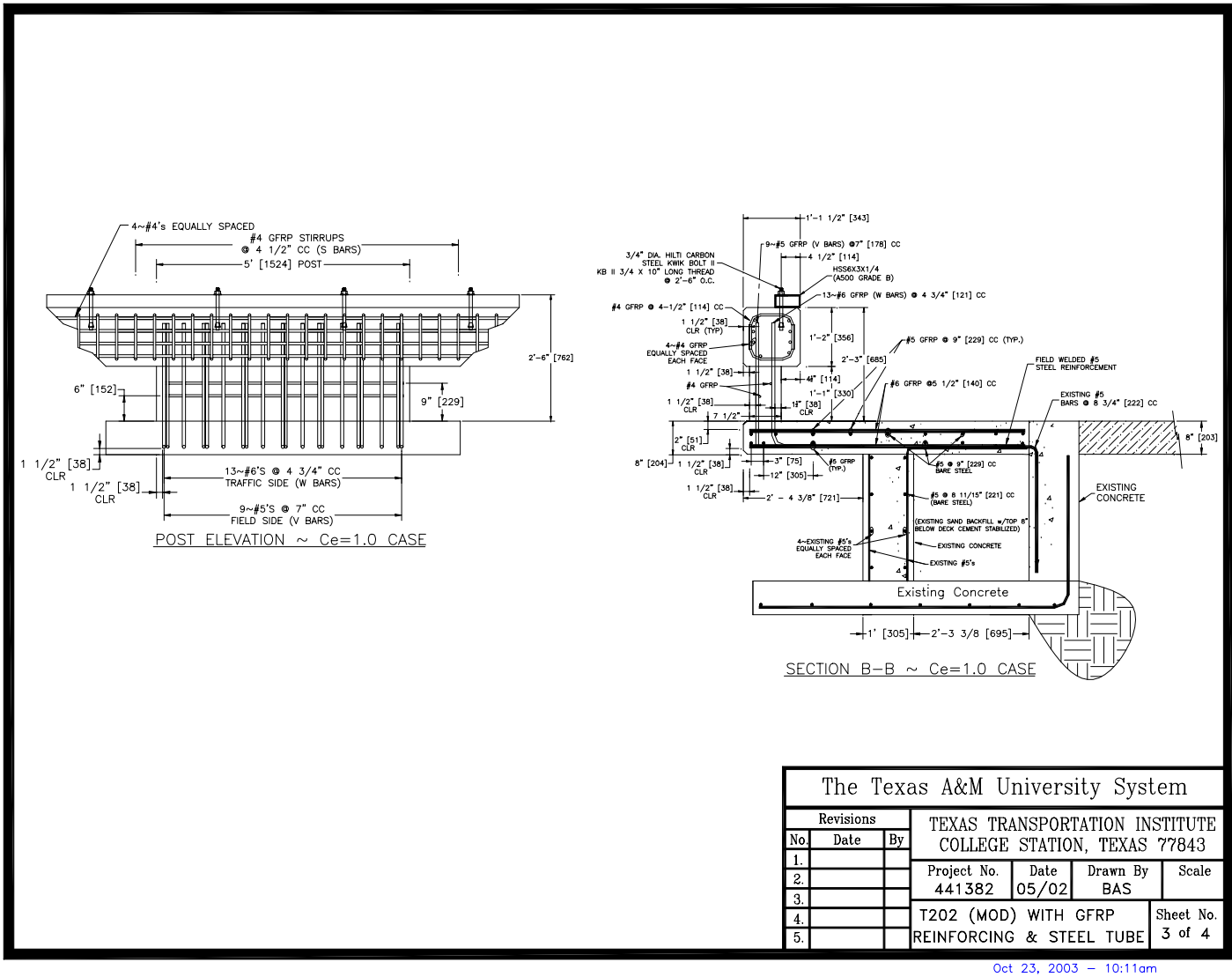


Figure B-1. Details of the TxDOT T202 (MOD) Bridge Rail with GFRP and Metal Rail (Continued).

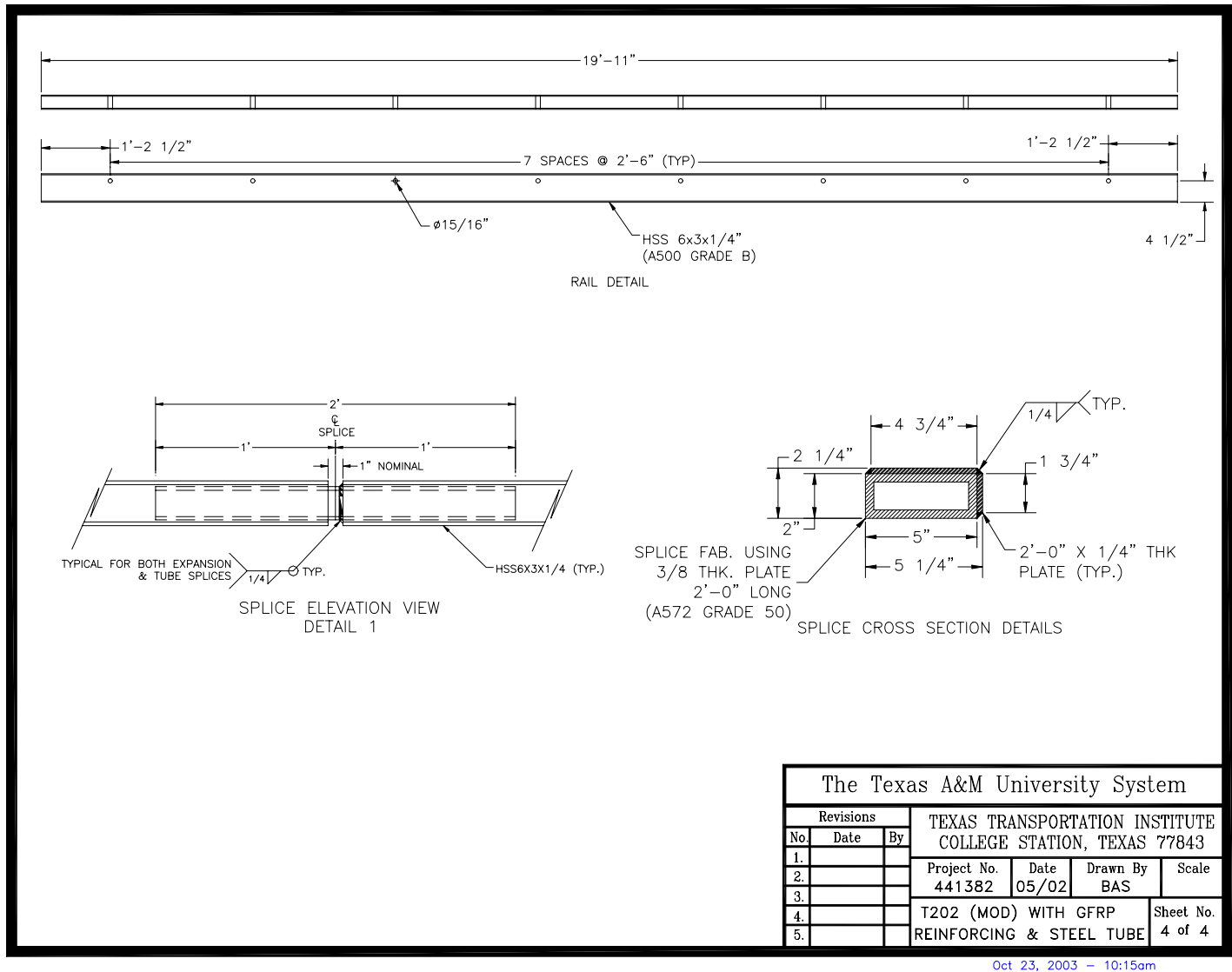


Figure B-1. Details of the TxDOT T202 (MOD) Bridge Rail with GFRP and Metal Rail (Continued).

(eight total). This longitudinal reinforcement was enclosed by #4 (#13) GFRP stirrups spaced 4½ inches (114 mm) apart. Researchers constructed each stirrup using two “U” shaped bars that were lapped together on the vertical faces of the rail. Hughes Brothers in Seward, Nebraska, provided all the GFRP reinforcement used for this project. TxDOT Class “C” concrete was used to construct the bridge rail. The average compressive strength of the Class “C” concrete exceeded the required strength of 3600 psi (25 MPa) at the time the test was performed.

In an effort to enhance vehicle performance, the height of the rail was increased to 30 inches (762 mm). This modification was achieved by attaching a TS6×3×¼ (TS 152 mm × 76 mm × 6 mm) steel tube to the top of the concrete rail and flush with the traffic face of the rail. The steel tube was anchored to the top of the concrete rail using ¾-inch (19 mm) diameter Hilti Kwik Bolt II anchor bolts spaced 2 ft-6 inches (0.76 m) apart. Please refer to [Figure B-1](#) for additional details. [Figure B-2](#) shows photographs of the completed installation.

