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## **BRIDGE RAIL ANALYSIS AND CRASH TESTING**

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**TEXAS TRANSPORTATION INSTITUTE  
THE TEXAS A&M UNIVERSITY SYSTEM  
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## **KEY WORDS**

Bridge rail, guide rail, computer simulation, crash testing, roadside safety.

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16. Abstract <p>The original objective of the proposed research study is to determine if PENNDOT's Structure Mounted Guide Rail (SMR) Bridge Barrier meets the requirements of <i>NCHRP Report 350</i> Test Level 3.</p> <p>Prior to performing the crash testing, nonlinear, dynamic, finite element modeling with LS-DYNA was performed on the bridge rail system. Results from this modeling effort allowed the team to examine a range of the barrier's performance characteristics, and enabled the research team to make reasonable assessments for improving the performance of the barrier during the actual crash testing. The research team performed parametric investigations that examined four parameters: the Post Strength, W-Beam Stiffness, Connection Bolt Strength and the Post Anchor Bolt Strength. From the modeling effort, the team proposed necessary recommendations for modifying the existing bridge rail to enhance the probability of a successful crash test.</p> <p>After review of the results from the LS-DYNA computer simulation, the research team implemented changes into the standard bridge rail design to improve the crash performance of the barrier system. After review of those modifications, the research team concluded that the probability of success for TL-3 was very high. As a result, the team decided to perform the crash test with respect to TL-4 requirements. A full-scale crash test installation was then constructed with the proposed changes.</p> <p><i>NCHRP Report 350</i> test designation 4-12 was performed on the modified PENNDOT Structure Mounted Guide Rail Bridge Barrier. This test involved an 17,636 lb (8000 kg) single-unit truck impacting the critical impact point of the length of need at a speed of 50 mi/h (80 km/h) and an angle of 15 degrees. The details of the system, description of the crash test procedures and results, and assessment of the crash test are reported herein. According to the results of the full-scale crash test, the PENNDOT Structure Mounted Guide Rail Barrier marginally passed the requirement for <i>NCHRP Report 350</i> test designation 4-12.</p>					
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
<b>AREA</b>				
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
yd <sup>2</sup>	square yard	0.836	square meters	m <sup>2</sup>
ac	acres	0.405	hectares	ha
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>VOLUME</b>				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
NOTE: volumes greater than 1000 L shall be shown in m <sup>3</sup>				
<b>MASS</b>				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
<b>TEMPERATURE (exact degrees)</b>				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
<b>ILLUMINATION</b>				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>FORCE and PRESSURE or STRESS</b>				
lbf	poundforce	4.45	newtons	N
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa

## APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
<b>LENGTH</b>				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
<b>AREA</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>
ha	hectares	2.47	acres	ac
km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>
<b>VOLUME</b>				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m <sup>3</sup>	cubic meters	35.314	cubic feet	ft <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>
<b>MASS</b>				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
<b>TEMPERATURE (exact degrees)</b>				
°C	Celsius	1.8C+32	Fahrenheit	°F
<b>ILLUMINATION</b>				
lx	lux	0.0929	foot-candles	fc
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	fl
<b>FORCE and PRESSURE or STRESS</b>				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>

\*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.  
(Revised March 2003)

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# INTRODUCTION

## PROBLEM

In July 2000, Texas Transportation Institute performed a crash test on Pennsylvania Department of Transportation (PENNDOT) Standard BC-739M Bridge Barrier to Guide Rail Transition. This test was performed in accordance with *NCHRP Report 350* Test Level 3 conditions. The test was successful. This transition is commonly used in conjunction with PENNDOT's Structure Mounted Guide Rail (SMR) Bridge Rail. The purpose of this research study was to determine if the PENNDOT SMR meets the crash test requirements of TL-3. PENNDOT currently uses this bridge rail system on low volume roads throughout the state. Additional testing to determine if this barrier system meets the requirements of Test Level 4 conditions is an option for this study.

## OBJECTIVES/SCOPE OF RESEARCH

The objective of the proposed research study is to determine if PENNDOT's Structure Mounted Guide Rail Bridge Barrier meets the requirements of *NCHRP Report 350* Test Level 3. This barrier has been commonly used by PENNDOT for over 15 years on low volume roadways. In addition, it also has been the preferred alternate to the 32-inch (813 mm) F-Shape concrete barrier on many low volume structures that have limited sight distances.

Prior to performing the crash testing, nonlinear, dynamic, finite element modeling with LS-DYNA was performed on the bridge rail system. Results from this modeling effort allowed the team to examine a range of the barrier's performance characteristics, and enabled the research team to make reasonable assessments for improving the performance of the barrier before the actual crash testing. The research team conducted parametric investigations that examined four parameters: the Post Strength, W-Beam Stiffness, Connection Bolt Strength and the Post Anchor Bolt Strength. From the modeling effort, the team proposed necessary recommendations for modifying the existing bridge rail details to enhance the probability of a successful crash test.

After review of the results from the LS-DYNA computer simulation, the research team made modifications to the standard bridge rail design to improve the crash performance of the barrier system. After review of these modifications, the research team concluded that the probability of success for TL-3 was very high. As a result, the research team decided to perform a full-scale crash test on the modified design with respect to TL-4 requirements. A full-scale crash test installation was then constructed with the proposed changes.

*NCHRP Report 350* test designation 4-12 was performed on the modified PENNDOT Structure Mounted Guide Rail Bridge Barrier. This test involved an 17,636 lb (8000 kg) single-unit truck impacting the critical impact point of the length of need at a speed of 50 mi/h (80 km/h) and an angle of 15 degrees. The details of the system, description of the crash test procedures and results, and assessment of the crash test are reported herein.



## COMPUTER SIMULATION

LS-DYNA, a commercial non-linear finite element program was used to simulate the impact performance of the PENNDOT Structure Mounted Guide Rail Bridge Barrier when impacted by a 2000P pickup truck.

The rail, posts, rub-rail, deck, steel reinforcement and connections were modeled. The model was constructed using 281,336 nodes and 241,196 elements. The system model had 23 different components. Different parts were modeled explicitly, including the curb, deck, reinforcement, anchor bolts, posts, base plates, blockouts, W-beam rail, rub-rail and connections. Material properties were assigned to each part based on available tests and/or data from the literature. Contacts were also defined to account for inter-part interactions to simulate physical contact among the parts. The different colors of the model represent different parts of the rail and the truck as shown figure 1. The outer ends of the deck and the curb sections were assumed rigid to reduce computational time. However, the middle section of the curb and the deck (impact region) was assigned deformable material behavior with embedded reinforcements.

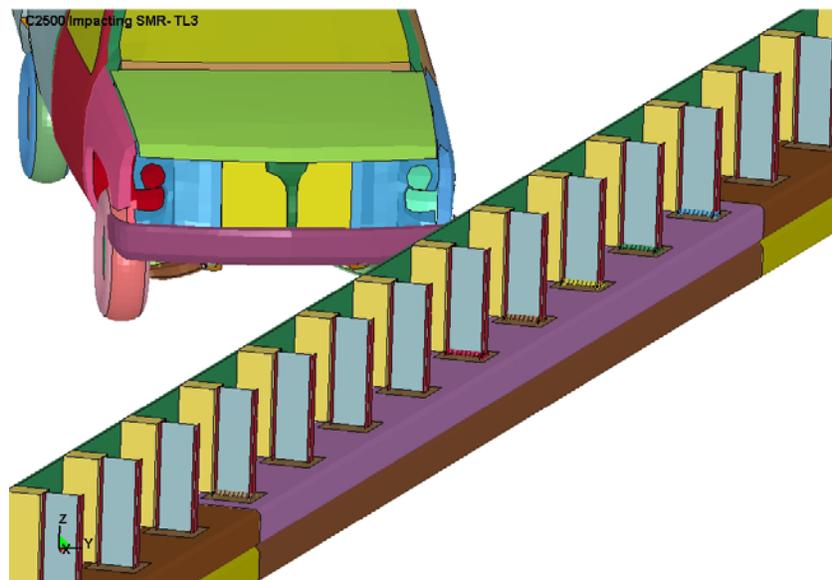


Figure 1. Model representation.

The 2000P pickup truck model is the reduced Chevrolet C2500 truck model developed by the National Crash Analysis Center (NCAC). The truck model consists of 22,148 nodes and 22,227 elements.

The combined model has 303,492 nodes and 263,656 elements, and includes 14 contact definitions to simulate physical impact-contact behavior amongst various parts in the model. The simulation required 72 hours of CPU time to run on a dual processor Itanium2 machine to simulate 0.363 second of the impact event. The truck model had an initial impact velocity of

100 km/h (62 mi/h) and impacted the bridge rail at a 25 degree angle to represent the impact conditions of *NCHRP Report 350* test 3-11.

Once the simulation was completed, several variables were post-processed to evaluate the bridge rail performance under these impact conditions. The threshold for a 7/8 inch A325 anchor bolts is 90 ksi (yield) and 120 ksi (ultimate). In the simulation, the axial stress in the anchor bolts reached its peak value at 0.06 seconds. The analysis indicated a few spots would reach a maximum axial stress of 91.8 ksi (633.7 MPa). Although this value is slightly above the yield point, it was limited in terms of its distribution along the bolts and its duration. This indicated a low probability of yielding of the anchor bolts. Figure 2 shows an overall distribution of bolt stresses at 0.06 second after impact.

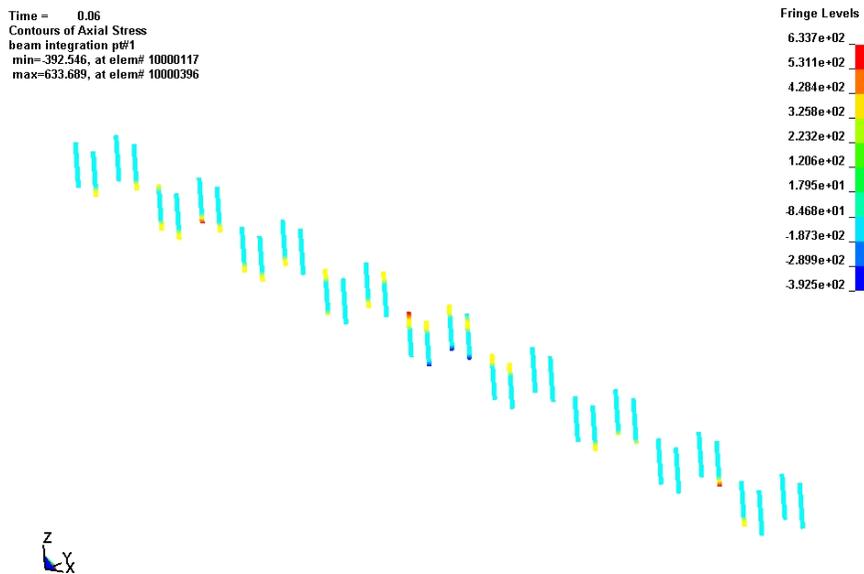


Figure 2. Axial stress in the anchor bolts.

The tensile stress state in the concrete curb and deck was also examined. Figure 3 shows the contour of the maximum principle stress which is an indicator of the state of tensile stresses in the curb. Concrete can develop cracking and fracture under very low tensile stresses. For the concrete specified, a maximum of 8 MPa was reached at a point in the end corners. These end values are due to the boundary condition approximation used to model continuity of the rail. The mean value is approximately 337 psi (2.33 MPa). This is less than the estimate splitting tensile strength of 443 psi obtained using the formula:  $f_{split} = 7\sqrt{fc'}$ , where  $fc'$  is the concrete compressive strength which is 4000 psi.

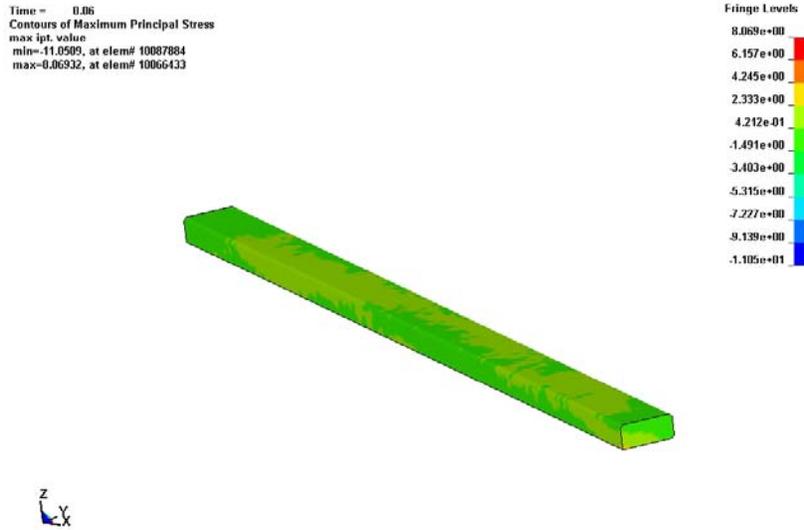


Figure 3. Contour of maximum principle stress in the curb.

Similarly, figure 4 shows maximum principal stress fringe which is an indicator of the tensile stresses in the deck. These stresses were highest in magnitude at 0.065 sec. The tensile stresses are indicators of the probability of cracks or fracture. A maximum of 1,064 psi (7.34 MPa) in the middle of the top traffic side edge of the deck was reached, which is more than the estimated splitting strength of 443 psi. However, this edge is artificially constrained by boundary conditions to represent the continuation of the deck, and the maximum stress occurs in a very limited area. This means that the deck has a low probability of having cracking if this loading condition is achieved.

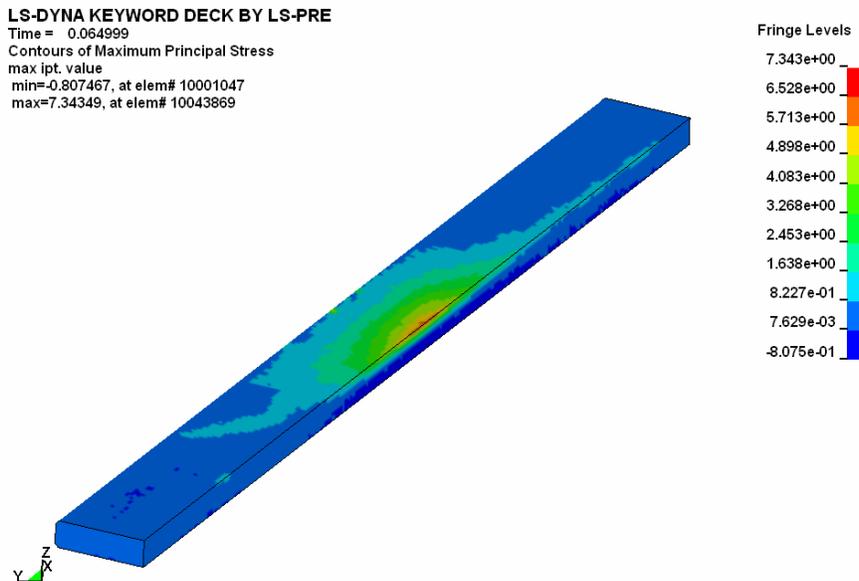


Figure 4. Maximum principle stress in the deck.

