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CRASH TESTING AND EVALUATION OF W-BEAM GUARDRAIL ON BOX CULVERT

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DISCLAIMER

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16. Abstract

The primary objective of this project was to test and evaluate a guardrail design with standard post spacing for use across low-fill box culverts in accordance with *NCHRP Report 350* TL-3. A second objective of this project, was to develop a W6x9 post with welded base plate detail for use with an epoxy anchoring system that simplifies installation. Posts anchored to a simulated concrete box culvert using the Hilti RE500 Epoxy anchoring system were evaluated through pendulum testing. The strength of the base plate, post welds, and anchoring system was sufficient to result in plastic failure of the posts under an impact load. The W6x9 post and anchorage detail was subsequently incorporated into the full-scale crash test installation.

NCHRP Report 350 test 3-11 was performed to evaluate the guardrail system across low-fill culvert. The W-beam rail element was ruptured by the impact from the vehicle. Even though the rail element was ruptured, the vehicle was contained and redirected without penetrating, underriding, or overriding the installation. The rail element ruptured after the vehicle was redirected and while it was exiting out of the barrier system.

Based on the review of all available test data, the W-Beam Guardrail on Box Culvert met the required criteria for TL-3 according to the specifications for *NCHRP Report 350* test 3-11. The adhesive anchoring system worked as designed with the new W6x9 post and welded baseplate detail. No damage to the deck or failure of the adhesive anchors was observed. The new adhesive anchoring system is considered suitable for implementation as an alternative to through-bolted anchorage in successfully crash tested guardrail systems designed for use across low-fill culverts.

17. Key Words
Box culvert, guardrail, drainage structure, roadside safety, crash testing.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
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
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*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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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

INTRODUCTION

PROBLEM

New or replacement guardrail installations frequently must pass over new or existing reinforced concrete box culverts for various types of highways. In many cases, the depth of fill over the box culvert is very shallow and it will not allow the proper length of steel or timber posts to be installed without interfering with the concrete box culvert. A typical detail in these cases is a shortened W6x9 or W6x20 steel post attached to a steel base plate bolted into the box culvert. For existing box culverts, a proprietary epoxy injected bolt system or equivalent is often desirable. The use of an epoxy adhesive anchoring system would permit installation of the post without the need to enter in the culvert and install a bolt-thru anchoring system. This type of bolt-thru anchoring system can be difficult to install and hazardous to workers. This project addresses the use of anchoring W6x9 guardrail post using a proprietary epoxy adhesive anchoring system with a shallow soil cover on top of the box culvert.

BACKGROUND

In 1988, Hirsch and Beggs reported on a study using a W6x9 steel guardrail post with a base plate anchored to a 6-inch thick culvert slab. [(1)] Static load tests and a full-scale crash test were performed on this design as part of this study. The testing performed on this design was successful with respect to National Cooperative Highway Research Program (NCHRP) *Report 230* performance level 2. [(2)] In 2002, Polivka, Reid, Faller, Rohde, and Sicking reported on a similar design bolted to a box culvert with approximately 9 inches of fill on top of the box culvert. [(3)] The objective of this research was to develop a strong-post, W-beam guardrail system that can be rigidly attached to the surface of concrete box culverts. This new guardrail system with one-half post spacing (3 ft-1-1/2 inch) was designed to meet the Test Level 3 (TL-3) performance criteria found in *NCHRP Report 350*. [(4)] Dynamic pendulum and full scale crash testing on this design was also successful. Information from these studies as well as other research were used to develop a new box culvert guardrail post design that meets TL-3 requirements.

OBJECTIVES/SCOPE OF RESEARCH

The primary objective of this project was to test and evaluate a guardrail design with standard post spacing for use across low-fill box culverts in accordance with *NCHRP Report 350* TL-3.

A second objective of this project, was to develop a W6x9 post with welded base plate detail for use with an epoxy anchoring system that would simplify installation. Posts anchored to the simulated concrete box culvert using the Hilti RE500 Epoxy anchoring system were evaluated through pendulum testing. The strength of the base plate, post welds, and anchoring system was sufficient to result in a plastic failure of the posts under an impact load. The W6x9 post and anchorage detail was subsequently incorporated into the full-scale crash test installation.