CRASH TEST CONDITIONS

NCHRP Report 350 recommends two tests for Test Level 3 evaluation of longitudinal barriers, such as the T202 (MOD) with GFRP reinforcement:

NCHRP Report 350 test designation 3-10: This test involves an 1806-lb (820 kg) passenger car impacting the critical impact point (CIP) in the length of need (LON) of the longitudinal barrier at a nominal speed and angle of 62 mi/h (100 km/h) and 20 degrees. The purpose of this test is to evaluate the overall performance of the LON section in general and occupant risks in particular.

NCHRP Report 350 test designation 3-11: This test involves a 4405-lb (2000 kg) pickup truck impacting the CIP in the LON of the longitudinal barrier at a nominal speed and angle of 62 mi/h (100 km/h) and 25 degrees. The test is intended to evaluate the strength of the section for containing and redirecting the pickup truck.

This report documents the results of test 441382-2, which corresponds to *NCHRP Report 350* test designation 3-11.

The crash test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. [Appendix C](#) presents brief descriptions of these procedures.

EVALUATION CRITERIA

The crash test performed was evaluated in accordance with *NCHRP Report 350*. As stated in *NCHRP Report 350*, “Safety performance of a highway appurtenance cannot be measured directly but can be judged on the basis of three factors: structural adequacy, occupant risk, and vehicle trajectory after collision.” Accordingly, researchers used the safety evaluation criteria from Table 5.1 of *NCHRP Report 350* to evaluate the crash test reported herein.



Figure B-2. Test Article/Installation before Test 441382-2

CHAPTER 3. CRASH TEST RESULTS

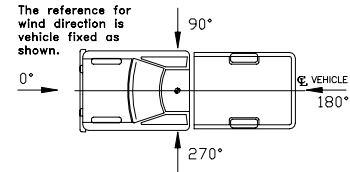
TEST NO. 441382-2 (NCHRP Report 350 TEST NO. 3-11)

Test Vehicle

Figures B-3 and B-4 show the 1997 Chevrolet 2500 pickup truck used for the crash test. Test inertia mass of the vehicle was 4502 lb (2044 kg), and its gross static mass was 4502 lb (2044 kg). The height to the lower edge of the vehicle bumper was 17.3 inches (440 mm), and it was 25.9 inches (660 mm) to the upper edge of the bumper. Figure B-5 shows additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

Weather Conditions

Researchers performed the test on the morning of June 14, 2002. Weather conditions at the time of testing were as follows: Wind speed: 10 mi/h (16 km/h); Wind direction: 180 degrees with respect to the vehicle (vehicle was traveling in a southwesterly direction); Temperature: 84 °F (29 °C); Relative humidity: 63 percent.



Test Description

The 4502-lb (2044 kg) pickup truck traveling at 62.6 mi/h (100.7 km/h) impacted the TxDOT T202 (MOD) bridge rail with GFRP 54.7 inches (1390 mm) upstream of leading edge of post 3 at an impact angle of 25.0 degrees. At approximately 0.051 s after impact, the passenger's side door (impact side) opened slightly, and at 0.055 s the vehicle began to redirect. The left front tire lost contact with the ground at 0.116 s. At 0.212 s the vehicle became parallel with the bridge rail and was traveling at a speed of 48.3 mi/h (77.7 km/h). The vehicle lost contact with the bridge rail at 0.594 s while traveling at a speed of 41.6 mi/h (66.9 km/h) and an exit angle of 14.2 degrees. Brakes on the vehicle were applied at 1.8 s after impact. The vehicle subsequently came to rest upright, 187.7 ft (57.2 m) downstream of impact and 15.7 ft (4.8 m) forward of the traffic face of the rail. Figures B-6 and B-7 show sequential photographs of the test period.



Figure B-3. Vehicle/Installation Geometrics for Test 441382-2.



Figure B-4. Vehicle before Test 441382-2.

DATE: 06/14/02 TEST NO.: 441382-2 VIN NO.: 1GCGC24R1VZ159705
 YEAR: 1997 MAKE: Chevrolet MODEL: 2500 Pickup
 TIRE INFLATION PRESSURE: _____ ODOMETER: 166209 TIRE SIZE: LT245 75R16

MASS DISTRIBUTION (kg) LF 578 RF 574 LR 434 RR 458

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:

● Denotes accelerometer location.
 NOTES: _____

ENGINE TYPE: 8 CYL
 ENGINE CID: 5.7 L
 TRANSMISSION TYPE:
 AUTO
 MANUAL

OPTIONAL EQUIPMENT:
8 LUGS

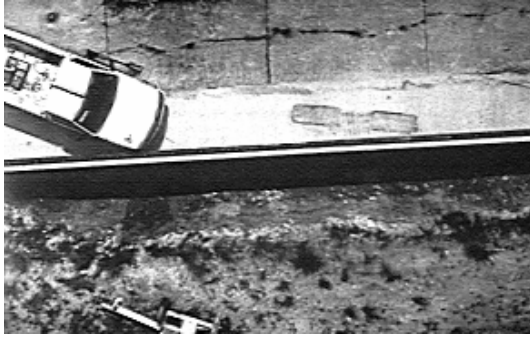
DUMMY DATA:
 TYPE: _____
 MASS: _____
 SEAT POSITION: _____

GEOMETRY - (mm)

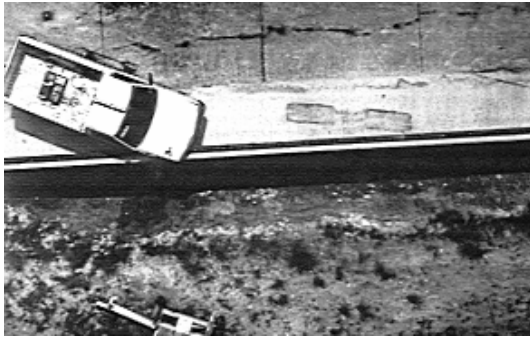
A	<u>1860</u>	E	<u>1330</u>	J	<u>1090</u>	N	<u>1600</u>	R	<u>740</u>
B	<u>870</u>	F	<u>5550</u>	K	<u>440</u>	O	<u>1620</u>	S	<u>910</u>
C	<u>3350</u>	G	<u>1461.9</u>	L	<u>70</u>	P	<u>730</u>	T	<u>1450</u>
D	<u>1845</u>	H	_____	M	<u>660</u>	Q	<u>445</u>	U	<u>3400</u>

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M ₁	<u>1242</u>	<u>1152</u>	_____
M ₂	<u>920</u>	<u>892</u>	_____
M _T	<u>2162</u>	<u>2044</u>	_____

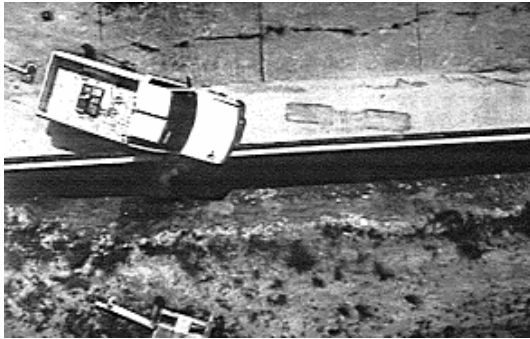
Figure B-5. Vehicle Properties for Test 441382-2.



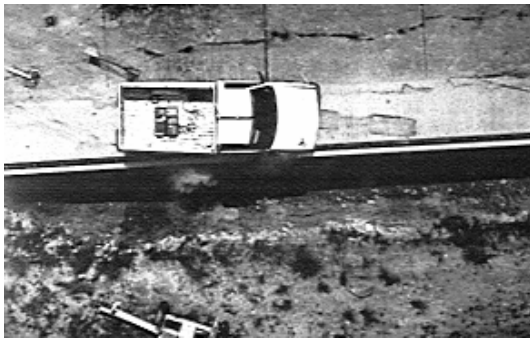
0.000 s



0.046 s



0.092 s



0.184 s



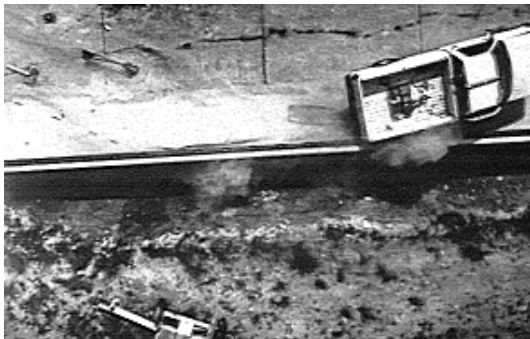
Figure B-6. Sequential Photographs for Test 441382-2 (Overhead and Frontal Views).