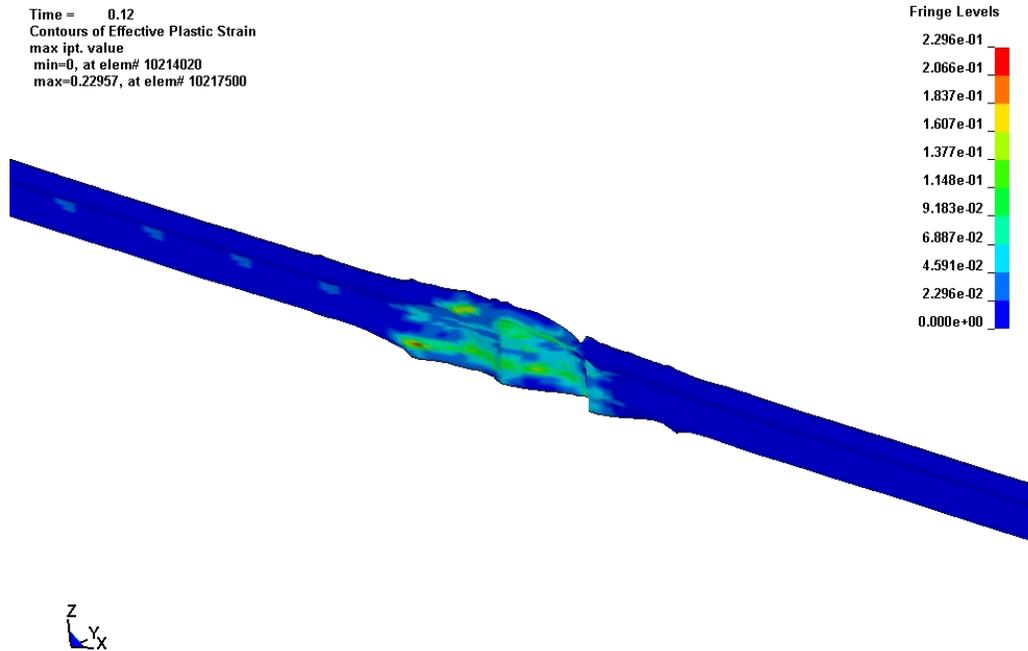


Figure 5. Rail rupture at 0.12 sec.

Strain in the W-beam rail element was also analyzed. The simulation indicated that the rail elements in the barrier exhibit pronounced pocketing and a high probability of tearing or rupture in-between posts in the impact region. Two indicators were used to predict this mode of failure. First, the plastic strain in the rail reached the ultimate true strain of the W-beam steel in the impact region of the rail. Secondly, the development of rail pockets in the impact region will increase the probability of rail tearing or rail rupture. Rail rupture and/or severe vehicle snagging was estimated to occur at 0.12 sec due to the pocketing profile and effective plastic strain as shown in figure 5. The maximum ductility specified in the AASHTO M-180 material specification for the W-beam rail is 12%. Testing of W-beam rails commonly results in rupture strains of 18% to 25%.

Based on the results from the simulation effort, it was concluded that the original Structure Mounted Guide Rail design with posts spaced at 1 ft-6-3/4 inches on center using a single W-beam rail element would exhibit poor crash performance with respect to *NCHRP Report 350* TL-3 requirements. The strength of the rail was increased by adding two TS4x3x3/16 tube members behind the W-beam rail member. In addition the C6x8.2 rub-rail was blocked out to closely match the original Structure Mounted Rail profile. With the addition of the tubular rail elements, the Structure Mounted Rail closely resembled the Texas Department of Transportation (TxDOT) Type T101 Bridge Rail. In addition, the post spacing for the Structure Mounted Rail was increased to 6 ft-3 inches like the T101 Bridge Rail. Details of the new SMR Bridge Rail design are presented in figures 6 through 14.

# TECHNICAL DISCUSSION

## TEST PARAMETERS

### Test Facility

The test facilities at the Texas Transportation Institute's Proving Ground consist of a 809-hectare complex of research and training facilities situated 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 the placement of the PENNDOT Structure Mounted Guide Rail Bridge Barrier is along a wide out-of-service apron. The apron consists of an unreinforced jointed concrete pavement in 12.5 ft x 15 ft (3.8 m x 4.6 m) blocks nominally 8-12 inches (203-305 mm) deep. The apron is over 50 years old and the joints have some displacement, but are otherwise flat and level.

### Test Article – Design and Construction

The modified Pennsylvania Department of Transportation (PENNDOT) Structure Mounted Rail (SMR) Bridge Rail consists of two tubular steel rail elements, W-beam rail element, and a rubrail supported by W6x20 steel posts. The bridge railing system is supported by a cast-in-place concrete deck and curb. Detailed design information on the bridge rail was provided by Mr. Will Longstreet with Pennsylvania Department of Transportation.

The modified SMR 2-Tube Bridge Rail tested for this project consisted of two TS4x3x3/16 (TS192x76x4.8) structural tubes with a w-beam rail element and a C6x8.2 (C150x12) channel rubrail. The total height of the bridge rail was approximately 31-3/8 inches (797 mm). Mid-height of the rubrail was approximately 13 inches (330 mm) above the pavement surface and was blocked out with TS7x3x1/4 (TS178x76x6.4) tubular blockouts that were 6 inches (150 mm) long. The steel posts were spaced 6 feet-3 inches (1905 mm) on centers and were fabricated from W6x20 (W150x30) structural shape. The bridge rails were attached to the posts using two 5/8 inch (16 mm) diameter A307 hex head bolts at each post location. The steel posts were welded to 12 inch (305 mm) by 12 inch (305 mm) by 1 inch (25 mm) thick base plates. The posts were anchored to the 8-inch (203 mm) high concrete curb and 8-1/2-inch (216 mm) thick deck using four 7/8-inch (22 mm) diameter ASTM A325 Anchor Bolts. These bolts were anchored to #6 (#19) Richmond Threaded Anchor (hook anchor) inserts cast within the deck. The tubular rails, w-beam and rubrail were blocked out from the steel posts using 6x6x22-1/4 (150x150x565) wood blockouts. For additional information on the bridge rail please refer to figures 6 through 14. The SMR 2-Tube Bridge Rail tested for this project was supplied to TTI by GSI Highway Products, Hutchins, Texas.

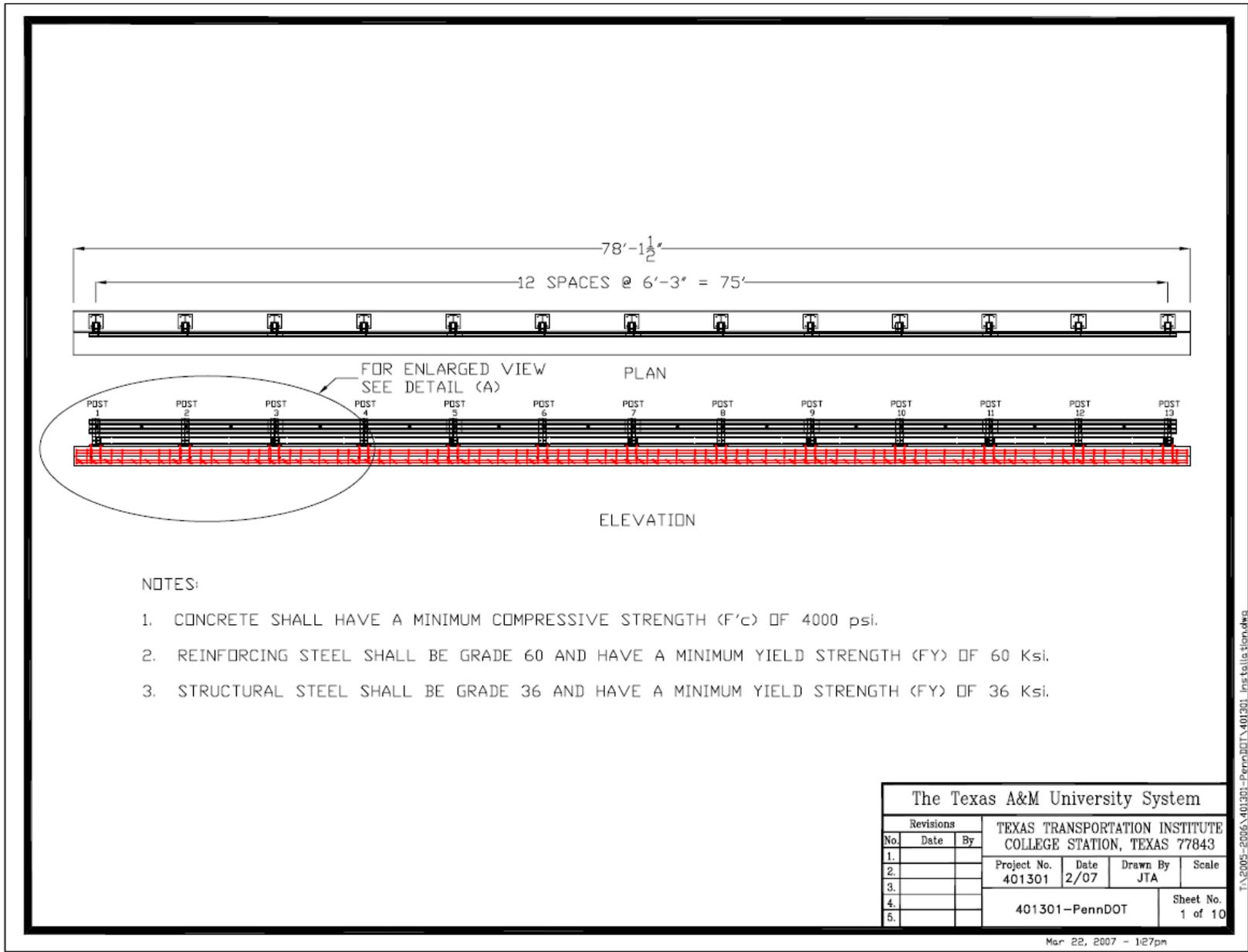
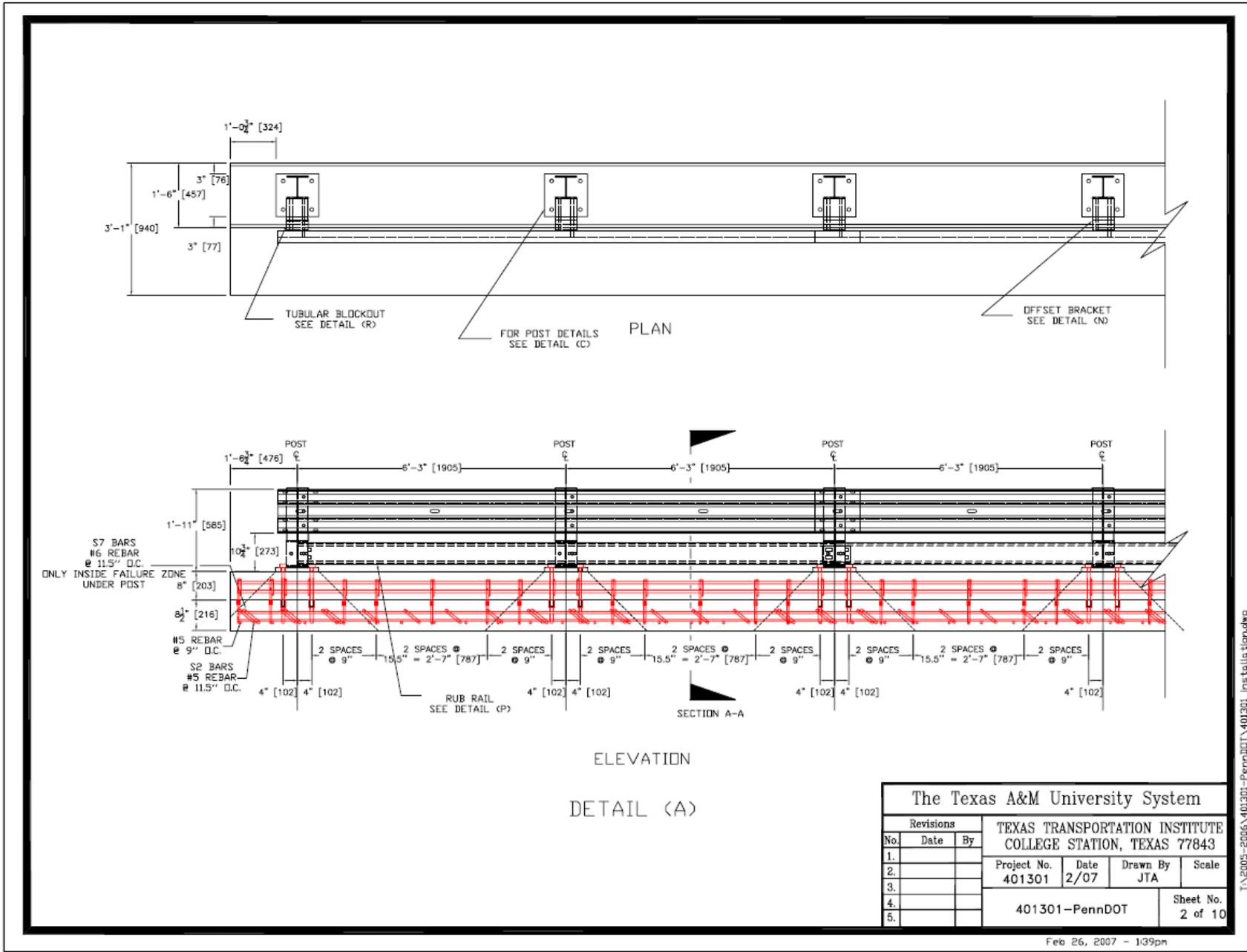


Figure 6. Layout of the PENNDOT Structure Mounted Guide Rail Barrier.



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1.			401301	2/07
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3.			JTA	
4.			401301-PennDOT	
5.			Sheet No. 2 of 10	

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Figure 7. Details of test installation.