Included in this report are the details of the strength analyses and pendulum testing performed on the post anchorage system, details of the installations used in both the pendulum testing and the crash testing, details of the full-scale crash testing, and evaluation of the crash test.

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 W-beam guardrail on box culvert is along the edge of a wide out-of-service apron. The apron consists of an unreinforced jointed concrete pavement in 15 ft by 12.5 ft blocks nominally 8-12 inches mm deep. The aprons are over 50 years old and the joints have some displacement, but are otherwise flat and level.

Test Article – Design and Construction

Prior to constructing the full-scale test installation, full-scale pendulum tests were performed on W6x9 steel posts anchored to smaller deck sections as previously described. Two pendulum tests were performed on two W6x9 steel posts anchored to the deck specimens. Each post was anchored using four 7/8-inch diameter Super Hilti Anchoring System (HAS) rods. The rods were anchored to the concrete using Hilti's RE500 epoxy anchoring system. Full-scale pendulum testing performed on the post and base plate connection design revealed that the base plate connection strength was suitable to resist the ultimate plastic bending strength of the W6x9 steel shape. The results of the pendulum testing served to validate the calculated strength of the base plate and anchor design for the W6x9 steel post. For addition information on the pendulum testing, please refer to the pendulum test report provided in appendix B.

The base plate connection design utilizing 7/8-inch diameter A193 HAS threaded rods and anchored using Hilti's RE500 epoxy adhesive anchoring systems was adequate to develop the plastic strength of the W6x9 posts. This base plate connection was designed to resist the full plastic bending strength of the W6.9 post. Based on the results from the full-scale pendulum testing on the W6x9 post design, the similar design performed on the W8x21 would also likely develop the full plastic strength of this larger post size. The W8x21 base plate connection was also designed to resist the plastic bending strength of the W8x21 post. One of the intended applications of the W8x21 post is for stiffening guardrail in the vicinity of bridge piers when the standard design cannot be accommodated. In such situations, the guardrail posts may need to be bolted to the surface of a spread footing.

The W-Beam Guardrail on Box Culvert installation consisted of a 12 gauge W-beam guardrail system supported by W6x9 steel posts anchored to a simulated box culvert. Standard

6 inch x 8 inch x 14 inch long wood blockouts were used to block out the W-beam guardrail from the steel posts. The height of the W-beam guardrail system was 27 inches from finished grade. The posts were spaced on 6 ft - 3 inches on centers. The posts were anchored to the top of a simulated box culvert slab using Hilti RE500 epoxy anchoring system. For this test installation, 9 inches of compacted *NCHRP Report 350* standard soil material was constructed on top of the simulated box culvert slab. The total length of the simulated concrete slab was 105 ft. The W-beam guardrail system was anchored on each end using ET Plus extruder terminals. TTI received detailed information regarding the box culvert slab from Mike Elle with Minnesota DOT. These details were incorporated into the box culvert slab installation tested for this project, which can be found in figures 1 through 7.

The W6x9 steel posts were welded to 12 inch x 12 inch x 7/8 inch thick base plates. The total length of the posts was 37 inches. Each steel post with base plate was anchored to the 9-inch thick simulated box culvert slab using four 7/8-inch diameter A193 Super HAS all-threaded rods, 8½ inches in length. These threaded rods were embedded 6 inches in the box culvert slab and were anchored using HILTI RE500 Epoxy Anchoring System. Prior to performing this full scale crash test, structural analyses were performed on the steel post, base plate, and epoxy anchoring system. The size and thickness of the base plate, as well as the final details of the epoxy anchor rods, were determine from these analyses. A copy of the strength analyses performed on the W6x9 steel post and base plate can be found in appendix A. Based on information supplied from the supporting pooled fund states, separate analyses were performed on a similar post design (W8x21) that can be attached to a shallow footing. In cases where a post is anchored to a shallow footing, a deeper embedment would likely be provided since the thickness of the footing is likely greater than the 9 inches used for the box culvert slab. A copy of the analyses performed on the W8x21 steel post anchored to a concrete footing is also included in Appendix A. Please refer to figures 2 and 5 for additional details on the W6x9 steel post and base plate design tested for this project.