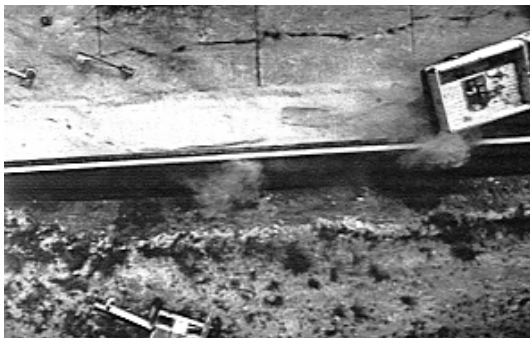
0.276 s



0.368 s



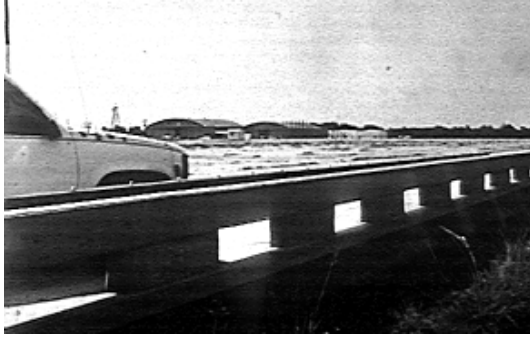
0.483 s



0.599 s



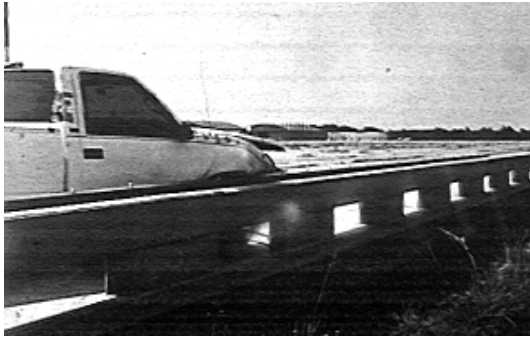
**Figure B-6. Sequential Photographs for Test 441382-2
(Overhead and Frontal Views) (Continued).**



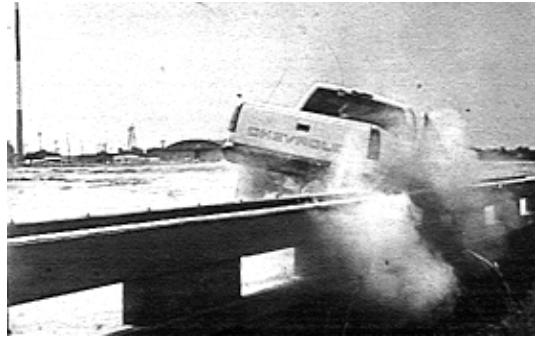
0.000 s



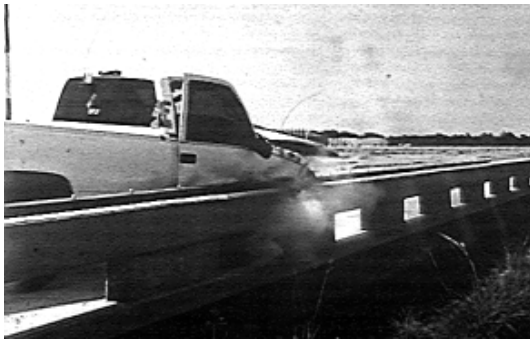
0.276 s



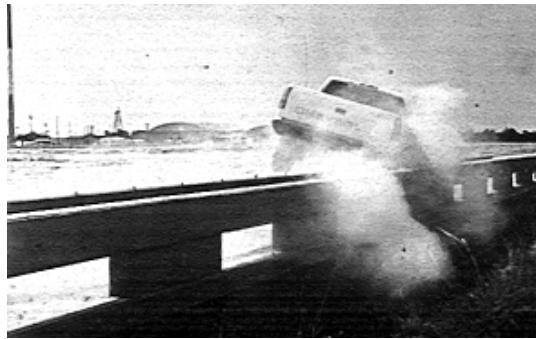
0.046 s



0.368 s



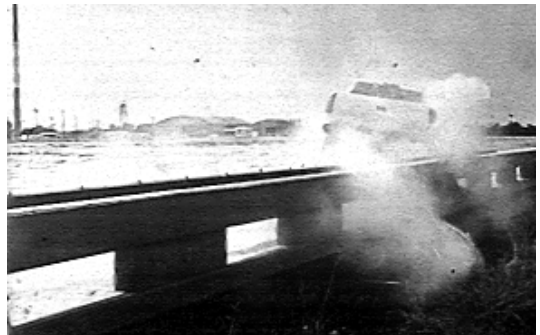
0.092 s



0.483 s



0.184 s



0.599 s

**Figure B-7. Sequential Photographs for Test 441382-2
(Rear View).**

Damage to Test Installation

Tire marks were located on the face of post 8 and small pieces of concrete were chipped out of the underside of lower edge of the beam rail between posts 8 and 9 where the vehicle's tire/wheel contacted it. The upper beam experienced hairline cracks 14.2 inches (360 mm) and 33.9 inches (860 mm) upstream of post 8. No cracks were evident in the deck. The vehicle was in contact with the bridge rail for a distance of 13.03 ft (3.97 m). Figures B-8 and B-9 show photographs of the damage to the bridge rail. There was no indication of significant structural damage to the rail or the deck. There was no indication that the GFRP exhibited any undesirable traits.

Vehicle Damage

Figure B-10 shows damage to the vehicle. Structural damage was imparted to the stabilizer bar, right upper and lower A-arms, right spindle, right rod ends, right front frame member, firewall, and floor pan. Also damaged were the front bumper, hood, radiator, fan, right front tire and wheel rim, right front quarter panel, right door, right rear exterior bed and right rear tire and wheel rim. The windshield sustained stress cracks. Maximum exterior crush to the exterior of the vehicle was 23.6 inches (600 mm) in the front plane at the right front corner near bumper height. Maximum occupant compartment deformation was 5.6 inches (143 mm) in the kick panel area on the passenger's side. Figure B-11 shows photographs of the interior of the vehicle. Tables B-1 and B-2 show exterior vehicle crush and occupant compartment measurements.

Occupant Risk Factors

Data from the tri-axial accelerometer, located at the vehicle center of gravity, were digitized to compute occupant impact velocity and ridedown accelerations. Only the longitudinal occupant impact velocity and ridedown accelerations are required for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 21.3 ft/s (6.5 m/s) at 0.099 s, maximum 0.010-s ridedown acceleration was -4.6 g's from 0.096 to 0.106 s, and the maximum 0.050-s average was -10.6 g's between 0.042 and 0.092 s. Figure B-12 presents data and other information pertinent to the test. Figures B-13 through B-19 show vehicle angular displacements and accelerations versus time traces.



Figure B-8. After Impact Trajectory for Test 441382-2.

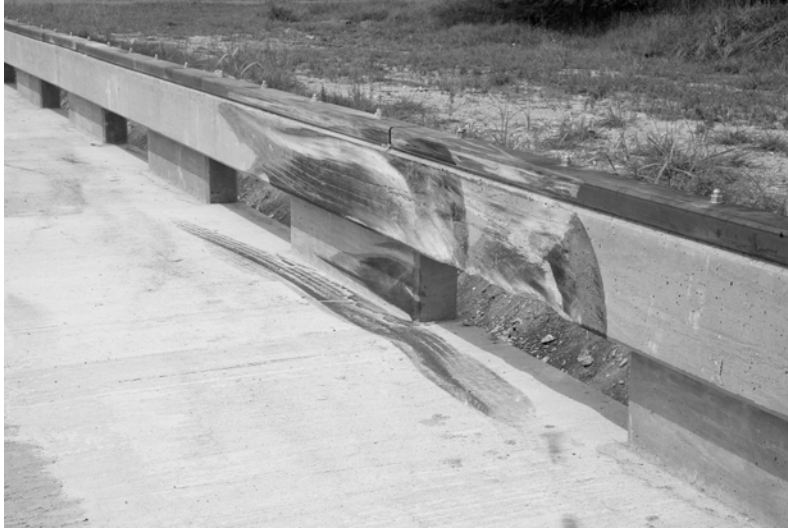


Figure B-9. Installation after Test 441382-2.



Figure B-10. Vehicle after Test 441382-2.



Before Test



After Test

Figure B-11. Interior of Vehicle for Test 441382-2.

Table B-1. Exterior Crush Measurements For Test 441382-2.