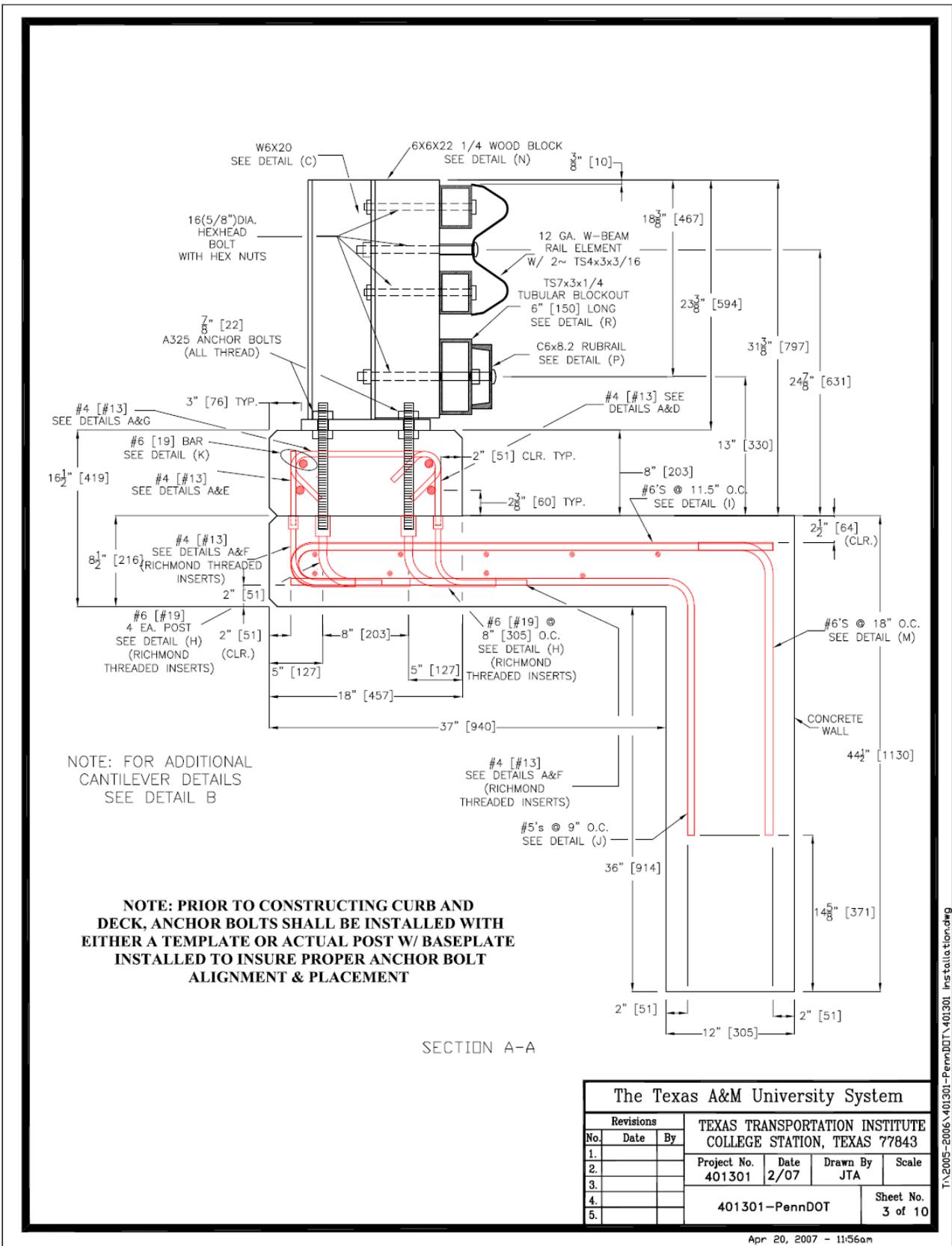


Figure 8. Cross section of the PENNDOT Structure Mounted Guide Rail Barrier.



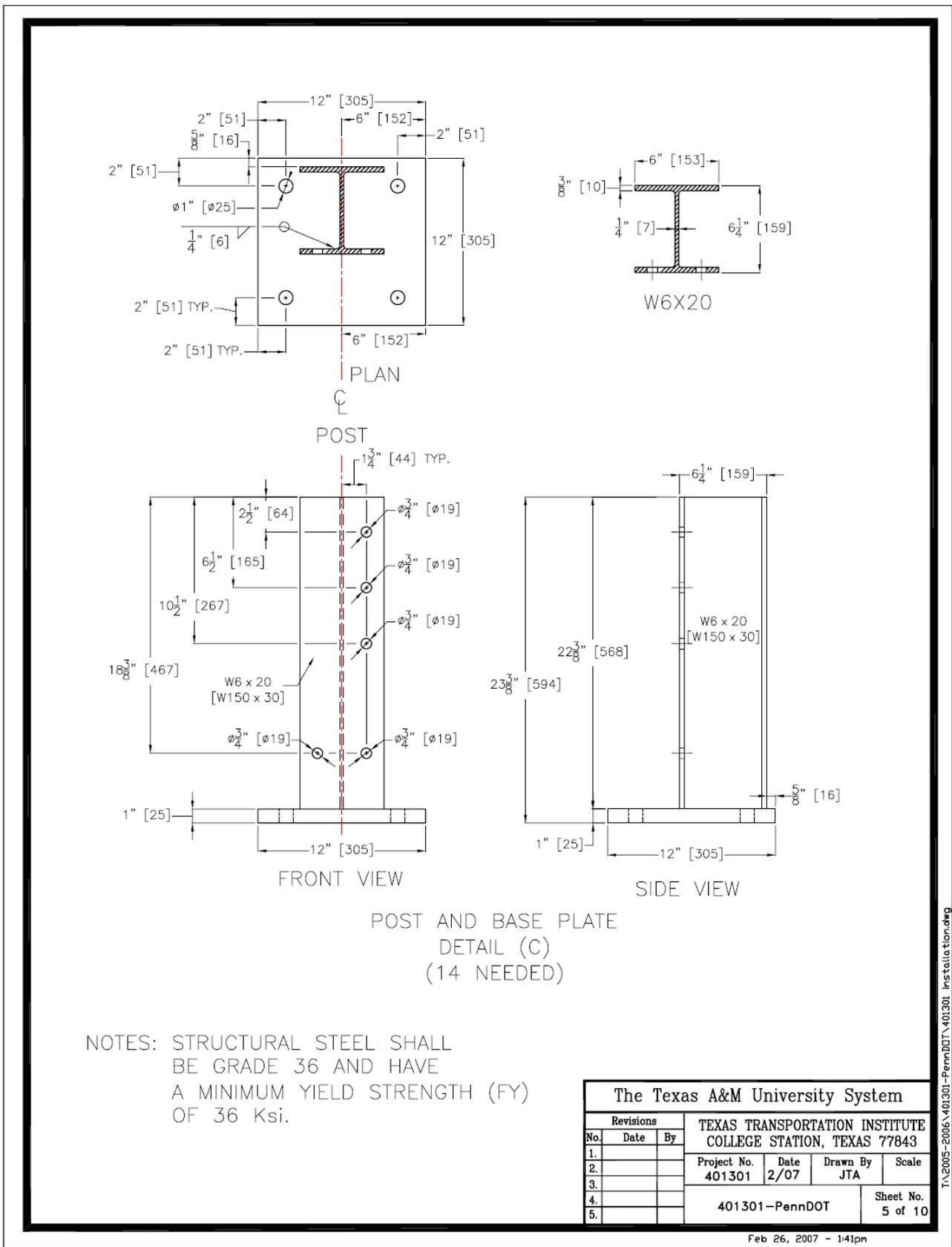


Figure 10. Details of the post and base plate.

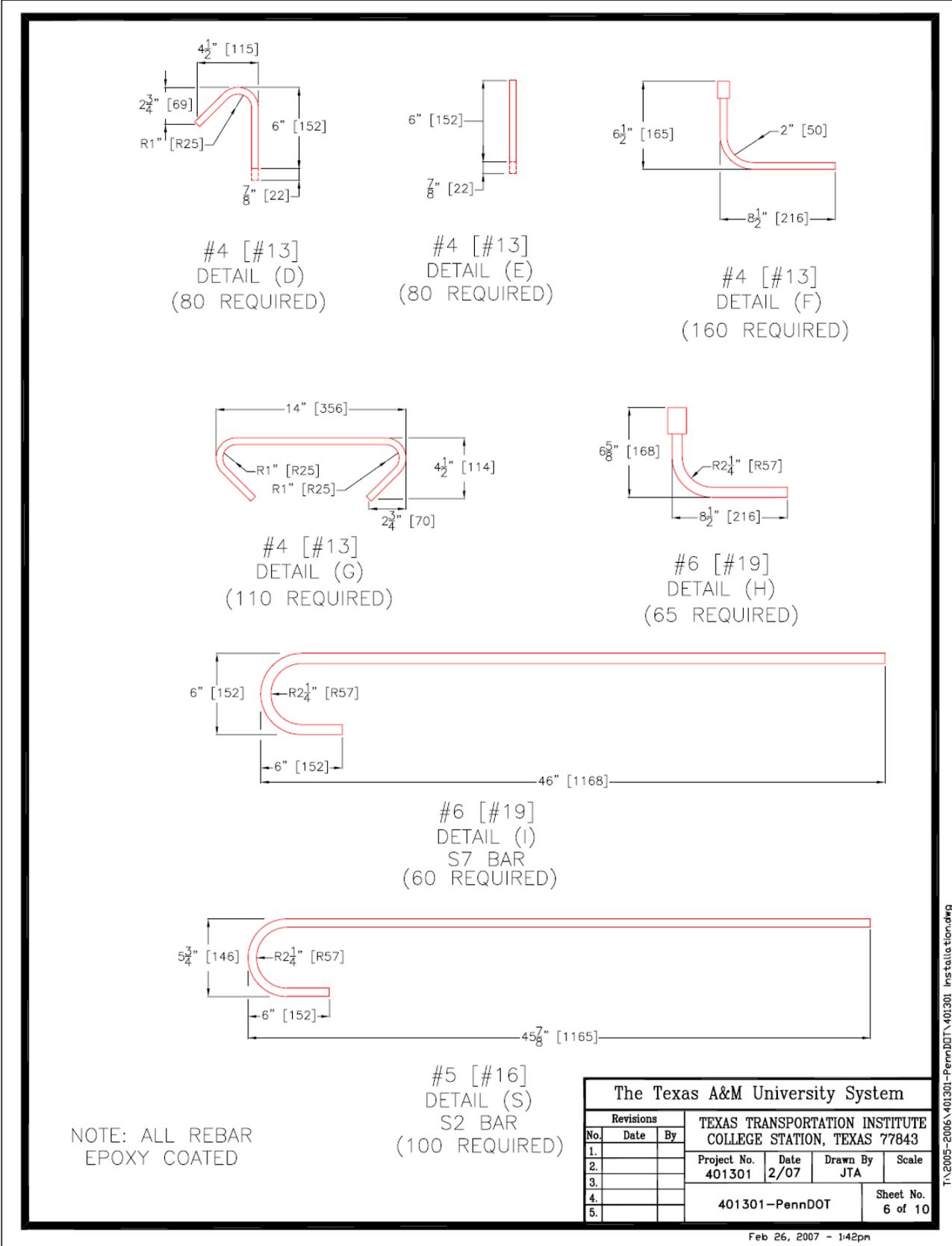


Figure 11. Rebar bend details.

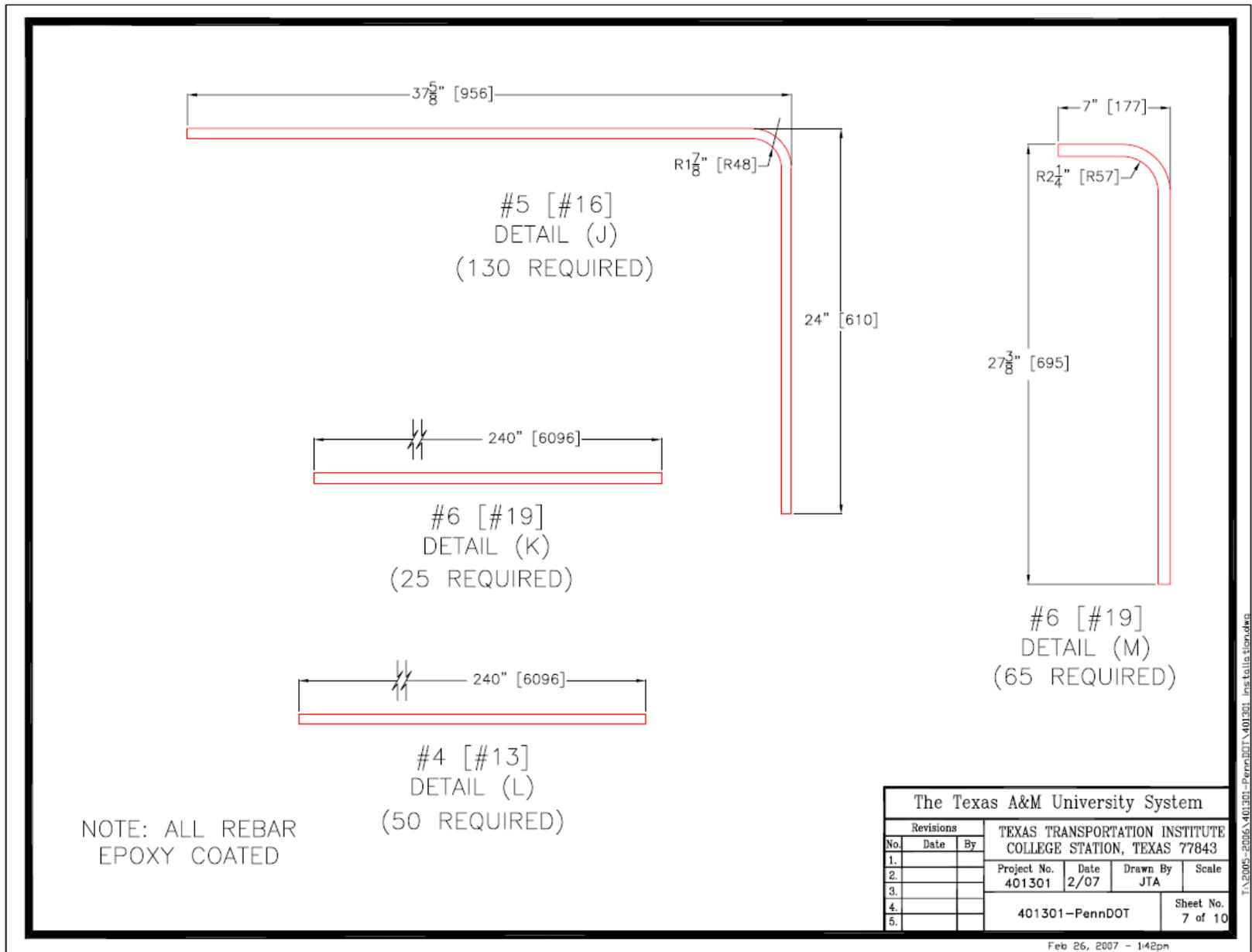


Figure 11. Rebar bend details (continued).