The simulated box culvert slab tested was 105 ft in length by 75 inches in width by 9 inches thick. The fill height constructed on top of the box culvert slab was 9 inches. A 9-inch high by 10-inch wide concrete headwall was constructed on the field side edge of the box culvert slab. The W6x9 steel posts were located 28 inches from the field side edge of the simulated box culvert slab. Transverse steel reinforcement in the slab consisted of #3 bars spaced at 12 inches on centers in the top and bottom mats. Longitudinal steel reinforcement in the bottom mat of steel reinforcement consisted of #5 bars spaced at 4½ inches on centers. Longitudinal steel reinforcement in the top mat of steel reinforcement consisted of #3 bars spaced at 6 inches on centers. Transverse reinforcement in the 9-inch high headwall consisted of #3 stirrups spaced at 12 inches on centers. Four #3 longitudinal steel bars were evenly spaced inside the stirrup reinforcement in the headwall. The specified concrete strength used in the box culvert slab was 5000 psi compressive strength. Please refer to figures 1 through 7 for additional information on the box culvert slab test installation. Photographs of the completed installation are shown in figure 8.

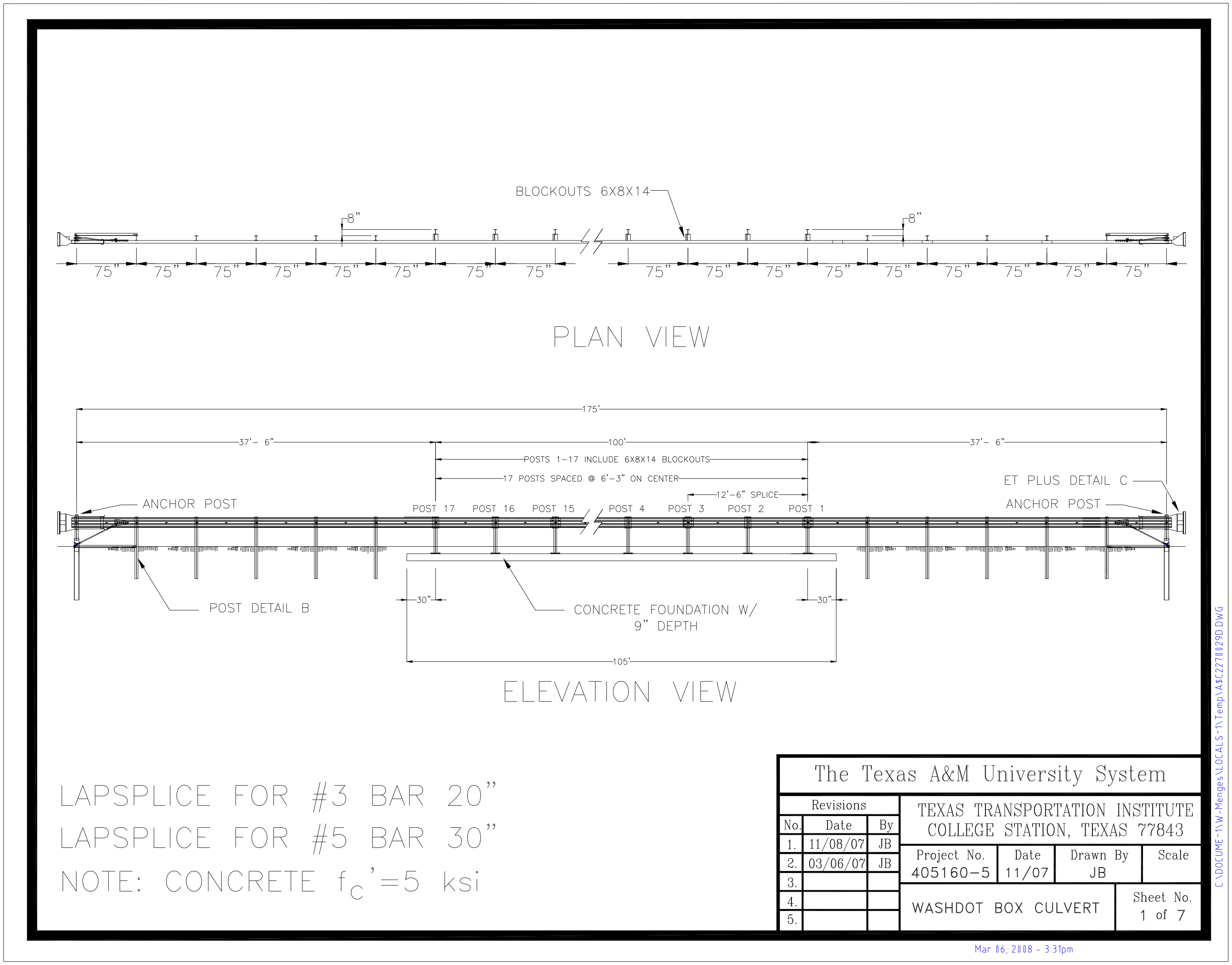


Figure 1. Layout of the W-Beam Guardrail on Box Culvert installation.

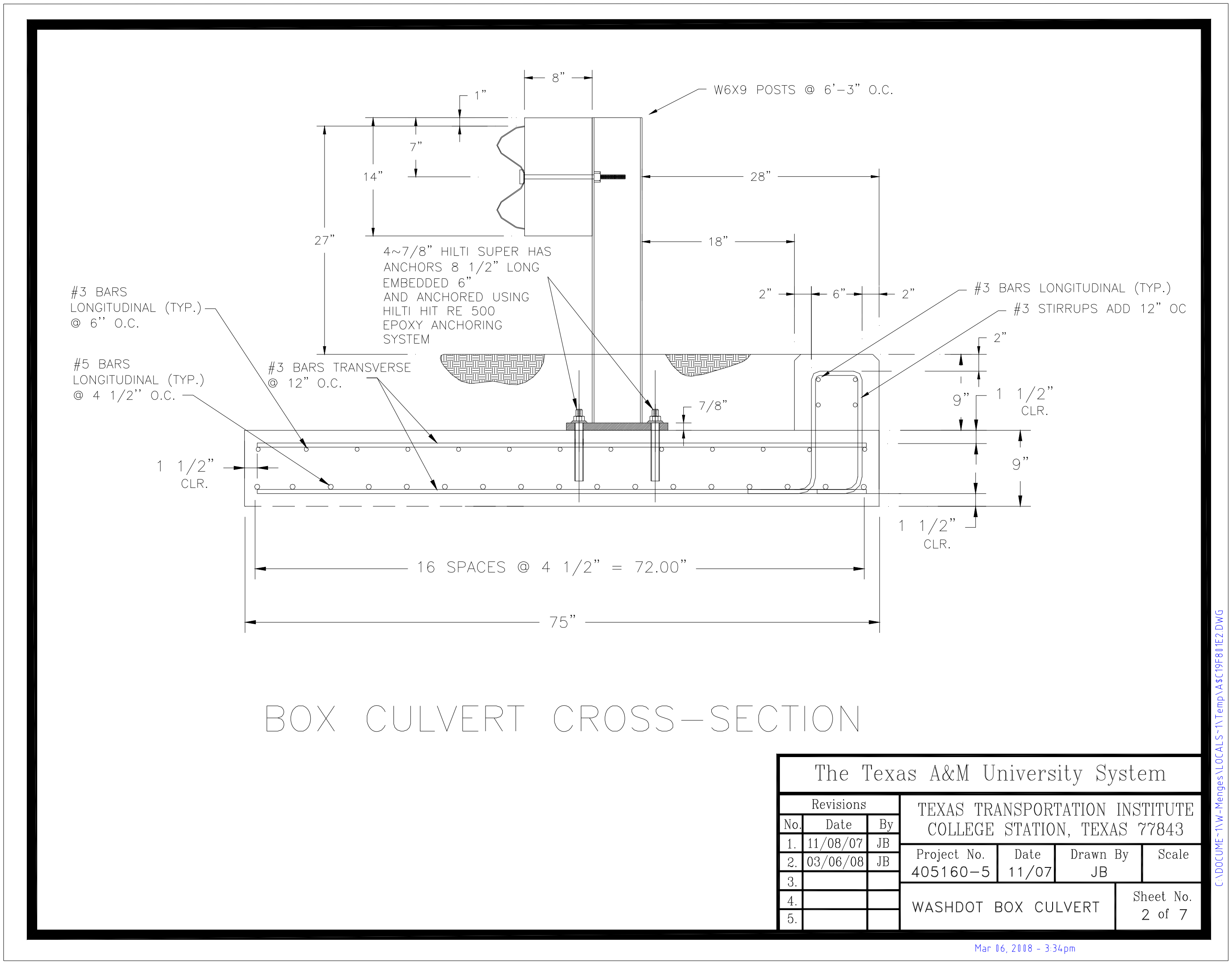


Figure 2. Cross section of the W-Beam Guardrail on Box Culvert installation.