VEHICLE CRUSH MEASUREMENT SHEET¹

Complete When Applicable	
End Damage	Side Damage
Undeformed end width _____ Corner shift: A1 _____ A2 _____ End shift at frame (CDC) (check one) < 4 inches _____ ≥ 4 inches _____	Bowing: B1 _____ X1 _____ B2 _____ X2 _____ Bowing constant $\frac{X1 + X2}{2} = \underline{\hspace{2cm}}$

Note: Measure C₁ to C₆ from Driver to Passenger side in Front or Rear impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C ₁	C ₂	C ₃	C ₄	C ₅	C ₆	±D
		Width** (CDC)	Max*** Crush								
1	Front bumper	1000	-600	1560	+80	+20	-20	-130	-360	-600	0
2	770 mm above ground	1000	520	2440	0	90	200	290	Wheel Well	0	+980

¹Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

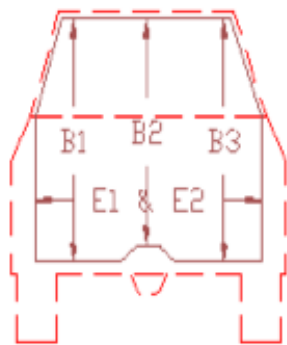
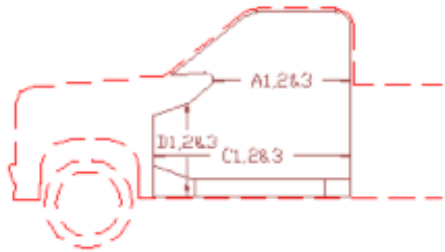
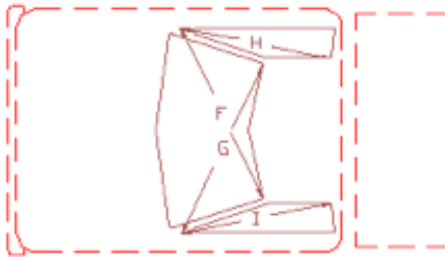
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

***Measure and document on the vehicle diagram the location of the maximum crush.

Note: Use as many lines/columns as necessary to describe each damage profile.

Table B-2. Occupant Compartment Measurements For Test 441382-2.

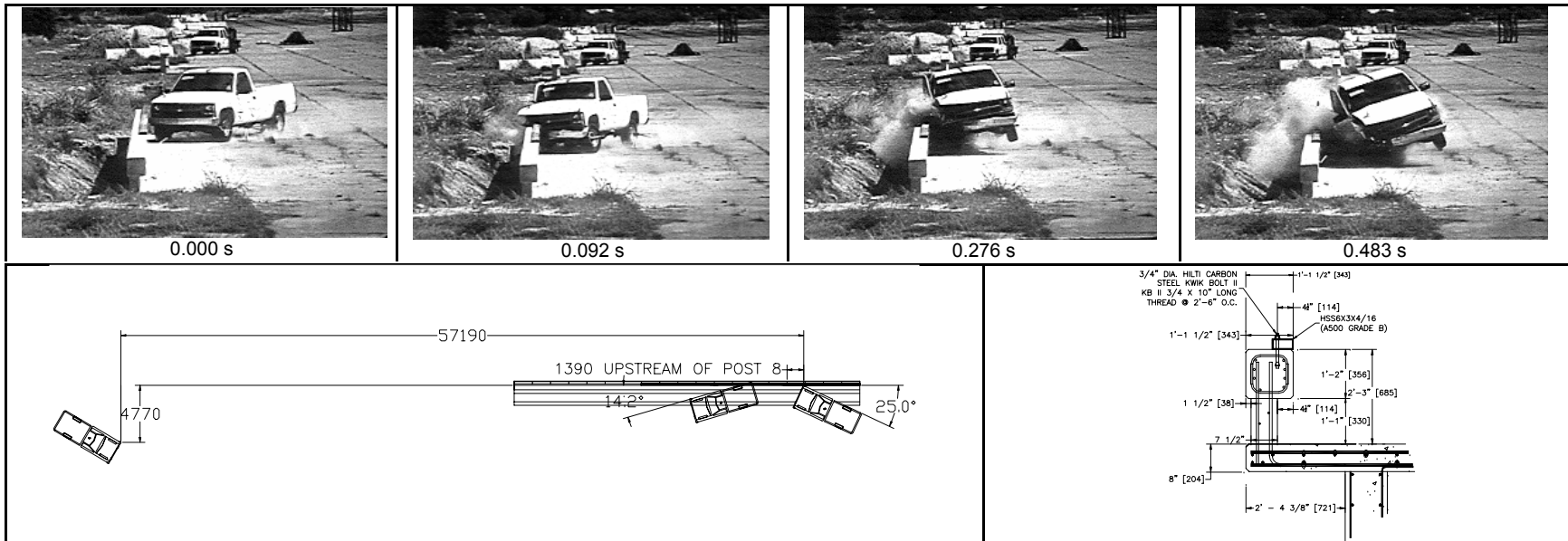
Occupant Compartment Deformation



	BEFORE (mm)	AFTER (mm)
A1	870	880
A2	930	926
A3	910	895
B1	1075	1065
B2	1030	958
B3	1070	1155
C1	1375	1375
C2	535	510
C3	1368	1315
D1	320	333
D2	161	145
D3	315	412
E1	1582	1587
E2	1592	1635
F	1460	1455
G	1460	1455
H	900	885
I	900	900
J*	1523	1380

*J = measurement laterally across occupant compartment from kickpanel to kickpanel.

Truck



B-27

General Information

Test Agency Texas Transportation Institute
 Test No. 441382-2
 Date 06/14/02

Test Article

Type Bridge Rail
 Name T202 (MOD) Bridge Rail With GFRP and Metal Rail
 Installation Length (ft) 95 (29.0 m)
 Material or Key Elements T202(MOD) Concrete Bridge Rail With GFRP Reinforcement And Metal Rail
 Soil Type and Condition Concrete Footing

Test Vehicle

Type Production
 Designation 2000P
 Model 1997 Chevrolet 2500 Pickup
 Mass (lbs)
 Curb 4761 (2162 kg)
 Test Inertial 4501 (2044 kg)
 Dummy N/A
 Gross Static 4501 (2044 kg)

Impact Conditions

Speed (mi/h) 62.6 (100.7 km/h)
 Angle (deg) 25.0

Exit Conditions

Speed (mi/h) 41.6 (66.9 km/h)
 Angle (deg) 14.2

Occupant Risk Values

Impact Velocity (ft/s)
 x-direction 21.3 (6.5 m/s)
 y-direction 23.9 (7.3 m/s)
 THIV (mi/h) 21.5 (34.6 km/h)
 Ridedown Accelerations (g's)
 x-direction -4.6
 y-direction -7.0
 PHD (g's) 7.5
 ASI 1.62
 Max. 0.050-s Average (g's)
 x-direction -10.6
 y-direction -11.8
 z-direction -4.0

Test Article Deflections (ft)

Dynamic None
 Permanent None
 Working Width 1.61 (0.49 m)

Vehicle Damage

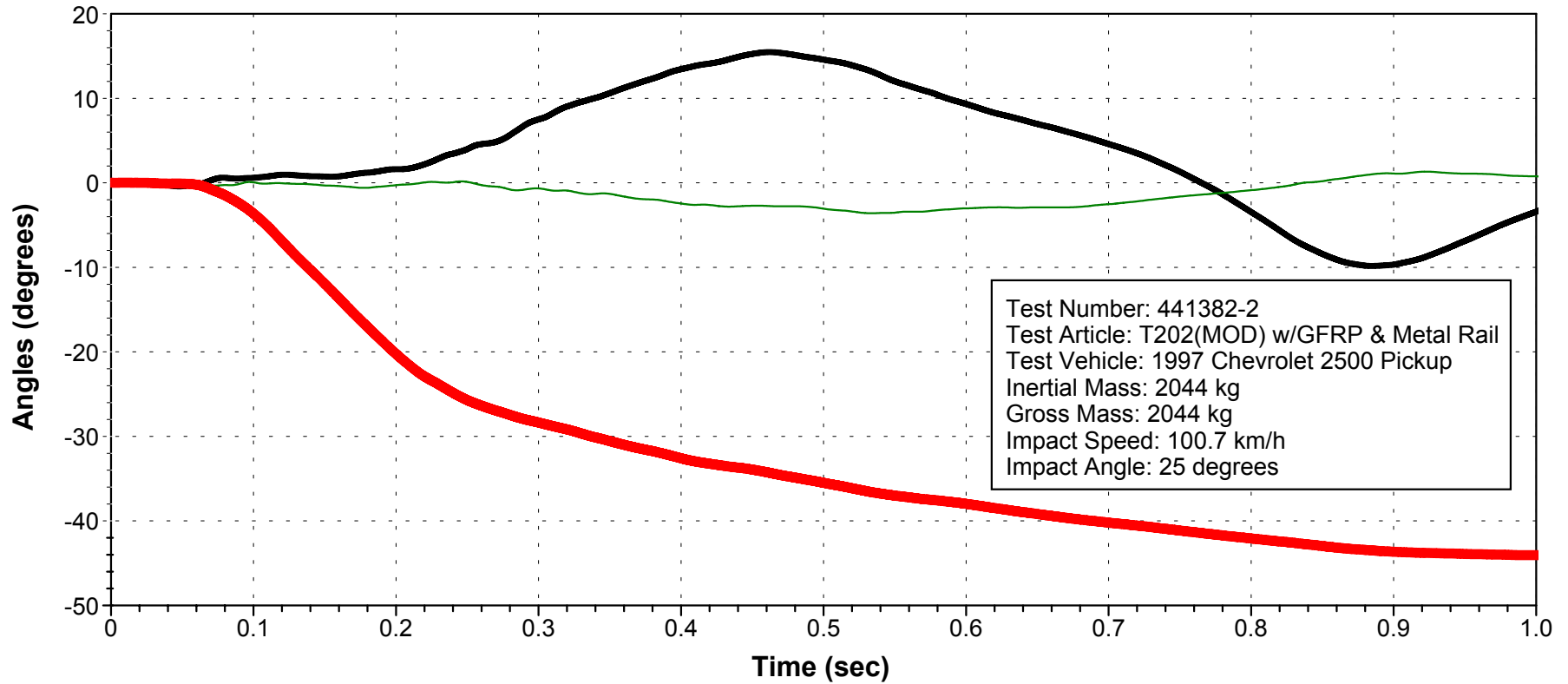
Exterior
 VDS 01FR3
 CDC 01FREW3
 Maximum Exterior
 Vehicle Crush (inch) 5.6 (143 mm)
 Interior
 OCDI RF0111000
 Max. Occ. Compart.
 Deformation (inch) 23.4 (600 mm)