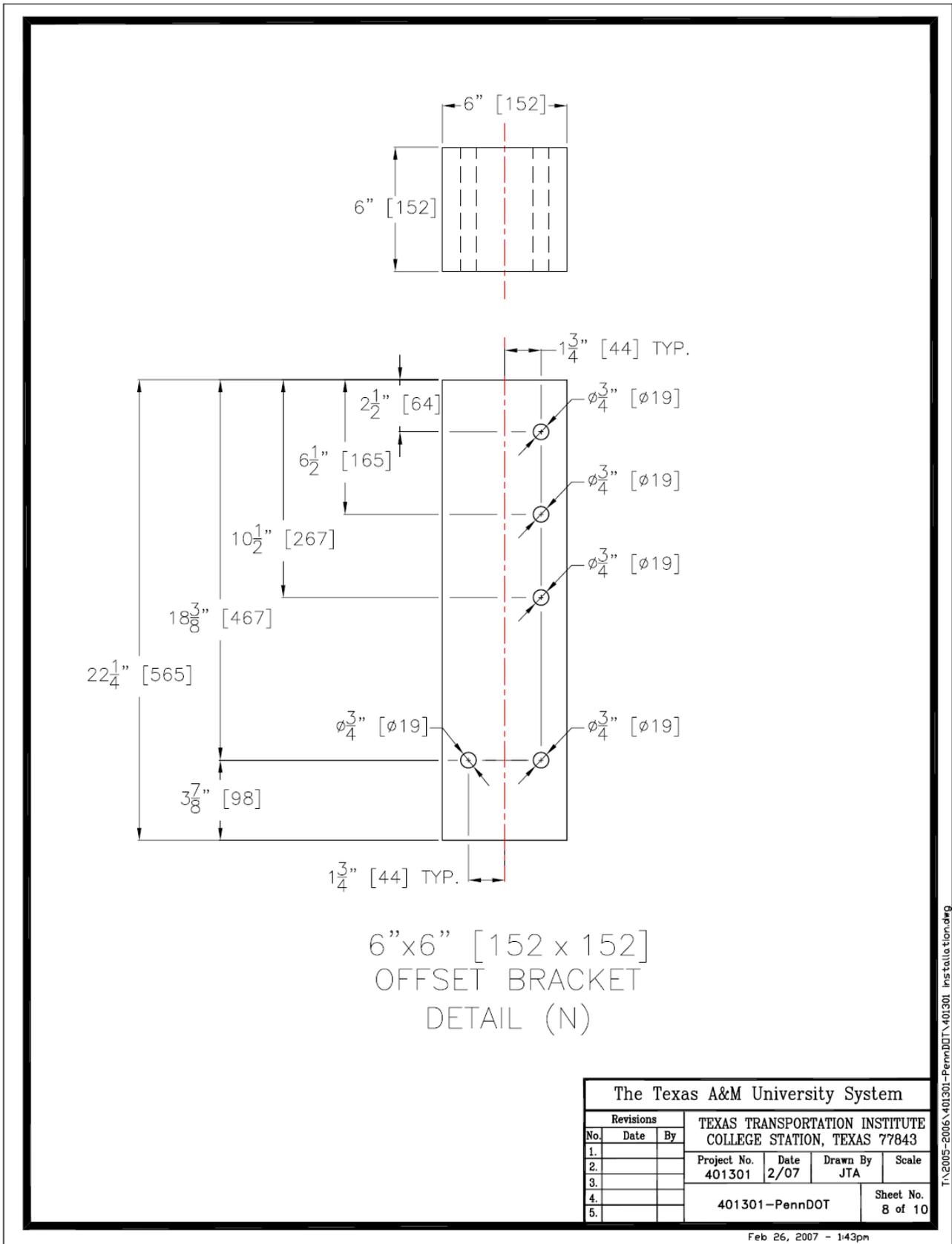


Figure 12. Details of the offset bracket.

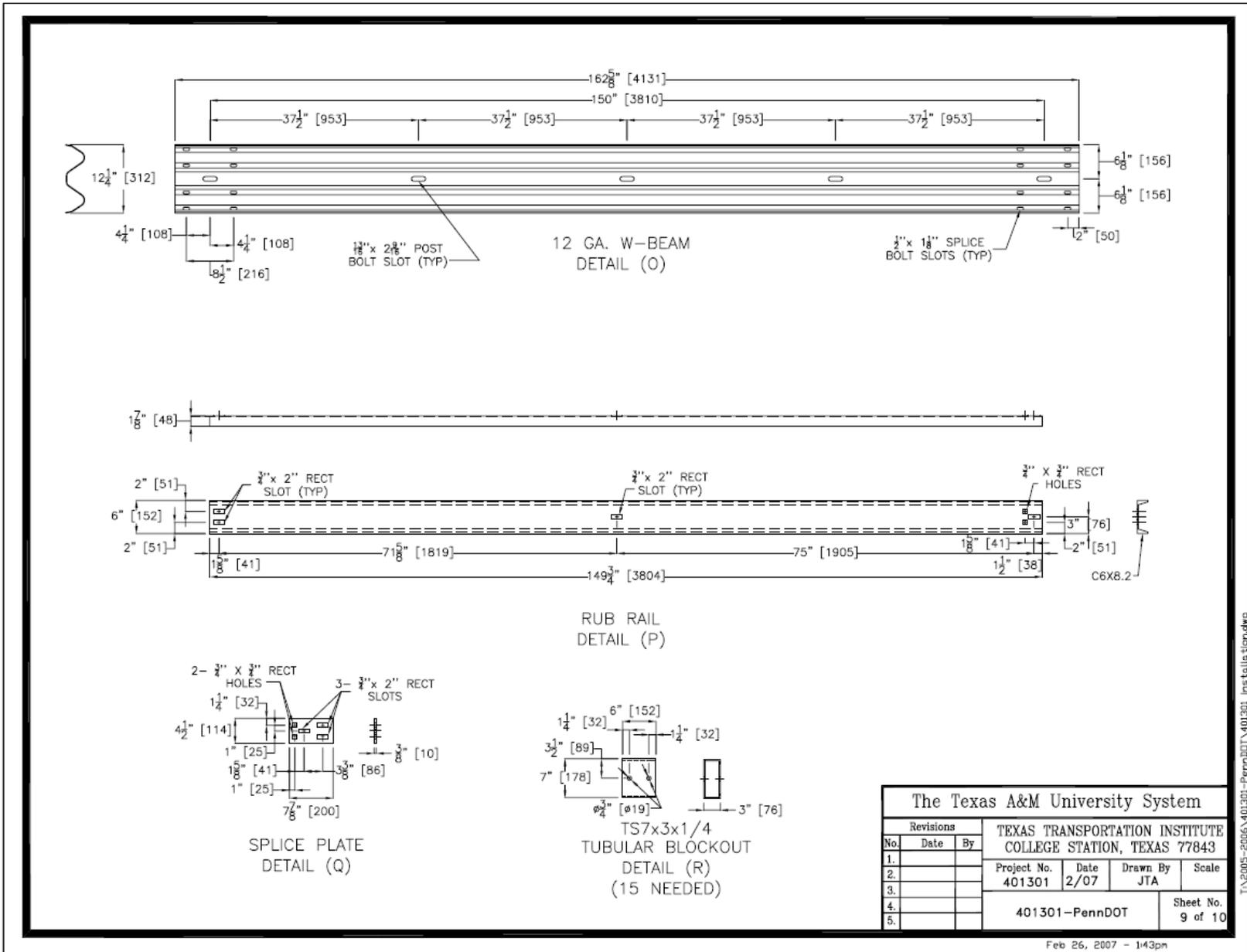


Figure 13. Details of the W-beam and rub rail.

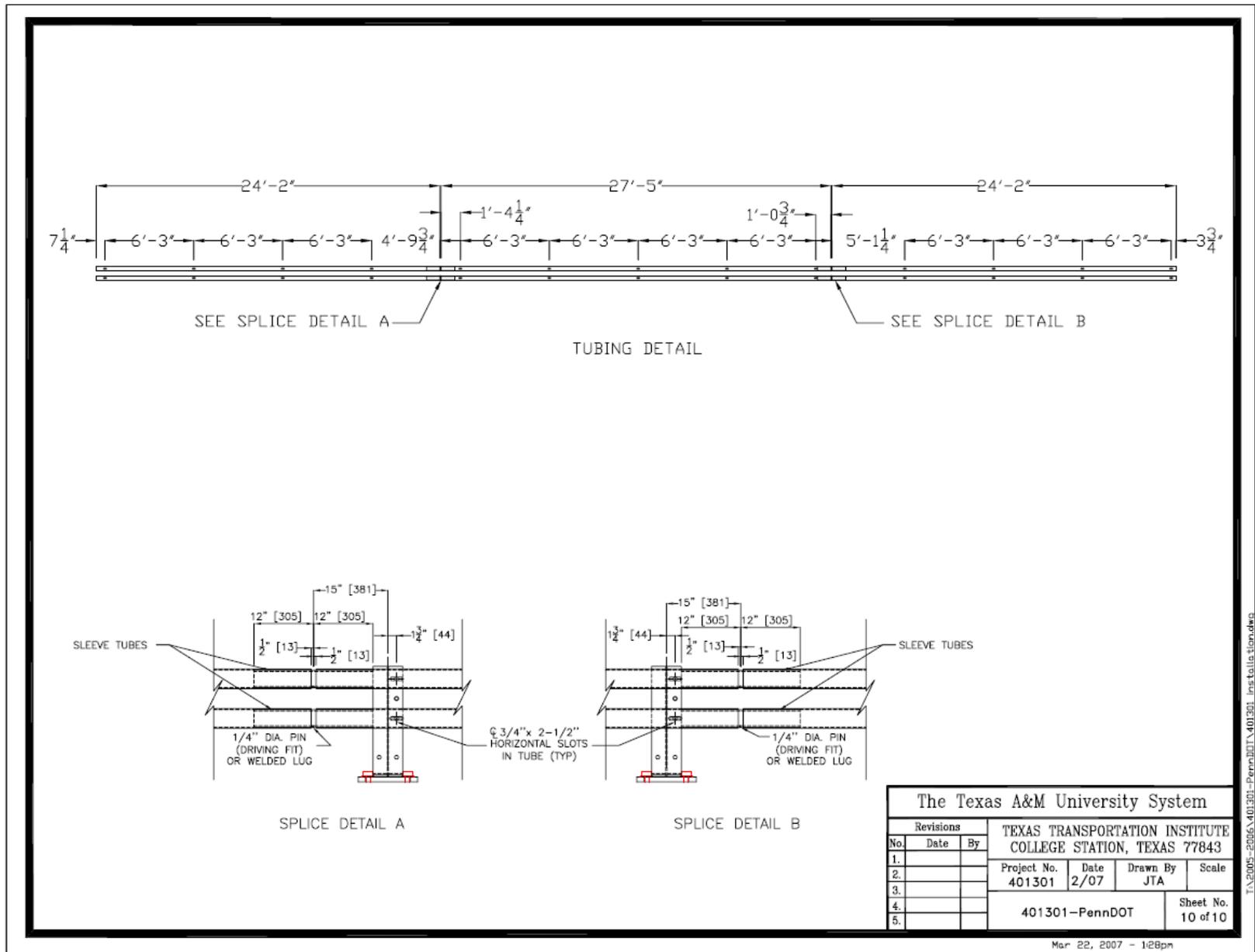


Figure 14. Splice details.

A simulated concrete bridge deck cantilever and curb was constructed immediately adjacent to an existing concrete apron located at the TTI test facility. The total length of the installation was 78 feet-1-1/2 inch (23.8 meters) long. The bridge deck cantilever was 37 inches (940 mm) in width and was 8-1/2 inches (216 mm) thick. An 8-inch (203 mm) high concrete curb was cast on top of the concrete deck. The concrete deck and curb was anchored to an existing 12-inch (305 mm) thick reinforced vertical wall located adjacent to the concrete apron. The wall was supported by a 8-inch (203 mm) thick footing. Both the vertical wall and the deck were cast monolithically. The wall and the deck were reinforced to the existing concrete runway by “L” shaped dowels welded to existing dowels in the runway.

Reinforcement in the deck consisted of two layers of reinforcement both in the transverse and longitudinal directions. The top and bottom layers of transverse reinforcement consisted of #5 (#16) transverse bars located 11-1/2 inches (292 mm) on center with additional #6 (#19 mm) bars added in the top transverse layer in the immediate area of the posts. Bottom transverse reinforcement consisted of #5 (#16) located on 9-1/2 inch centers. Longitudinal reinforcement in the top and bottom layers consisted of #4 (#12) spaced at 8 inches (203 mm) on center in the top mat and 9 inches (229 mm) on center in the bottom mat. Transverse reinforcement in the curb consisted of #4 (#12) hooked bars spaced at 8-1/2 inches (216 mm) on center around the posts. This curb reinforcement was anchored to the deck using Richmond threaded inserts. Longitudinal reinforcement in the curb consisted of four #6 (#19) bars located within the transverse curb reinforcement as shown in figures 3 and 4. All reinforcement used in the concrete deck and curb had a minimum specified yield strength of 414 MPa (60 ksi) and was epoxy coated. Standard concrete compressive strength cylinders were cast for both the concrete deck and curb. For the concrete deck, strength tests performed at 12 days age resulted in an average compressive strength of 5048 psi (34.8 MPa). For the concrete curb, strength tests performed at 10 days age resulted in an average compressive strength of 4380 psi (30.2 MPa). For additional information on the bridge railing test installation, please refer to figures 6 through 14. Photographs of the installation are shown in figure 15.

## **Test Conditions**

According to *NCHRP Report 350*, three tests are recommended to evaluate longitudinal barriers to test level four (TL-4):

***NCHRP Report 350 Test Designation 4-10:*** 820 kg vehicle impacting the length of need section at a speed of 100 km/h and an angle of 20 degrees.

***NCHRP Report 350 Test Designation 4-11:*** 2000 kg pickup truck impacting the length of need section at a speed of 100 km/h and an angle of 25 degrees.

***NCHRP Report 350 Test Designation 4-12:*** 8000 kg single-unit truck impacting the length of need section at a speed of 80 km/h and an angle of 15 degrees.



Figure 15. PENNDOT Structure Mounted Guide Rail Barrier prior to testing.

The small car test is performed to evaluate the general overall performance characteristics of the length of need section of a longitudinal barrier and occupant risk in particular. The pickup truck test is performed to evaluate the ability of the barrier section to contain and redirect the vehicle. Occupant risk and vehicle stability are a concern in the evaluation of both these tests. The 8000 kg truck test is performed for the purpose of evaluating the ability of the barrier section to contain and redirect the larger, heavier vehicle. Based on the equivalence of the PENNDOT SMR Bridge Rail with the Texas Type T101 Bridge rail, which performed successfully in tests 4-10 and 4-11, it was determined that these two tests could be eliminated.

Test 4-12 was performed in this study, and the target impact point was 1.5 m upstream of bridge rail post 5 (see figure 16).

The crash test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. Appendix A presents brief descriptions of these procedures.

### **Evaluation Criteria**

The crash test was evaluated in accordance with the criteria presented in *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.” Safety evaluation criteria from table 5.1 of *NCHRP Report 350* were used to evaluate the crash test reported herein.