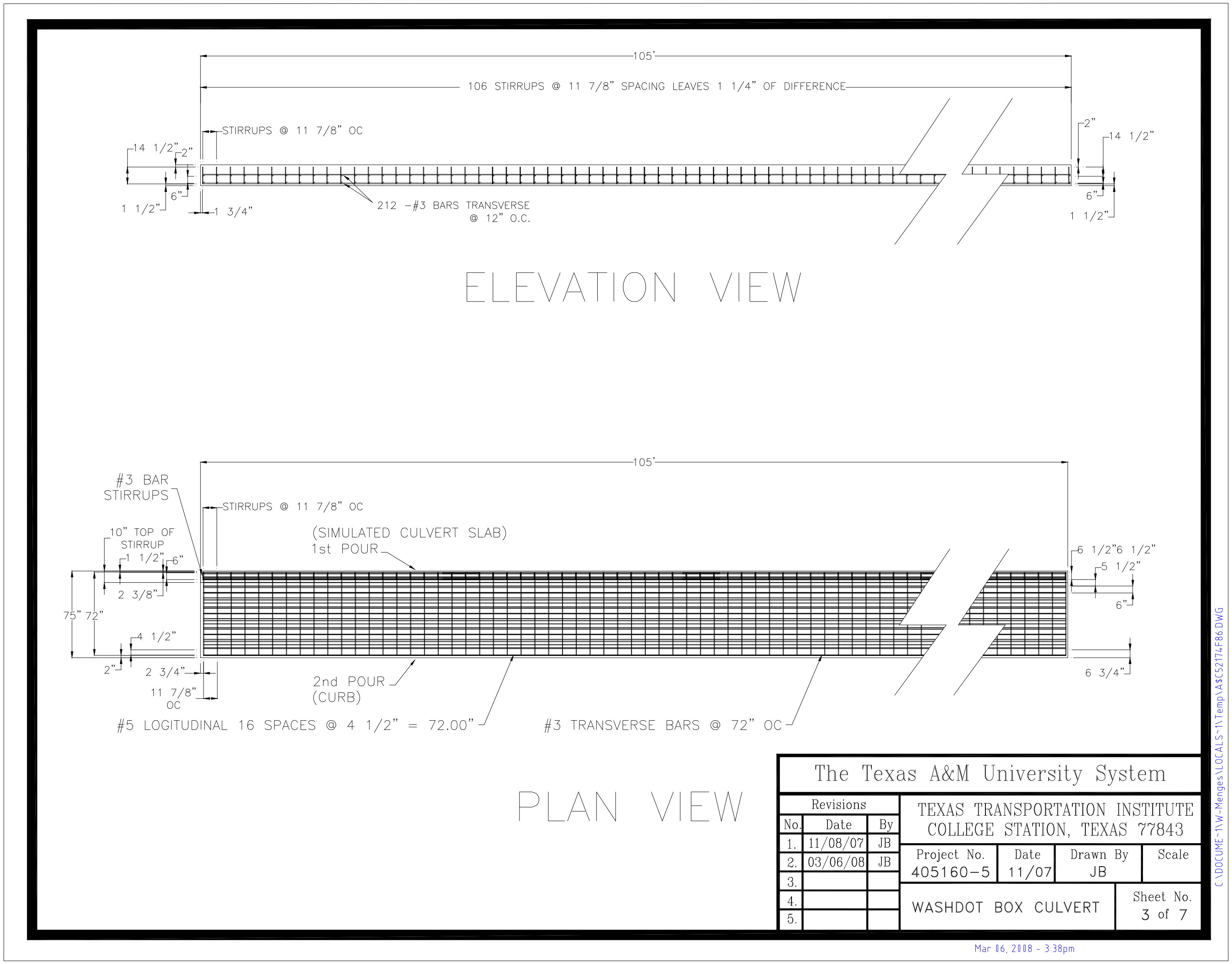


Figure 3. Rebar detail of the W-Beam Guardrail on Box Culvert installation.