Post-Impact Behavior

(during 1.0 s after impact)
 Max. Yaw Angle (deg) -44.1
 Max. Pitch Angle (deg) -3.6
 Max. Roll Angle (deg) 15.4

Figure B-12. Summary of Results for Test 441382-2, NCHRP Report 350 Test 3-11.

Roll, Pitch and Yaw Angles



Test Number: 441382-2
Test Article: T202(MOD) w/GFRP & Metal Rail
Test Vehicle: 1997 Chevrolet 2500 Pickup
Inertial Mass: 2044 kg
Gross Mass: 2044 kg
Impact Speed: 100.7 km/h
Impact Angle: 25 degrees

— Roll — Pitch — Yaw

Axes are vehicle-fixed.
Sequence for determining orientation:

- 4. Yaw.
- 5. Pitch.
- 6. Roll.

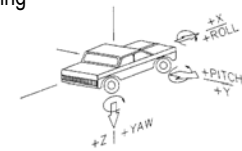


Figure B-13. Vehicular Angular Displacements for Test 441382-2.

B-29

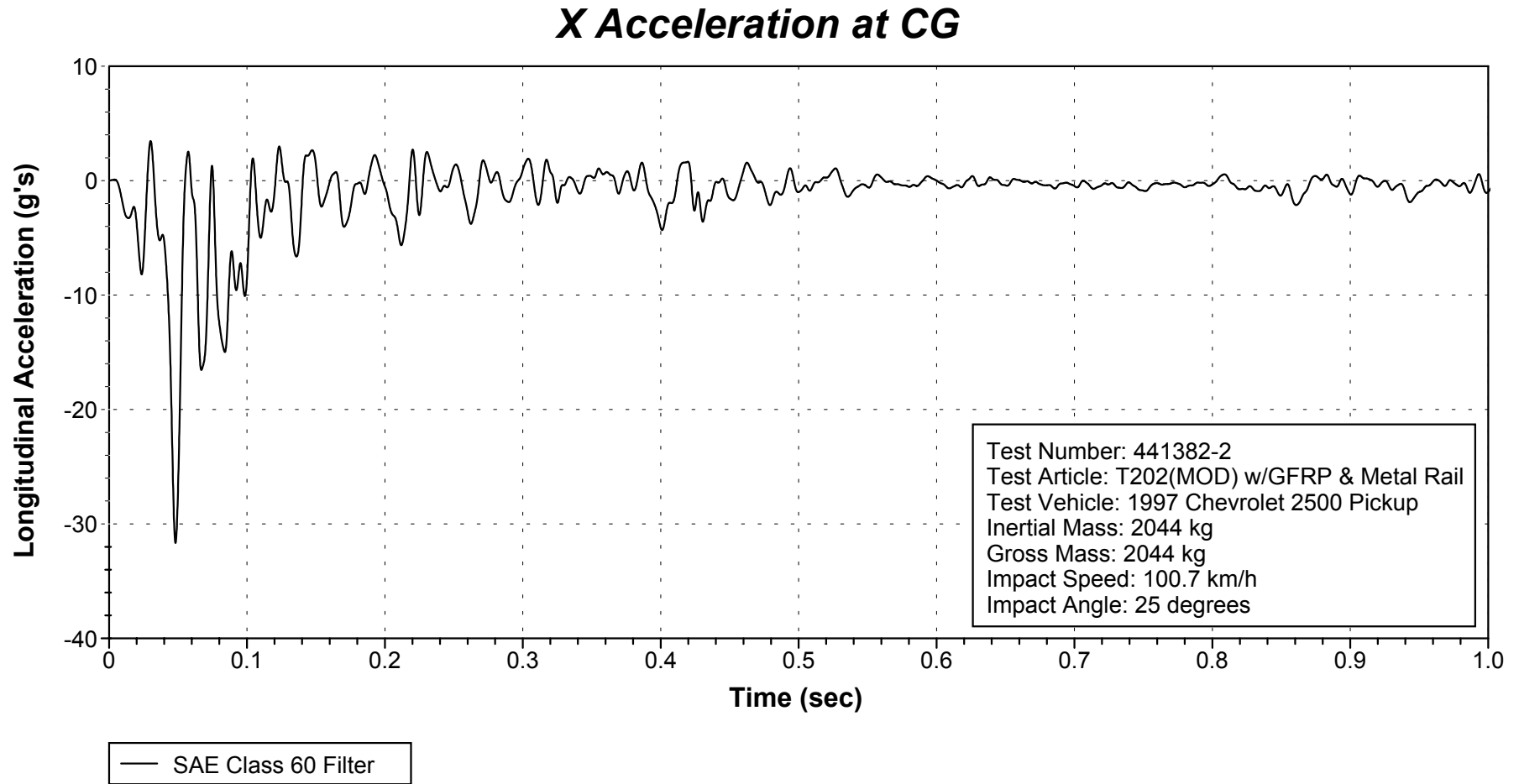
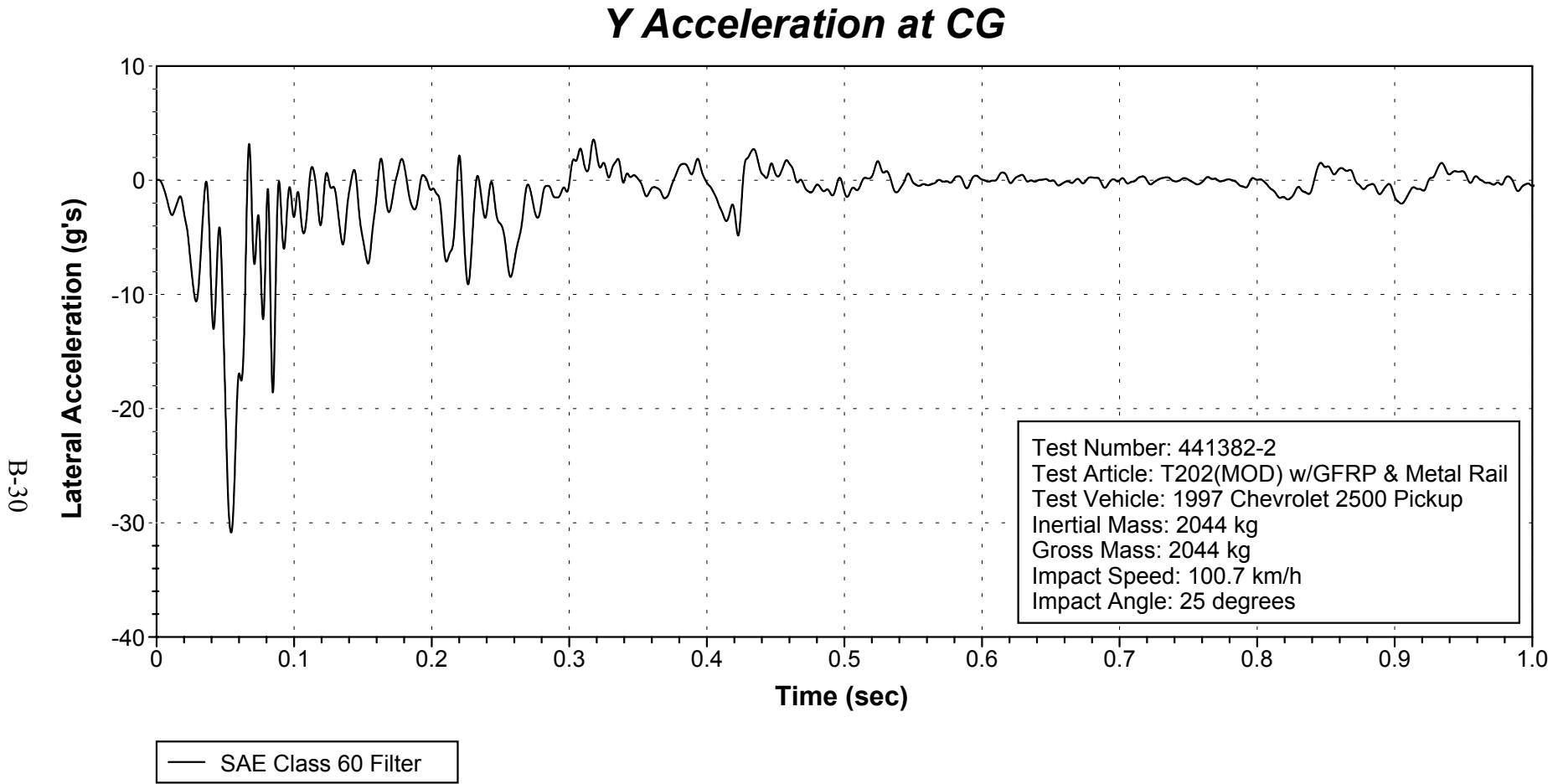
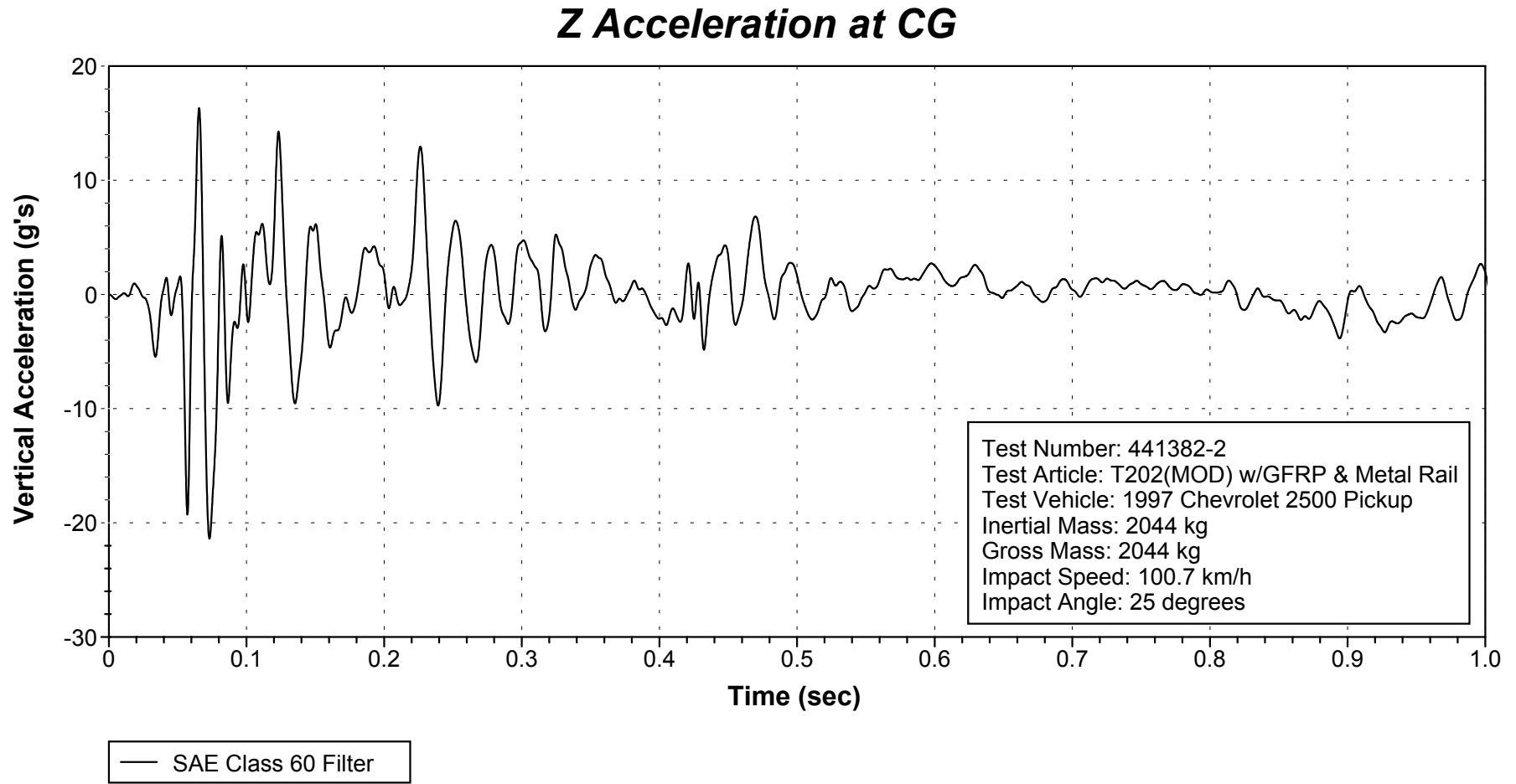