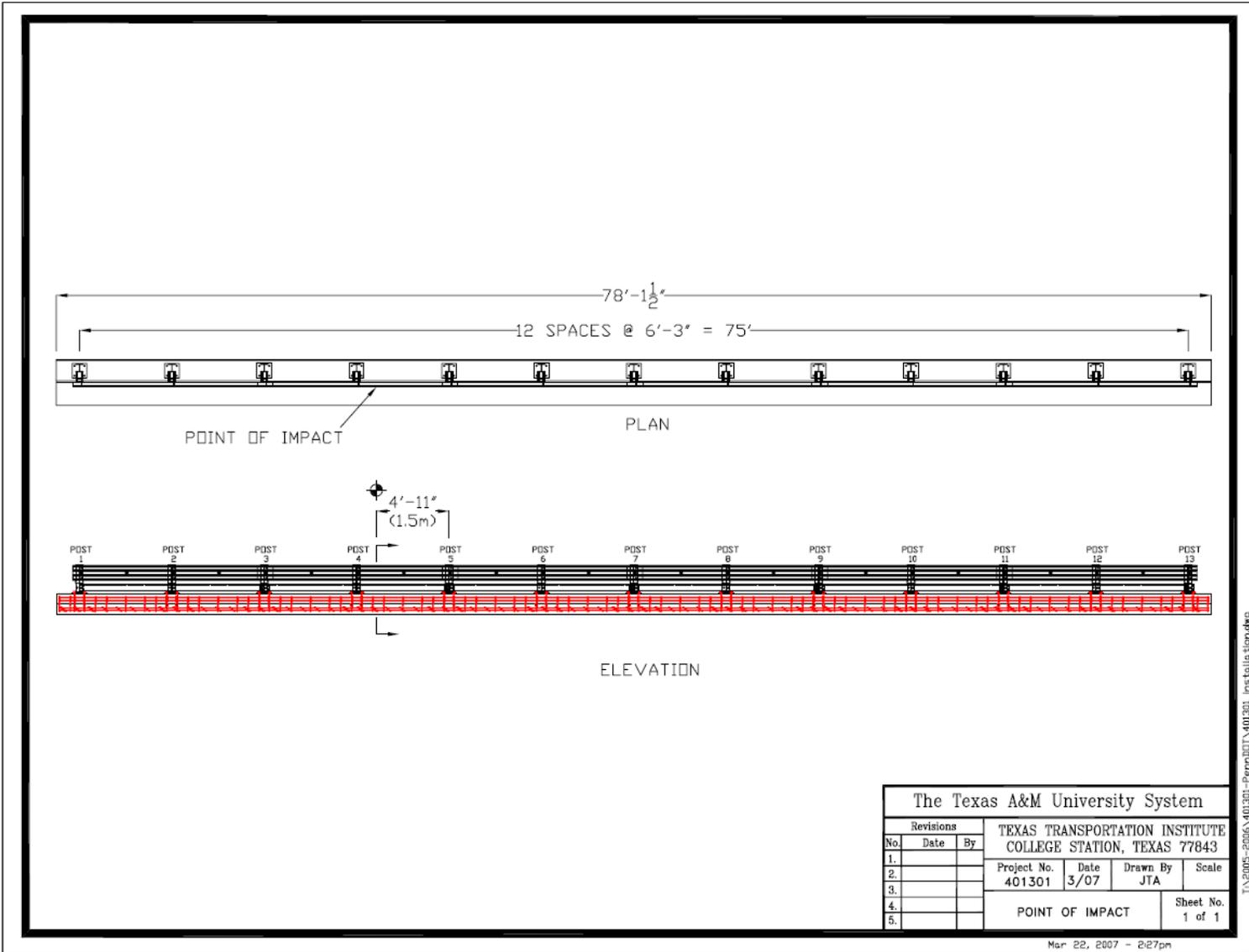


Figure 16. Location of impact point for the PENNDOT Structure Mounted Guide Rail Barrier.



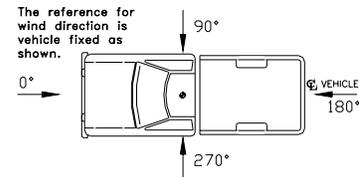
## CRASH TEST 401301-2 (NCHRP REPORT 350 TEST NO. 4-12)

### Test Vehicle

A 1998 Ford F series single-unit truck, shown in figures 17 and 18, was used for the crash test. Test inertia weight of the vehicle was 7970 kg, and its gross static weight was 7970 kg. The height to the lower edge of the vehicle front bumper was 489 mm, and the height to the upper edge of the front bumper was 802 mm. Additional dimensions and information on the vehicle are given in appendix B, figure 23. 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 crash test was performed the morning of April 2, 2007. Weather conditions at the time of testing were: Wind speed: 7 mi/h (12 km/h); wind direction: 180 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); temperature: 75°F (24°C); relative humidity: 45 percent.



### Impact Description

The 1998 Ford F series single-unit truck, traveling at an impact speed of 50.0 mi/h (80.4 km/h), impacted the PENNDOT Structure Mounted Guide Rail Barrier 3.4 ft (1.04 m) upstream of post 5 at an impact angle of 15.4 degrees. Shortly after contact, the W-beam rail element and rub-rail began to deform at the point of impact. The cab of the vehicle began to redirect at 0.031 s, and the box-van began to redirect at 0.114 s. At 0.310 s, the vehicle was parallel with the rail and traveling at a speed of 46.2 mi/h (74.3 km/h). The lower front corner of the box-van contacted post 3 at 0.320 s, and the lower rear of the box-van contacted post 2 at 0.331 s. By 0.379 s, the lower front corner of the box-van contacted post 4. The vehicle rode down the rail and out of view of the overhead camera while traveling at a speed of 42.1 mi/h (67.7 km/h). As the vehicle rode off the rail, it rolled over onto its top, coming to rest 105 ft (32 m) downstream of impact and to the field side of the installation with the right front corner aligned with the traffic face of the bridge rail. Sequential photographs of the test period are shown in appendix C, figures 24 and 25.



Figure 17. Vehicle/installation geometrics for test 401301-2.



Figure 18. Vehicle before test 401301-2.

## **Damage to Test Article**

Damage to the PENNDOT Structure Mounted Guide Rail Barrier is shown in figures 19 and 20. Actual impact occurred 3.4 ft (1.04 m) upstream of post 5. The right front corner of the blockout at post 5 was chipped, and the top of the blockout at post 4 was scraped. Cracks radiated from the left front anchor bolt at post 4 across the top of the curb only. At post 5, the top of the blockout and the traffic face of the post were marred. Cracks radiated from the front bolts on both sides across the top of the curb. A hairline crack on the downstream side radiated from the rear anchor bolt across and down the field side of the curb, with a very slight hairline crack into the upper part of the deck. The top of the blockout at post 6 was gouged, and the tops of the posts and blockouts at posts 7 and 8 were scraped. Length of contact of the vehicle with the rail was 29.5 ft (8.98 m), plus a second contact at 11.0 ft (3.34 m) from the end and off the end of the rail. Maximum dynamic deflection of the W-beam rail element was 2.6 inches (66 mm), as was the permanent deformation. Working width was 6.6 ft (2.015 m).

## **Vehicle Damage**

The single-unit truck was extensively damaged when it rolled over onto its top. However, as far as can be determined, damage from contact with the rail included the front bumper, hood, left door and glass, drive shaft, left rear leaf springs and rear U-bolts. Photographs of the vehicle are shown in figure 21.

## **Occupant Risk Factors**

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 8.5 ft/s (2.6 m/s) at 0.237 s, the highest 0.010-s occupant ridedown acceleration was -4.0 g's from 0.299 to 0.309 s, and the maximum 0.050-s average acceleration was -2.1 g's between 0.323 and 0.373 s. In the lateral direction, the occupant impact velocity was 11.2 ft/s (3.4 m/s) at 0.237 s, the highest 0.010-s occupant ridedown acceleration was 5.6 g's from 0.326 to 0.336 s, and the maximum 0.050-s average was 3.8 g's between 0.287 and 0.337 s. These data and other pertinent information from the test are summarized in figure 22. Vehicle angular displacements and accelerations versus time traces are presented in appendix D, figures 26 through 32.



Figure 19. Vehicle trajectory path after test 401301-2.

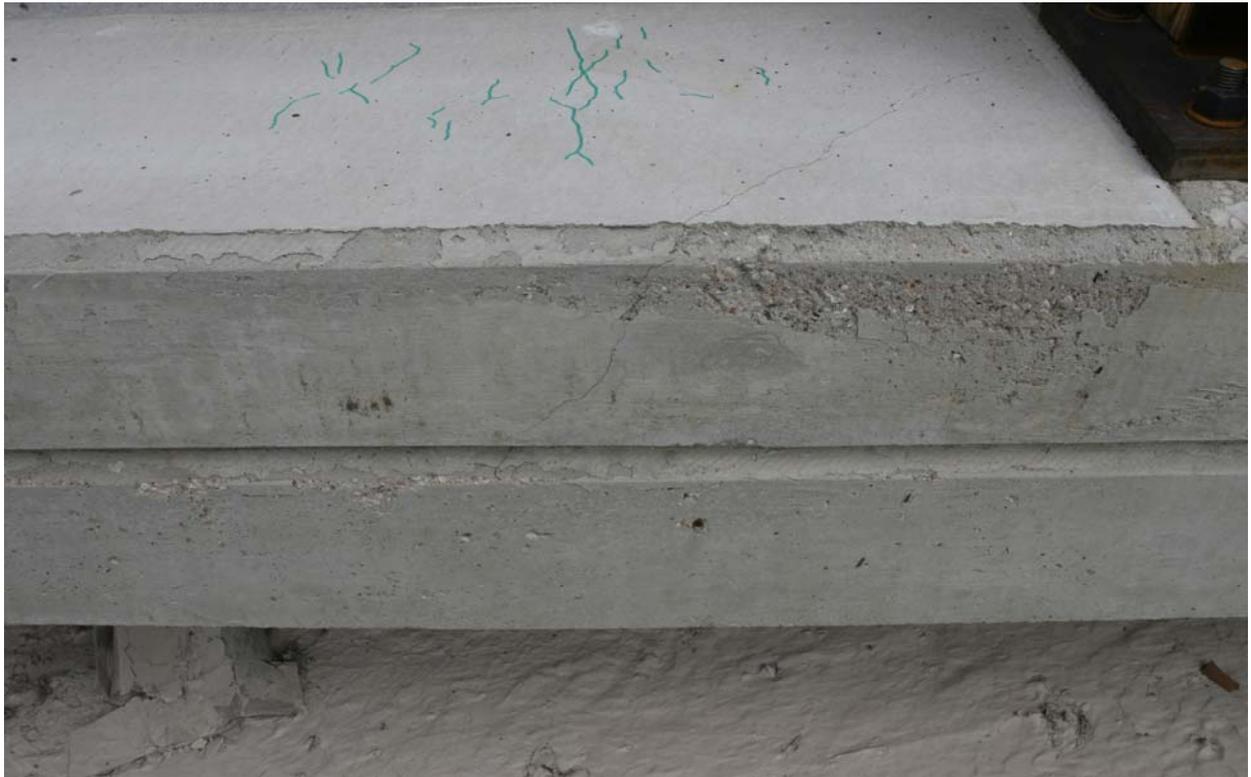
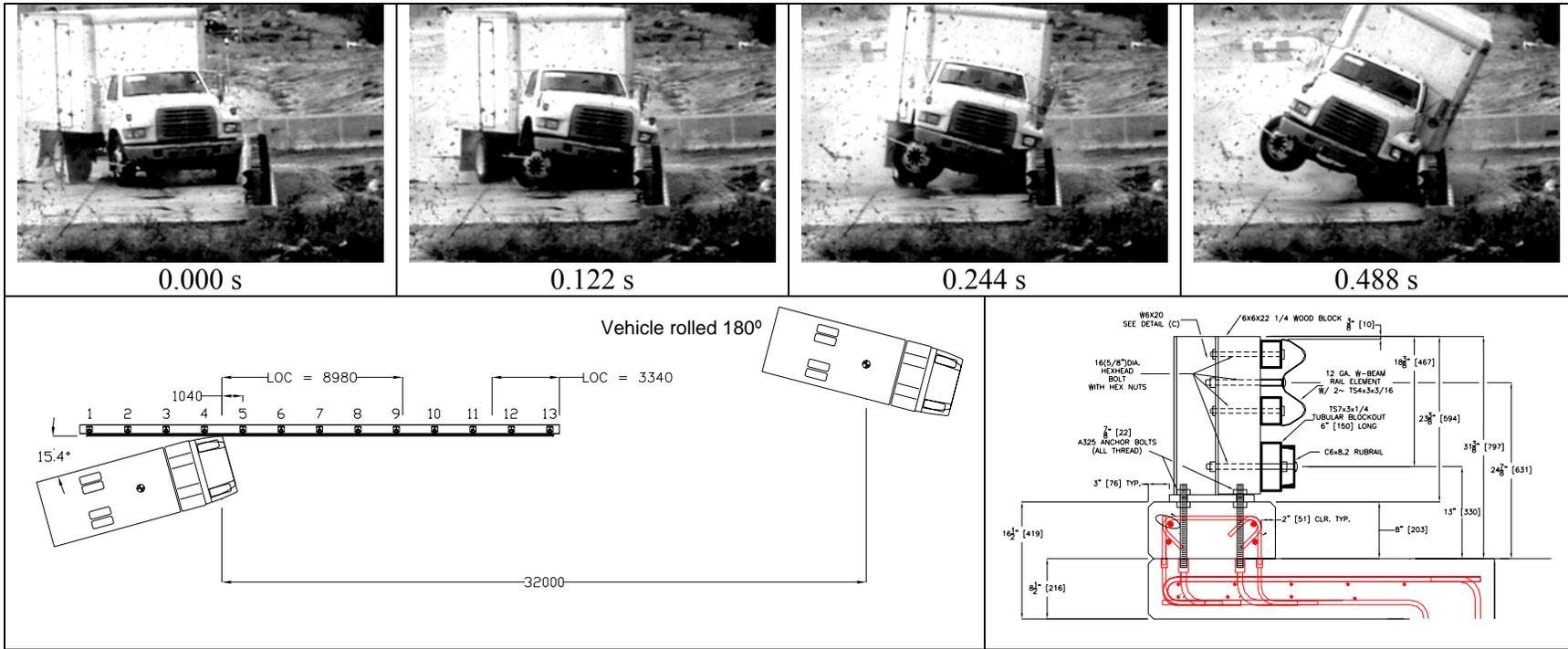


Figure 20. Installation after test 401301-2.



Figure 21. Vehicle (uprighted) after test 401301-2.



30

**General Information**

Test Agency..... Texas Transportation Institute  
 Test No. .... 401301-2  
 Date ..... 04-02-2007

**Test Article**

Type..... Bridge Rail  
 Name ..... Structure Mounted Guide Rail Barrier  
 Installation Length (m)..... 23.8  
 Material or Key Elements ..... Two tubular steel rail elements, W-beam rail element, and a rubrail supported by W6x20 steel posts

**Soil Type and Condition**

Concrete bridge deck, dry

**Test Vehicle**

Type..... Production  
 Designation..... 8000S  
 Model..... 1998 Ford F-Series Single-Unit Truck  
 Mass (kg)  
 Curb..... 4985  
 Test Inertial..... 7970

**Impact Conditions**

Speed (km/h) .....80.4  
 Angle (deg) .....15.4

**Exit Conditions**

Speed (km/h) .....Not  
 Angle (deg) .....Obtainable

**Occupant Risk Values**

Impact Velocity (m/s)  
 Longitudinal ..... 2.6  
 Lateral..... 3.4  
 THIV (km/h).....14.1  
 Ridedown Accelerations (g's)  
 Longitudinal .....-4.0  
 Lateral.....5.6  
 PHD (g's) ..... 6.6  
 ASI .....0.44  
 Max. 0.050-s Average (g's)  
 Longitudinal .....-2.1  
 Lateral..... 3.8  
 Vertical.....-1.2

**Test Article Deflections (m)**

Dynamic..... N/A  
 Permanent ..... 0.066  
 Working Width ..... 2.02

**Vehicle Damage**

Exterior  
 VDS ..... Rolled  
 CDC..... Over  
 Max. Exterior  
 Vehicle Crush (mm)..... Rolled 180  
 Interior  
 OCDI..... Rolled onto  
 Max. Occupant Compartment  
 Deformation (mm) ..... N/A

**Post-Impact Behavior**

(during 1.0 sec after impact)  
 Max. Yaw Angle (deg) ..... 25  
 Max. Pitch Angle (deg) ..... -7  
 Max. Roll Angle (deg)..... -46

Figure 22. Summary of results for NCHRP Report 350 test 4-12 on the PENNDOT Structure Mounted Guide Rail Barrier.

## SUMMARY AND CONCLUSIONS

### ASSESSMENT OF TEST RESULTS

An assessment of the test based on the following applicable *NCHRP Report 350* safety evaluation criteria.

#### **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 PENNDOT Structure Mounted Guide Rail Barrier contained and redirected the single-unit truck. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the rail was 2.6 inches (66 mm). (PASS)

#### **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 from the installation was present to penetrate, or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. Occupant compartment deformation was not able to be obtained, due to rollover. However, it is believed to be minimal, if any. (PASS)

- G. *It is preferable, although not essential, that the vehicle remain upright during and after the collision.*

Results: The single-unit truck remained upright while in contact with the bridge rail. However, as the vehicle rode off the end of the bridge rail, the vehicle rolled counterclockwise and came to rest on its top. (MARGINAL PASS)

#### **Vehicle Trajectory**

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

Result: The single-unit truck did not intrude into adjacent traffic lanes. (PASS)

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.

Result: Exit angle was not obtainable, as the vehicle rode the bridge rail out of view of the overhead camera. However, judging by the vehicle path, the exit angle was estimated to be near 0 degrees. (PASS)

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: <sup>(2)</sup>

***Passenger Compartment Intrusion***

1. *Windshield Intrusion*

a. *No windshield contact*

b. *Windshield contact, no damage*

c. *Windshield contact, no intrusion*

d. *Device embedded in windshield, no significant intrusion*

e. *Complete intrusion into passenger compartment*

f. *Partial intrusion into passenger compartment*

2. *Body Panel Intrusion*

yes or no

***Loss of Vehicle Control***

1. *Physical loss of control*

2. *Loss of windshield visibility*

3. *Perceived threat to other vehicles*

4. *Debris on pavement*

***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. *Vehicle Damage*

a. *None*

b. *Minor scrapes, scratches or dents*

c. *Significant cosmetic dents*

d. *Major dents to grill and body panels*

e. Major structural damage

2. *Windshield Damage*

a. None (none before rollover)

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 PENNDOT Structure Mounted Guide Rail Barrier contained and redirected the single-unit truck. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the rail was 2.6 inches (66 mm). No detached elements, fragments, or other debris from the installation was present to penetrate, or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. Occupant compartment deformation was not able to be obtained due to rollover. However, occupant compartment deformation was felt to be minimal, if any, prior to rollover. The single-unit truck remained upright while in contact with the bridge rail. However, as the vehicle rode off the end of the bridge rail, the vehicle rolled counterclockwise and came to rest on its top. The single-unit truck did not intrude into adjacent traffic lanes. Exit angle was not obtainable, as the vehicle rode the bridge rail out of view of the overhead camera. However, judging by the vehicle path, the exit angle was estimated to be near 0 degrees.

According to the results of the full-scale crash test, the PENNDOT Structure Mounted Guide Rail Barrier marginally passed the requirement for *NCHRP Report 350* test 4-12, as shown in table 1.

Table 1. Performance evaluation summary for *NCHRP Report 350* test 4-12 on the PENNDOT Structure Mounted Guide Rail Barrier.

Test Agency: Texas Transportation Institute

Test No.: 401301-2

Test Date: 04-02-2007

<b><i>NCHRP Report 350</i> Evaluation Criteria</b>	<b>Test Results</b>	<b>Assessment</b>
<p><b>Structural Adequacy</b></p> <p>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></p>	<p>The PENNDOT Structure Mounted Guide Rail Barrier contained and redirected the single-unit truck. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the rail was 2.6 inches (66 mm).</p>	<p>Pass</p>
<p><b>Occupant Risk</b></p> <p>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></p> <p>G. <i>It is preferable, although not essential, that the vehicle remain upright during and after collision.</i></p>	<p>No detached elements, fragments, or other debris from the installation was present to penetrate, or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. Occupant compartment deformation was not able to be obtained, due to rollover, however, it was felt to be minimal, if any.</p> <p>The single-unit truck remained upright while in contact with the bridge rail. However, as the vehicle rode off the end of the bridge rail, the vehicle rolled counterclockwise and came to rest on its top.</p>	<p>Pass</p> <p>Marginal</p>
<p><b>Vehicle Trajectory</b></p> <p>K. <i>After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</i></p>	<p>The single-unit truck did not intrude into adjacent traffic lanes.</p>	<p>Pass*</p>
<p>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></p>	<p>Exit angle was not obtainable, as the vehicle rode the bridge rail out of view of the overhead camera. However, judging by the vehicle path, the exit angle was estimated to be near 0 degrees.</p>	<p>Pass *</p>

\*Criterion K and M are preferable, not required.

## REFERENCES

1. H.E. Ross, Jr., D.L. Sicking, R.A. Zimmer and J.D. Michie, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program Report 350, Transportation Research Board, National Research Council, Washington, D.C., 1993.
2. Federal Highway Administration Memorandum, from the Director, Office of Engineering, entitled: "ACTION: Identifying Acceptable Highway Safety Features," dated July 25, 1997.



## **APPENDIX A. 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 backup biaxial accelerometer in the rear of the vehicle to measure longitudinal and lateral acceleration levels. These accelerometers were ENDEVCO<sup>®</sup> Model 2262CA, piezoresistive accelerometers with a  $\pm 100$  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  $\pm 2.5$  volt maximum level. The signal conditioners also provide the capability of an R-cal (resistive calibration) 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 (IRIG), FM/FM telemetry link for recording and for display. 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 TEAC<sup>®</sup> instrumentation data recorder. After the test, the data are played back from the TEAC<sup>®</sup> recorder 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<sup>®</sup> 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-milliseconds (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.

## **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 mini-DV camera and still cameras recorded and documented 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 vehicle 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.

## APPENDIX B. TEST VEHICLE PROPERTIES AND INFORMATION

Date: 04-02-2007 Test No.: 401301-2 VIN No.: 1FDNF70J6WVAG2882

Year: 1998 Make: Ford Model: F-Series

Tire Inflation Pressure: 90/100 psi Odometer: 178579 Tire Size: 295/275R22.5

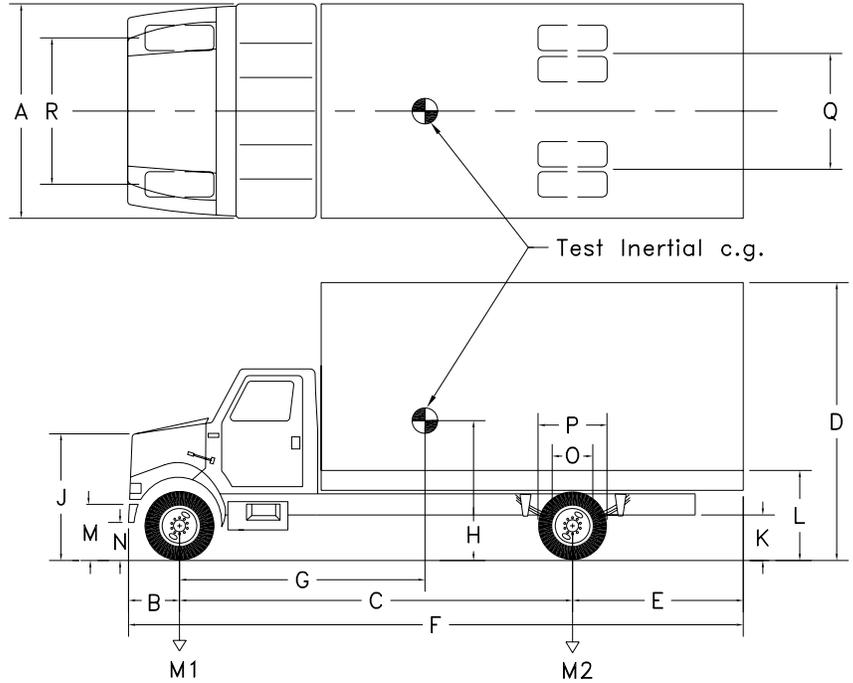
Describe any damage to the vehicle prior to test: \_\_\_\_\_

⊕ Denotes accelerometer location.

NOTES: \_\_\_\_\_  
 \_\_\_\_\_  
 \_\_\_\_\_

Accelerometer Locations (mm):

	x	y	z
f	_____	_____	_____
c	_____	_____	_____
r	_____	_____	_____



**Geometry (mm)**

A	<u>2438</u>	E	<u>2553</u>	J	<u>1638</u>	N	<u>489</u>	R	<u>2019</u>
B	<u>864</u>	F	<u>7760</u>	K	<u>676</u>	O	<u>597</u>	S	_____
C	<u>4343</u>	G	<u>2620.38</u>	L	<u>1135</u>	P	<u>994</u>		
D	<u>3366</u>	H	_____	M	<u>802</u>	Q	<u>1880</u>		

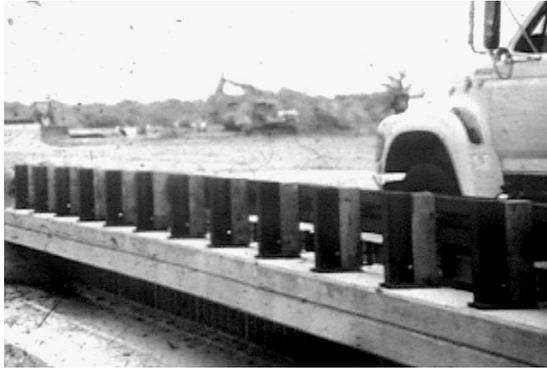
Mass (kg)	Curb	Test Inertial	Gross Static
M <sub>1</sub>	<u>2291</u>	<u>3162</u>	_____
M <sub>2</sub>	<u>2694</u>	<u>4808</u>	_____
M <sub>Total</sub>	<u>4985</u>	<u>7970</u>	_____

Mass Distribution (kg): LF: 1656 RF: 1506 LR: 2522 RR: 2286

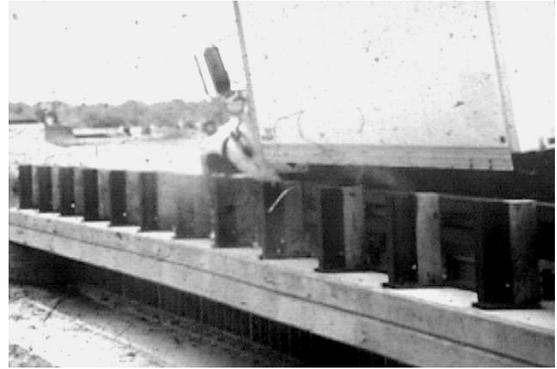
Figure 23. Vehicle properties for test 401301-2.



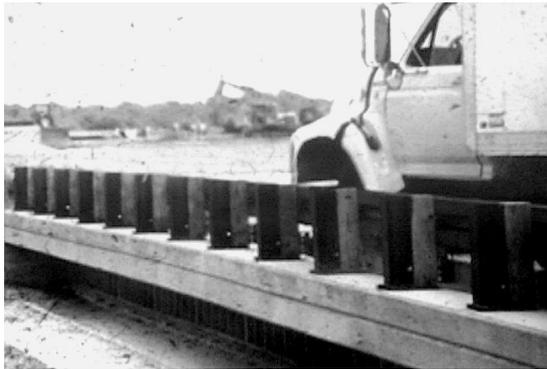
## APPENDIX C. SEQUENTIAL PHOTOGRAPHS



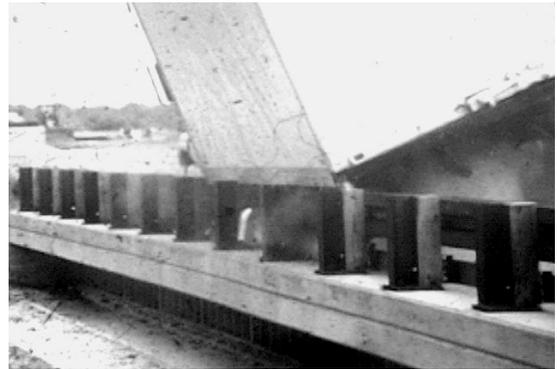
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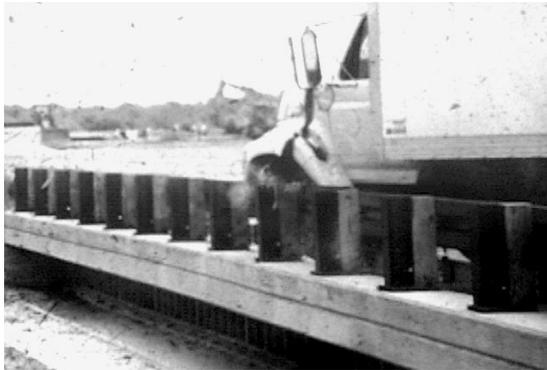
0.244 s



0.061 s



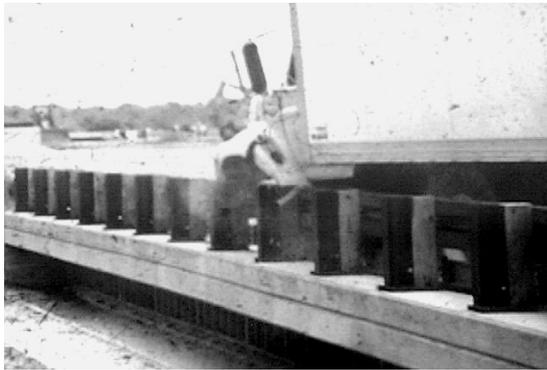
0.366 s



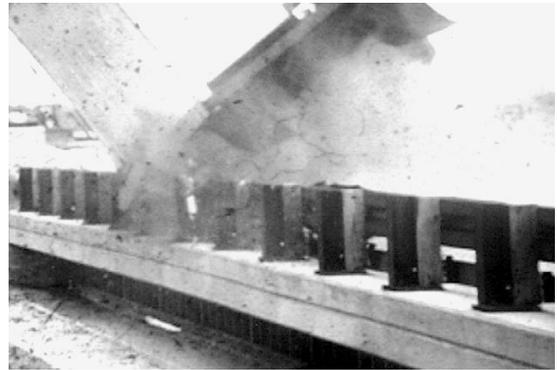
0.122 s



0.488 s

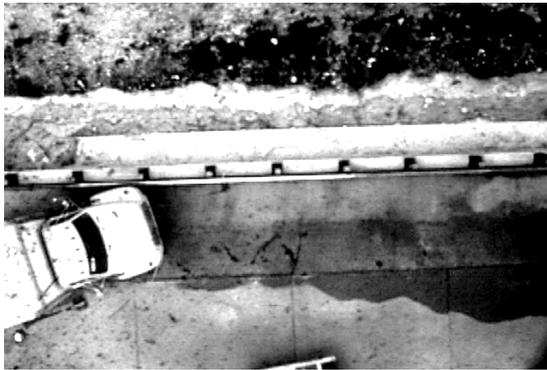


0.183 s



0.610 s

Figure 24. Sequential photographs for test 401301-2 (rear view).