Figure B-14. Vehicle Longitudinal Accelerometer Trace for Test 441382-2 (Accelerometer Located at Center of Gravity).

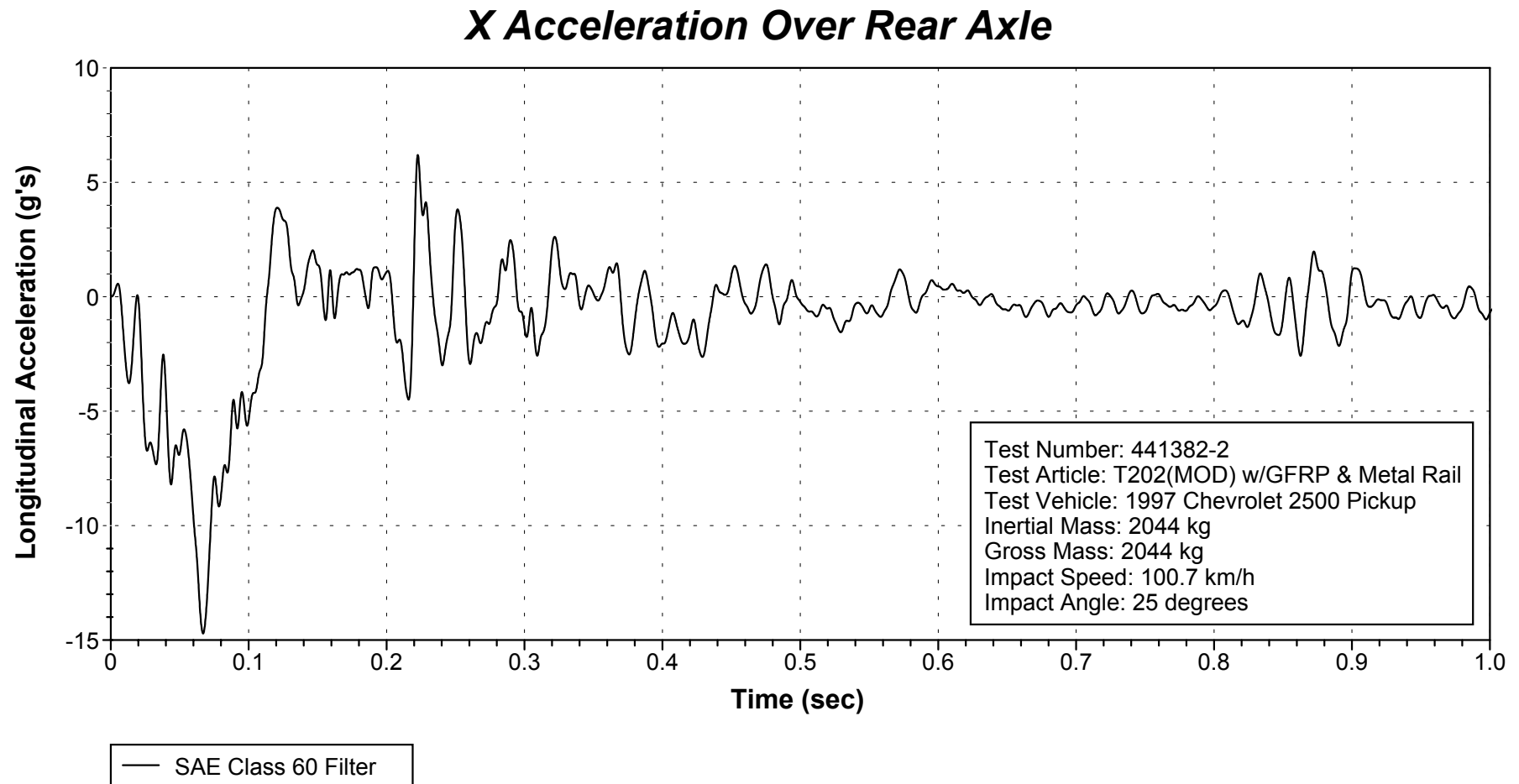


**Figure B-15. Vehicle Lateral Accelerometer Trace for Test 441382-2
(Accelerometer Located at Center of Gravity).**

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**Figure B-16. Vehicle Vertical Accelerometer Trace for Test 441382-2
(Accelerometer Located at Center of Gravity).**