0.000 s



0.061 s



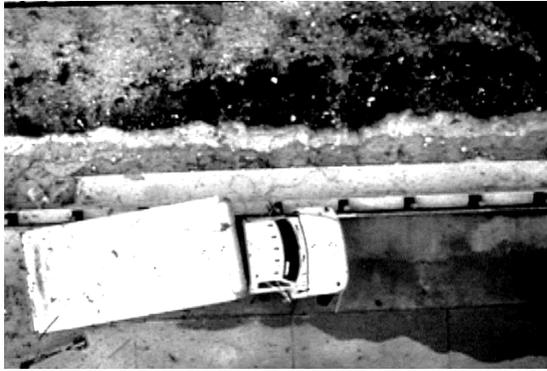
0.122 s



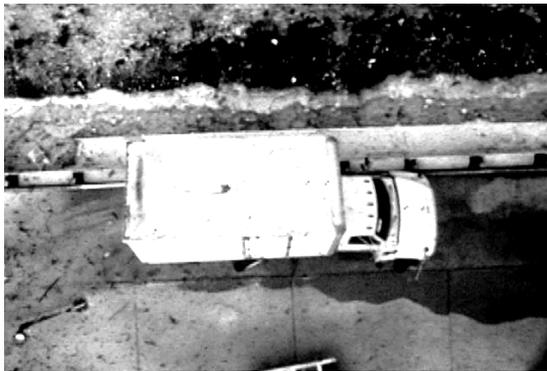
0.183 s



Figure 25. Sequential photographs for test 401301-2 (overhead and frontal views).



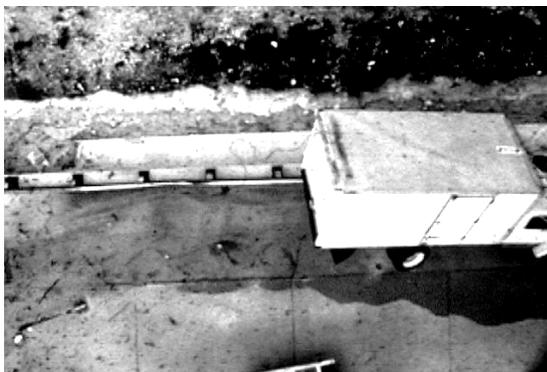
0.244 s



0.366 s



0.488 s



0.610 s



Figure 25. Sequential photographs for test 401301-2 (overhead and frontal views) (continued).



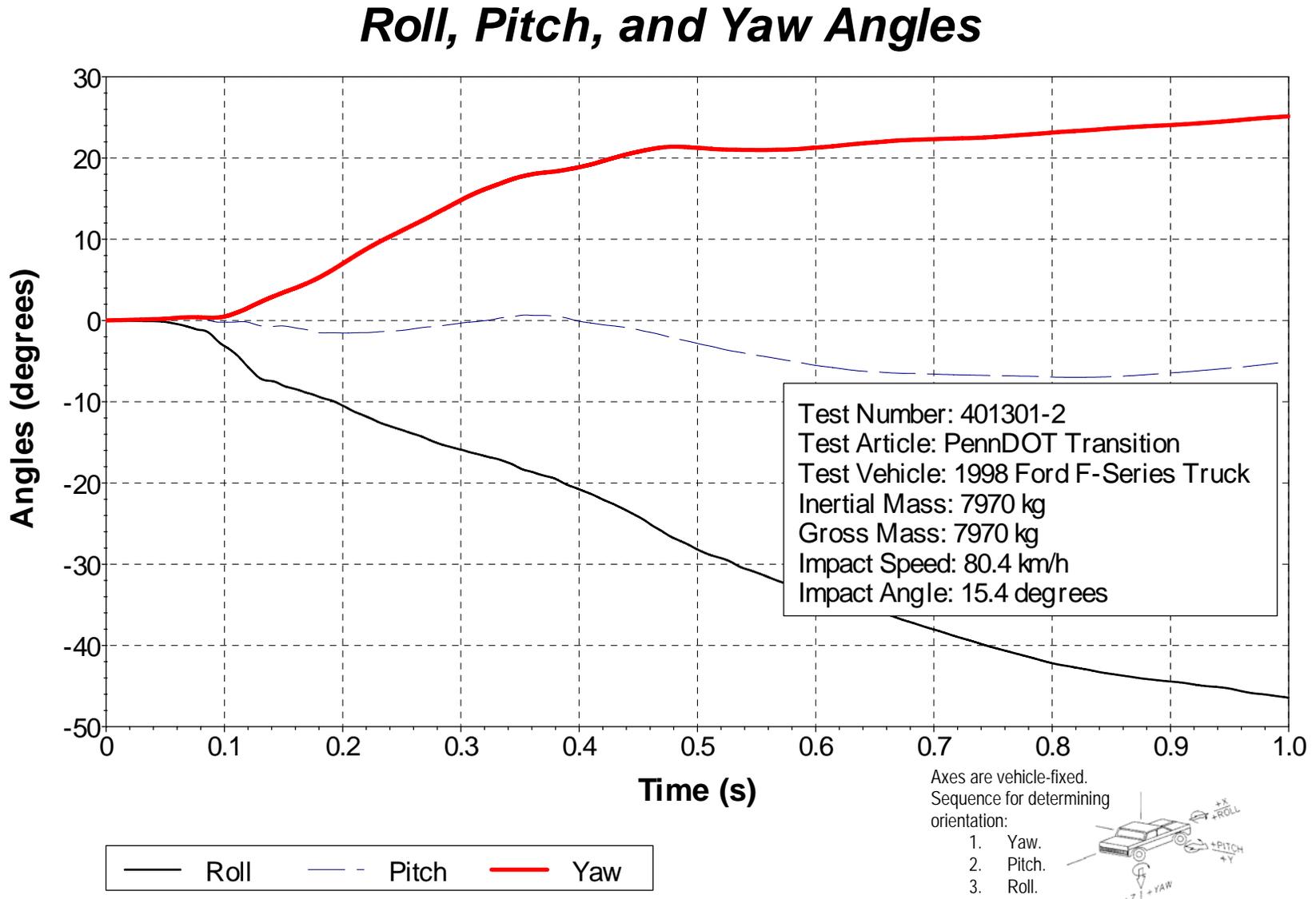


Figure 26. Vehicle angular displacements for test 401301-2.

# X Acceleration at CG

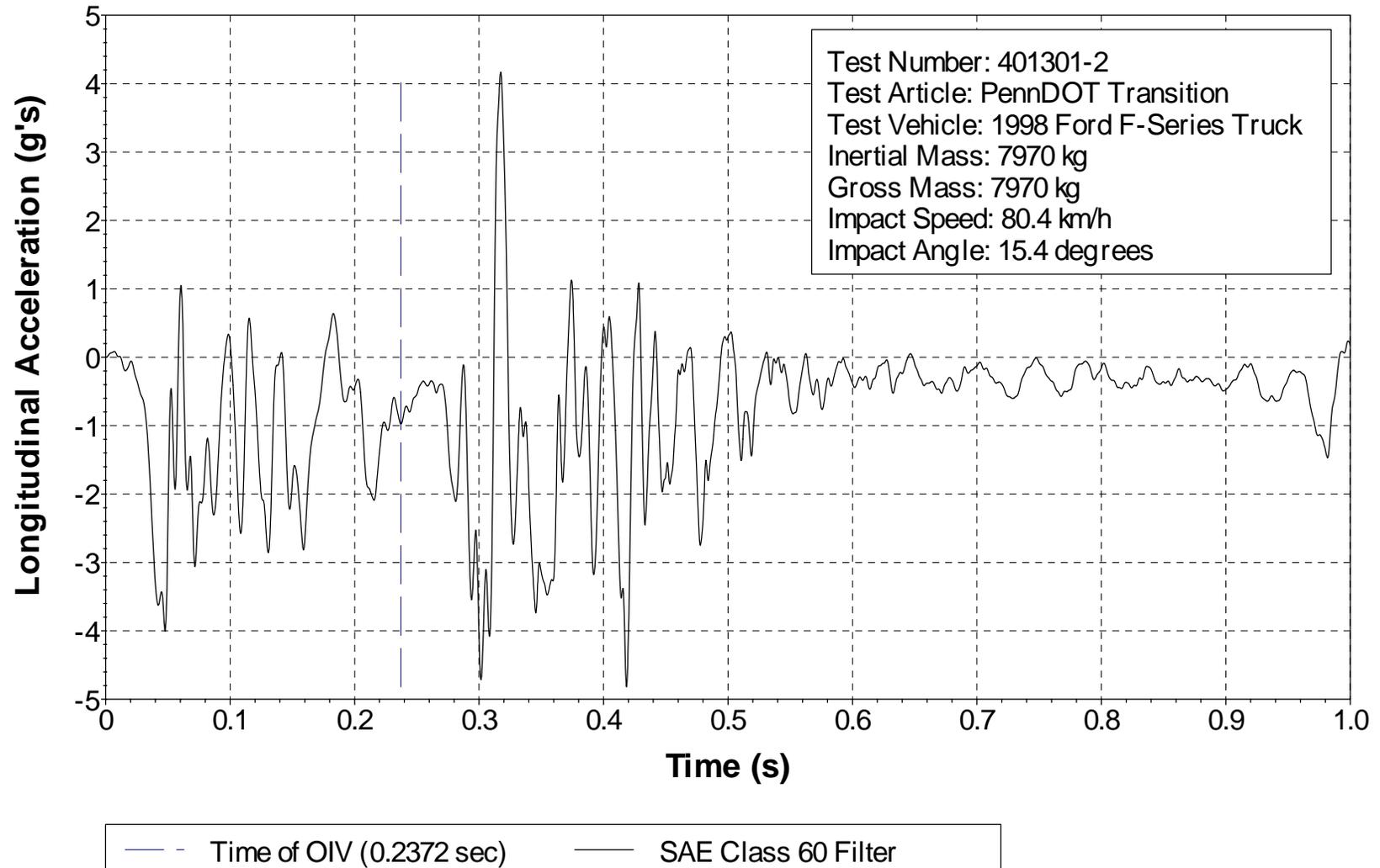
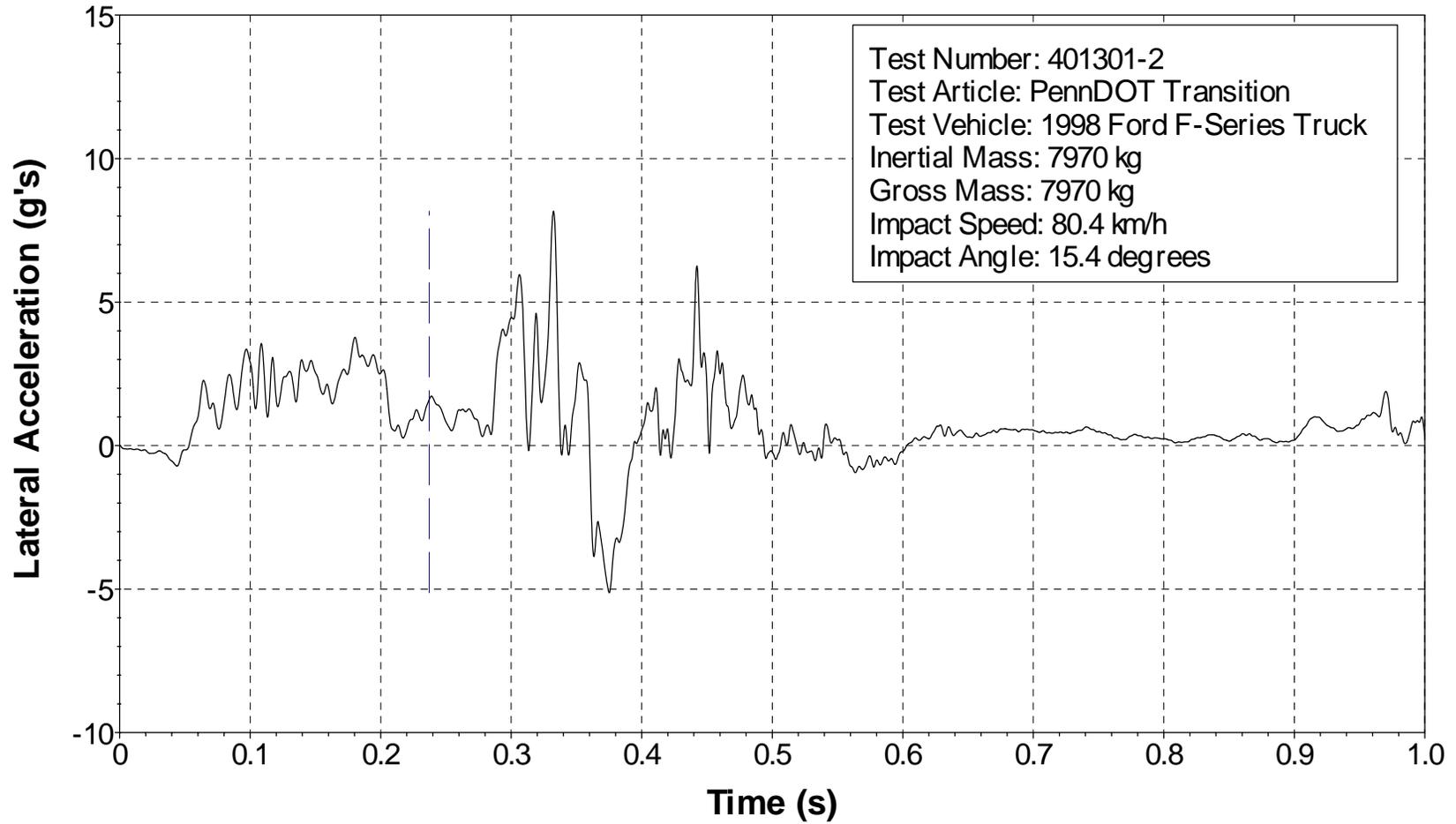


Figure 27. Vehicle longitudinal accelerometer trace for test 401301-2 (accelerometer located at center of gravity).

# Y Acceleration at CG

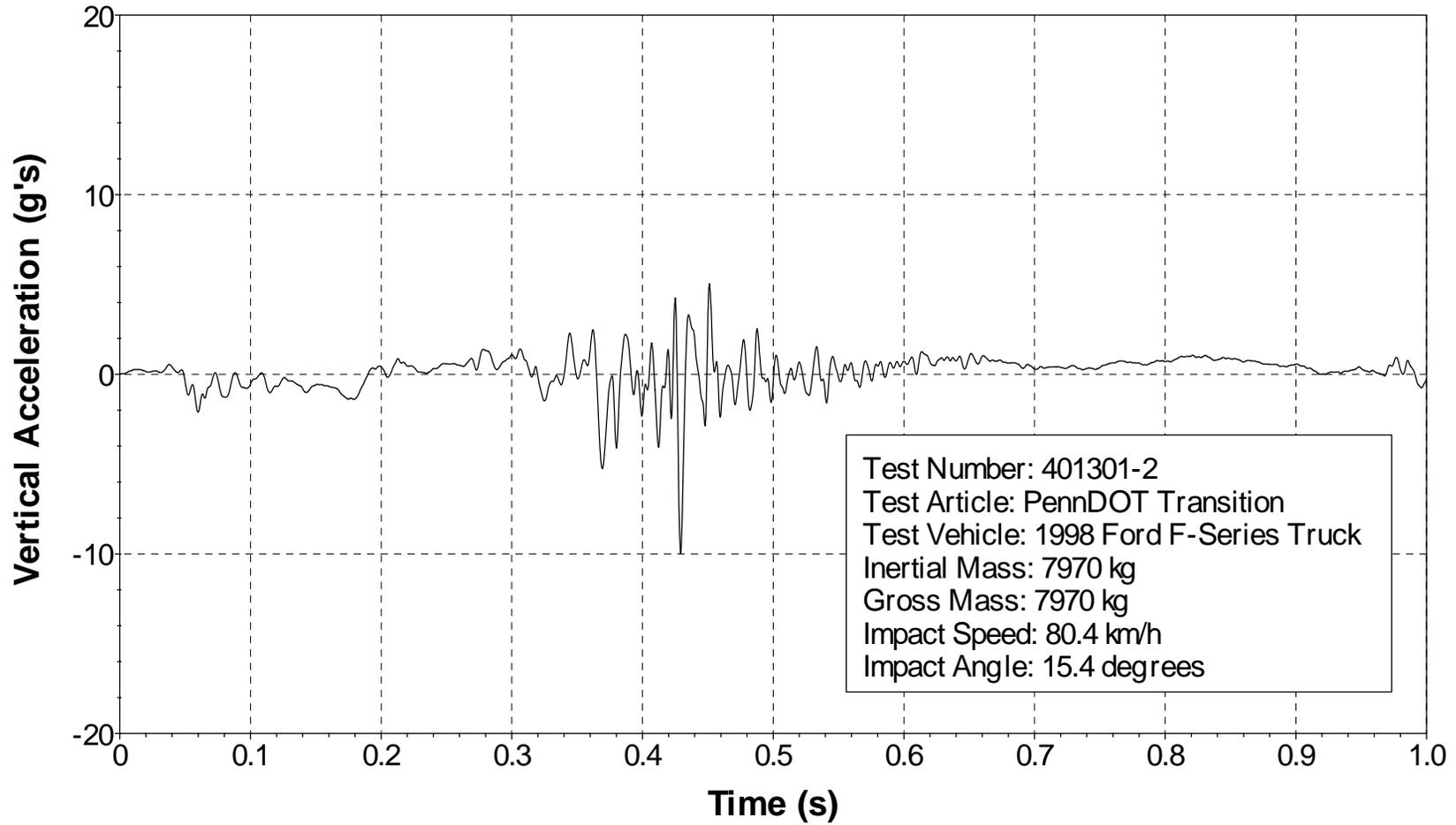


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— Time of OIV (0.3326 sec)      — SAE Class 60 Filter

Figure 28. Vehicle lateral accelerometer trace for test 401301-2 (accelerometer located at center of gravity).

# Z Acceleration at CG



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Figure 29. Vehicle vertical accelerometer trace for test 401301-2 (accelerometer located at center of gravity).

# *X Acceleration over Rear Axle*

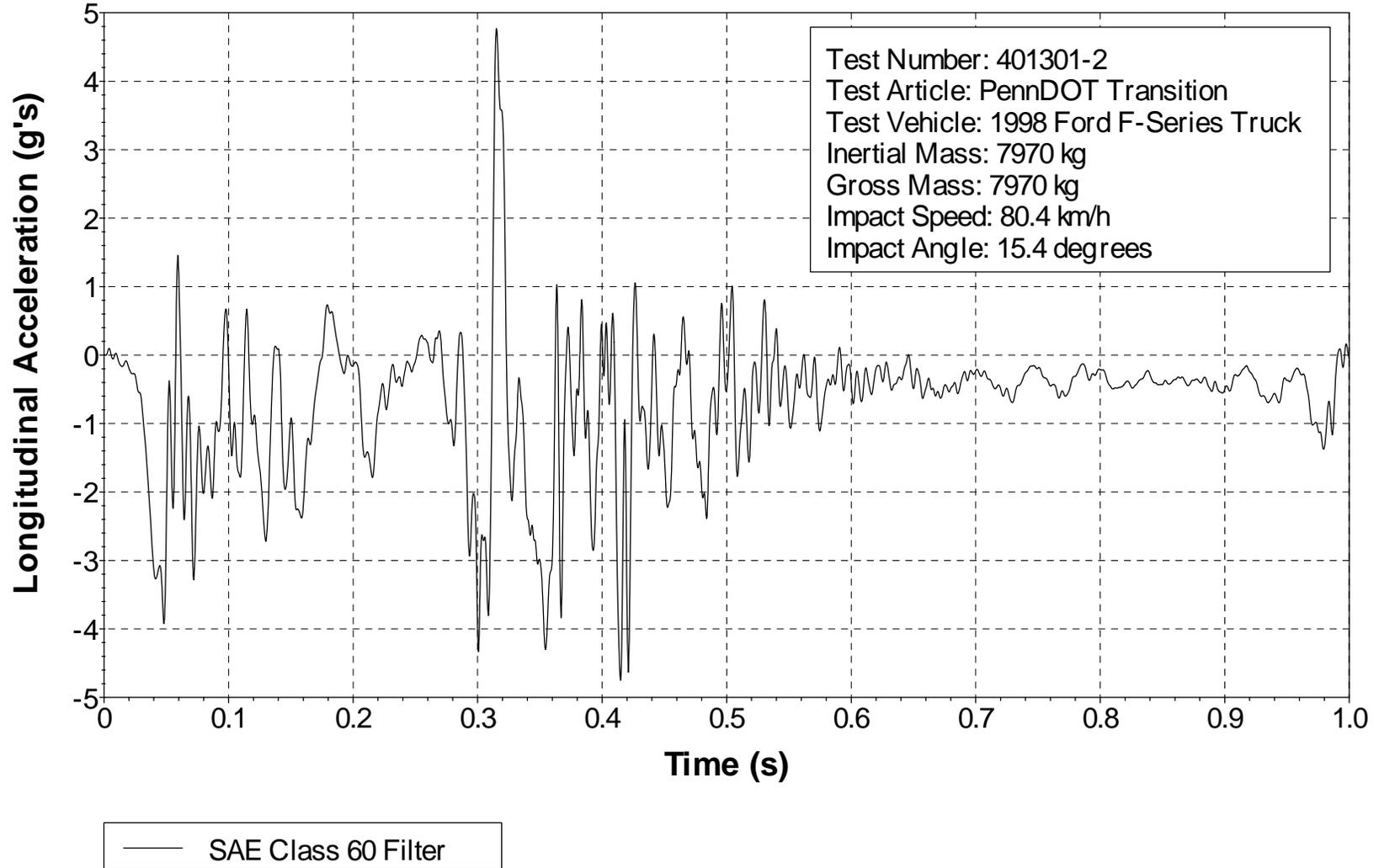


Figure 30. Vehicle longitudinal accelerometer trace for test 401301-2 (accelerometer located over rear axle).

# Y Acceleration over Rear Axle

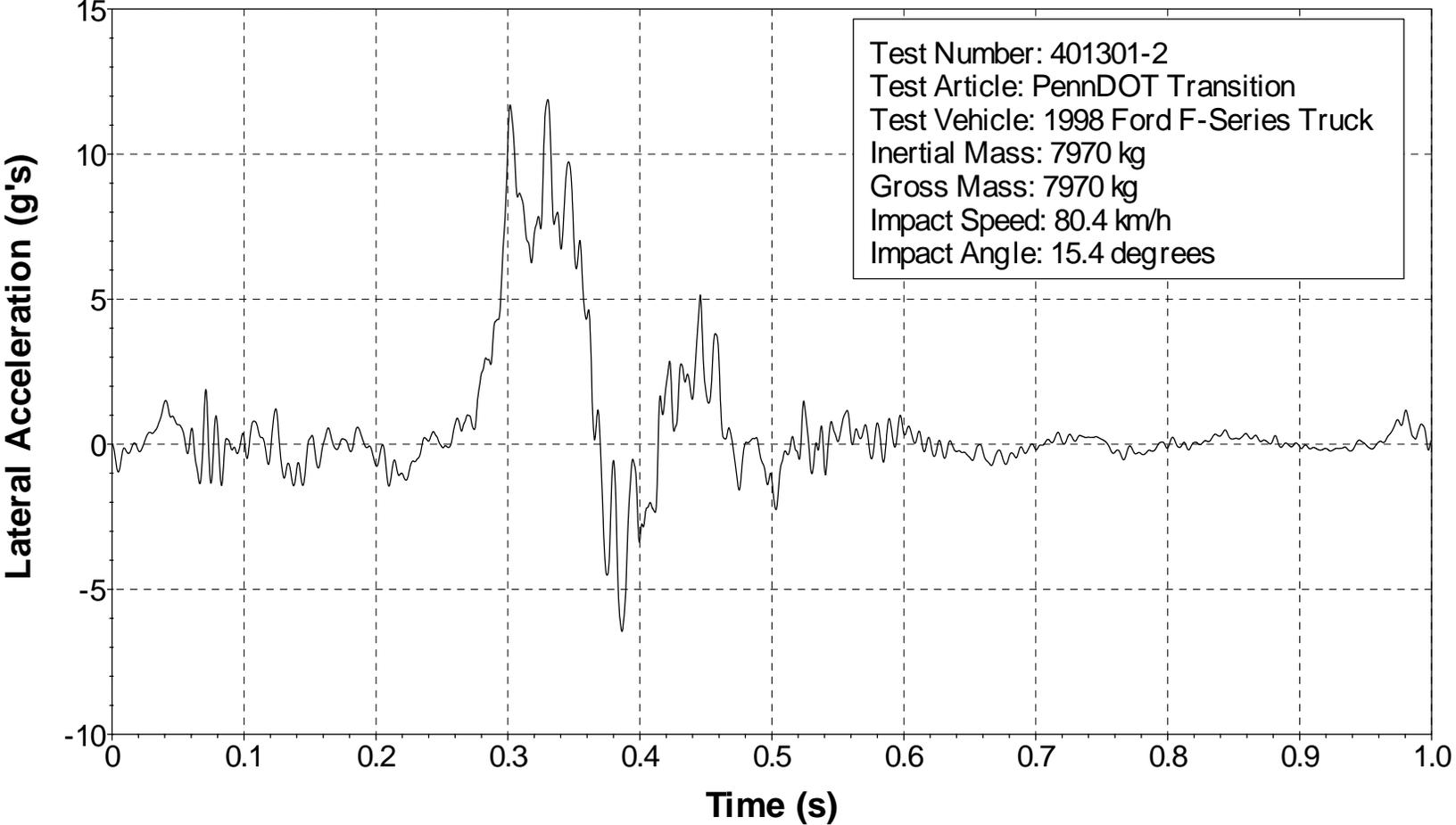


Figure 31. Vehicle lateral accelerometer trace for test 401301-2 (accelerometer located over rear axle).

# Z Acceleration over Rear Axle

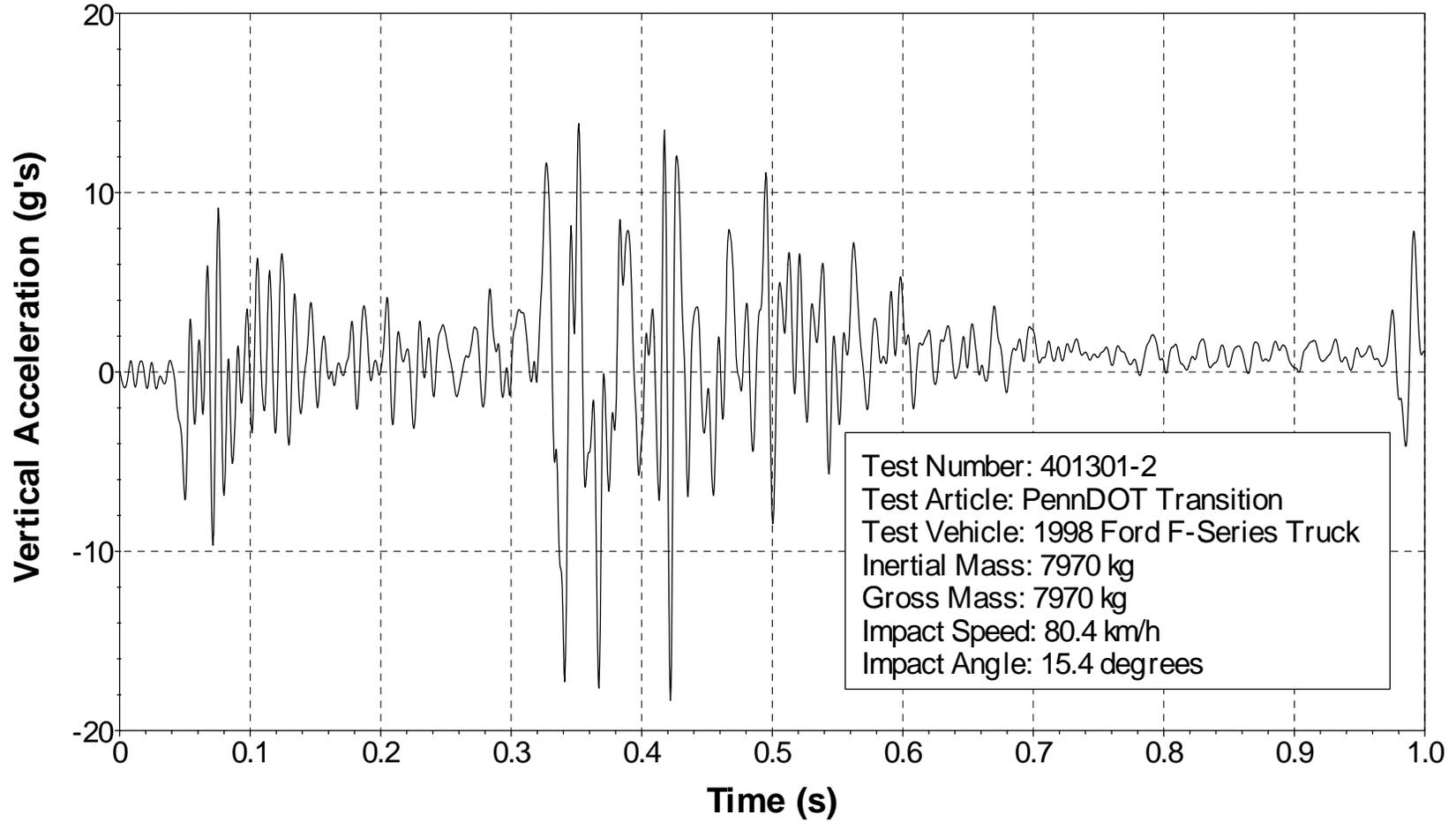


Figure 32. Vehicle vertical accelerometer trace for test 401301-2 (accelerometer located over rear axle).