**Figure B-17. Vehicle Longitudinal Accelerometer Trace for Test 441382-2
(Accelerometer Located over Rear Axle).**

Y Acceleration Over Rear Axle

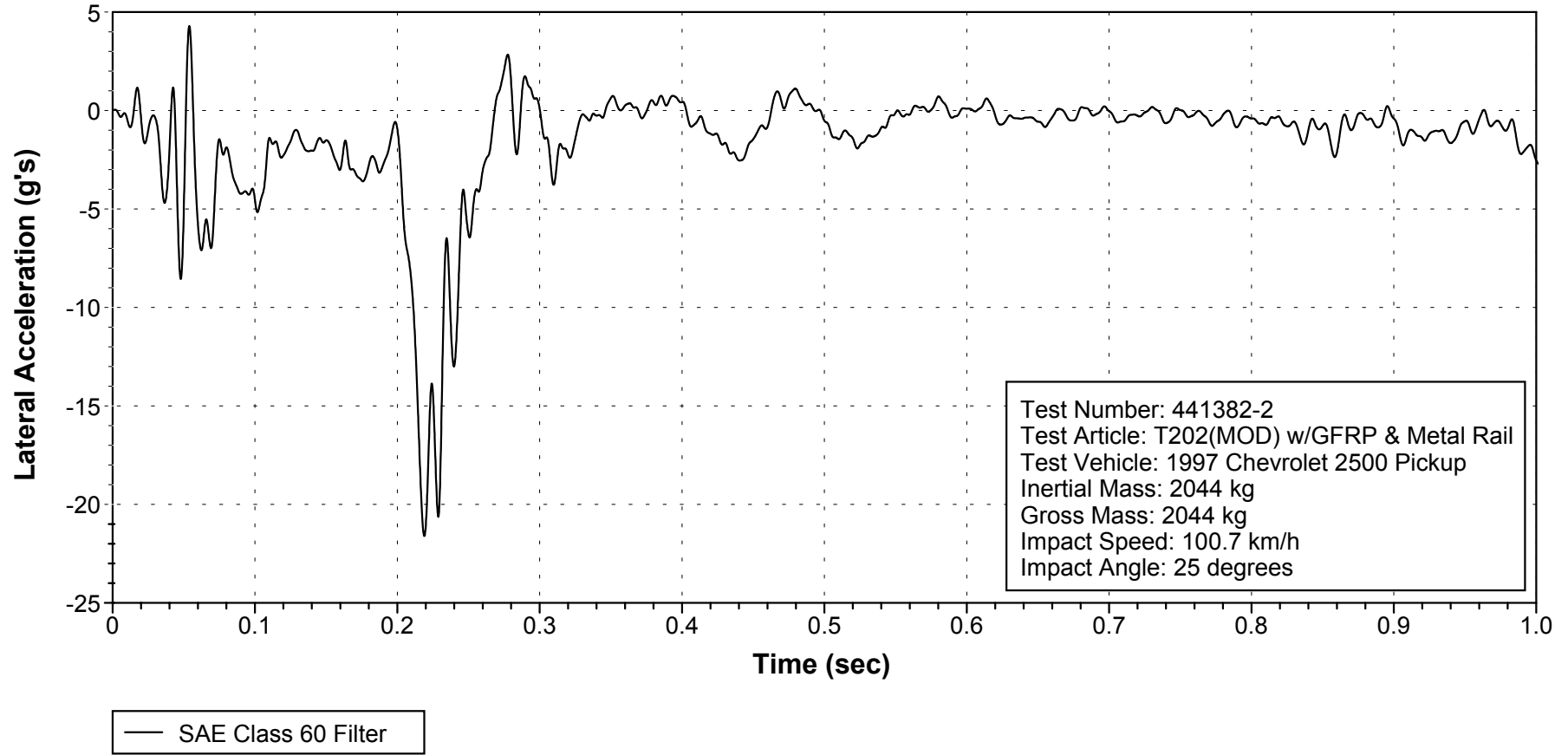
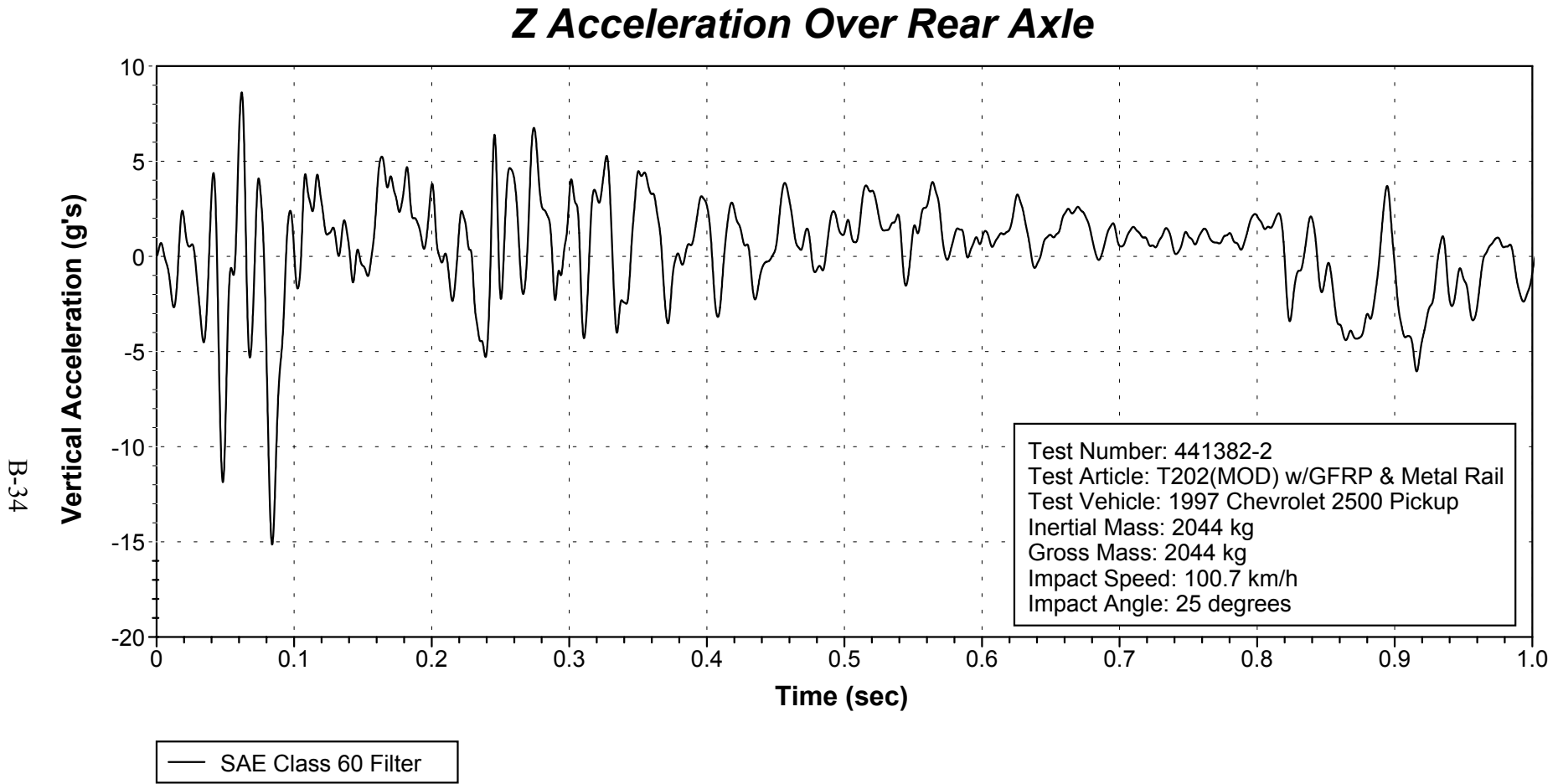


Figure B-18. Vehicle Lateral Accelerometer Trace for Test 441382-2 (Accelerometer Located over Rear Axle).



**Figure B-19. Vehicle Vertical Accelerometer Trace for Test 441382-2
(Accelerometer Located over Rear Axle).**

CHAPTER 4. SUMMARY AND CONCLUSIONS

ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *NCHRP Report 350* safety evaluation criteria (4) is provided below.

Structural Adequacy

B. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.

Results: The TxDOT T202 (MOD) with GFRP reinforcement and metal rail on top contained and redirected the 4502-lb (2044 kg) pickup truck. The vehicle did not penetrate, underride, or override the bridge rail. No measurable deflection was noted.

Occupant Risk

E. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.

Results: No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 5.6 inches (143 mm) in the floor pan to instrument panel on the right side near the driver's feet.

G. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.

Results: The 4502-lb (2044 kg) pickup truck remained upright during and after exiting the installation.

Vehicle Trajectory

K. After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.

Results: The vehicle subsequently came to rest upright, 187.7 ft (57.2 m) downstream of impact and 15.7 ft (4.8 m) forward of the traffic face of the rail.

L. *The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.*

Results: Longitudinal occupant impact velocity was 21.3 ft/s (6.5 m/s) and longitudinal occupant ridedown acceleration was -4.6 g's.

M. *The exit angle from the test article preferably should be less than 60 percent of the test impact angle, measured at time of vehicle loss of contact with the test device.*

Results: Exit angle at loss of contact was 14.2 degrees, which was 57 percent of the impact angle.

The following supplemental evaluation factors and terminology, as presented in the FHWA memo entitled "Action: Identifying Acceptable Highway Safety Features," were used for visual assessment of test results (20):

Passenger Compartment Intrusion

1. *Windshield Intrusion*

- | | |
|---|---|
| a. <i>No windshield contact (stress cracks)</i> | e. <i>Complete intrusion into passenger compartment</i> |
| b. <i>Windshield contact, no damage</i> | f. <i>Partial intrusion into passenger compartment</i> |
| c. <i>Windshield contact, no intrusion</i> | |
| d. <i>Device embedded in windshield, no significant intrusion</i> | |

2. *Body Panel Intrusion*

yes or no

Loss of Vehicle Control

- | | |
|---|--|
| 1. <i>Physical loss of control</i> | 3. <i>Perceived threat to other vehicles</i> |
| 2. <i>Loss of windshield visibility</i> | 4. <i>Debris on pavement</i> |

Physical Threat to Workers or Other Vehicles

1. *Harmful debris that could injure workers or others in the area*
 2. *Harmful debris that could injure occupants in other vehicles*
- No debris was present.

Vehicle and Device Condition

- | | |
|--|--|
| 1. <i>Vehicle Damage</i> | |
| a. <i>None</i> | d. <i>Major dents to grill and body panels</i> |
| b. <i>Minor scrapes, scratches, or dents</i> | e. <u><i>Major structural damage</i></u> |
| c. <i>Significant cosmetic dents</i> | |

2. *Windshield Damage*
 - a. *None*
 - b. *Minor chip or crack*
 - c. *Broken, no interference with visibility*
 - d. *Broken or shattered, visibility restricted but remained intact*
 - e. *Shattered, remained intact but partially dislodged*
 - f. *Large portion removed*
 - g. *Completely removed*
3. *Device Damage*
 - a. *None*
 - b. *Superficial*
 - c. *Substantial, but can be straightened*
 - d. *Substantial, replacement parts needed for repair*
 - e. *Cannot be repaired*

CONCLUSIONS

The TxDOT T202 (MOD) bridge rail with GFRP reinforcement and metal rail on top contained and redirected the 4502-lb (2044 kg) pickup truck. The vehicle did not penetrate, underride, or override the bridge rail. No measurable deflection was noted. No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 5.6 inches (143 mm) in the kickpanel area on the passenger's side. The 4502-lb (2044 kg) pickup truck remained upright during and after exiting the installation. The vehicle subsequently came to rest upright, 187.7 ft (57.2 m) downstream of impact and 15.7 ft (4.8 m) forward of the traffic face of the rail. Longitudinal occupant impact velocity was 21.3 ft/s (6.5 m/s), and longitudinal occupant ridedown acceleration was -4.6 g's. Exit angle at loss of contact was 14.2 degrees, which was 57 percent of the impact angle.

As seen in [Table B-3](#), the TxDOT T202 (MOD) bridge rail with GFRP reinforcement with metal rail on top passed the required specifications for occupant risk during *NCHRP Report 350* Test 3-11. No significant structural damage occurred to the rail or the deck. There was no indication that the GFRP exhibited any undesirable traits.

IMPLEMENTATION STATEMENT

No implementation is indicated at this time.

Table B-3. Performance Evaluation Summary for Test 441382-2, NCHRP Report 350 Test 3-11.

Test Agency: Texas Transportation Institute		Test No.: 441382-2	Test Date: 06/14/2002
NCHRP Report 350 Test 3-11 Evaluation Criteria		Test Results	Assessment
Structural Adequacy			
A.	<i>Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</i>	The TxDOT T202 (MOD) with GFRP reinforcement and metal rail on top contained and redirected the 4502-lb (2044 kg) pickup truck. The vehicle did not penetrate, underride, or override the bridge rail. No measurable deflection was noted.	Pass
Occupant Risk			
D.	<i>Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.</i>	No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 5.6 inches (143 mm) in the kickpanel area on the passenger's side.	Pass
F.	<i>The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.</i>	The 4502-lb (2044 kg) pickup truck remained upright during and after exiting the installation.	Pass
Vehicle Trajectory			
K.	<i>After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i>	The vehicle came to rest upright, 187.7 ft (57.2 m) downstream of impact and 15.7 ft (4.8 m) forward of the traffic face of the rail.	Fail*
L.	<i>The occupant impact velocity in the longitudinal direction should not exceed 12 m/s, and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 g's.</i>	Longitudinal occupant impact velocity was 21.3 ft/s (6.5 m/s), and longitudinal occupant ridedown acceleration was -4.6 g's.	Pass
M.	<i>The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.</i>	Exit angle at loss of contact was 14.2 degrees, which was 57 percent of the impact angle.	Pass*

*Criteria K and M are preferable, not required.

APPENDIX C: CRASH TEST PROCEDURES AND DATA ANALYSIS

The crash test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. Brief descriptions of these procedures are presented as follows.

ELECTRONIC INSTRUMENTATION AND DATA PROCESSING

The test vehicle was instrumented with three solid-state angular rate transducers to measure roll, pitch, and yaw rates; a triaxial accelerometer near the vehicle center of gravity (c.g.) to measure longitudinal, lateral, and vertical acceleration levels; and a back-up biaxial accelerometer in the rear of the vehicle to measure longitudinal and lateral acceleration levels. These accelerometers were ENDEVCO[®] Model 2262CA, piezoresistive accelerometers with a ± 100 g range.

The accelerometers are strain gage type with a linear millivolt output proportional to acceleration. Angular rate transducers are solid state, gas flow units designed for high-“g” service. Signal conditioners and amplifiers in the test vehicle increase the low level signals to a ± 2.5 volt maximum level. The signal conditioners also provide the capability of an R-cal or shunt calibration for the accelerometers and a precision voltage calibration for the rate transducers. The electronic signals from the accelerometers and rate transducers are transmitted to a base station by means of a 15-channel, constant-bandwidth, Inter-Range Instrumentation Group (I.R.I.G.), FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Calibration signals from the test vehicle are recorded before the test and immediately afterwards. A crystal-controlled time reference signal is simultaneously recorded with the data. Wooden dowels actuate pressure-sensitive switches on the bumper of the impacting vehicle prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produces an “event” mark on the data record to establish the instant of contact with the installation.

The multiplex of data channels, transmitted on one radio frequency, is received and demultiplexed onto separate tracks of a 28-track I.R.I.G. tape recorder. After the test, the data are played back from the tape machine and digitized. A proprietary software program (WinDigit) converts the analog data from each transducer into engineering units using the R-cal and pre-zero values at 10,000 samples per second per channel. WinDigit also provides Society of Automotive Engineers’ SAE J211 class 180 phaseless digital filtering and vehicle impact velocity.

All accelerometers are calibrated annually according to the SAE J211 4.6.1 by means of an ENDEVCO[®] 2901 precision primary vibration standard. This device and its support instruments are returned to the factory annually for a National Institute of Standards Technology (NIST) traceable calibration. The subsystems of each data channel are also evaluated annually, using instruments with current NIST traceability, and the results are factored into the accuracy of the total data channel, per SAE J211. Calibrations and evaluations are made any time data are suspect.

The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartiment impact velocities, time of occupant/compartiment impact after vehicle impact, and the highest 10-millisecond (ms) average ridedown acceleration. WinDigit calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a 60-Hz digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

TRAP uses the data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.0001-s intervals and then plots: yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate systems being initial impact.

ANTHROPOMORPHIC DUMMY INSTRUMENTATION

Use of a dummy in the 2000P vehicle is optional according to *NCHRP Report 350*, and there was no dummy used in the tests with the 2000P vehicle.

PHOTOGRAPHIC INSTRUMENTATION AND DATA PROCESSING

Photographic coverage of the test included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; one placed behind the installation at an angle; and a third placed to have a field of view parallel to and aligned with the installation at the downstream end. A flashbulb activated by pressure sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the installation and was visible from each camera. The films from these high-speed cameras were analyzed on a computer-linked Motion Analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A BetaCam, a VHS-format video camera and recorder, and still cameras were used to record and document conditions of the test vehicle and installation before and after the test.

TEST VEHICLE PROPULSION AND GUIDANCE

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A two-to-one speed ratio between the test and tow vehicles existed with this system. Just prior to impact with the installation, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared the immediate area of the test site, at which time brakes on the vehicle were activated to bring it to a safe and controlled stop.

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