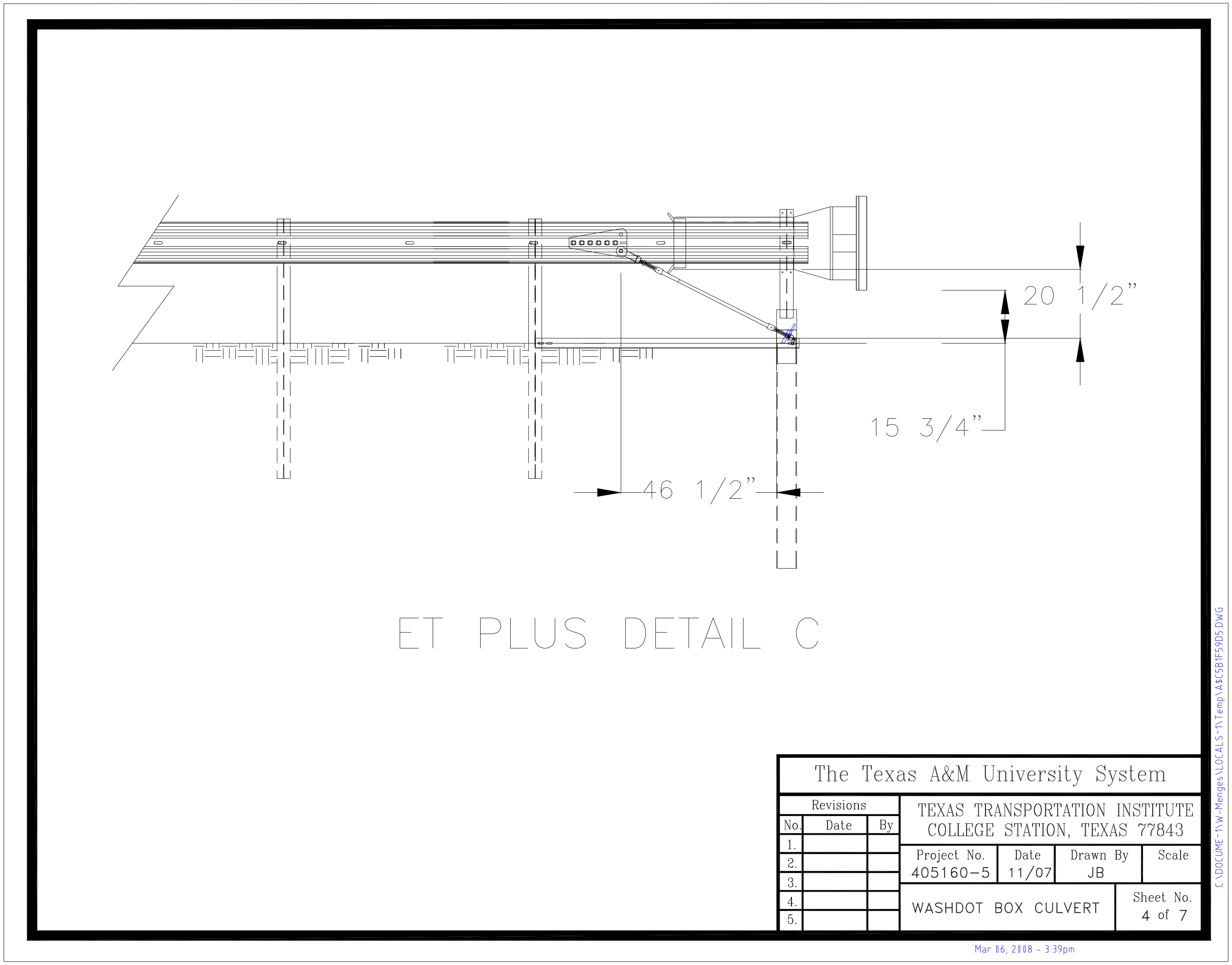


Figure 4. Terminal details for the W-Beam Guardrail on Box Culvert installation.

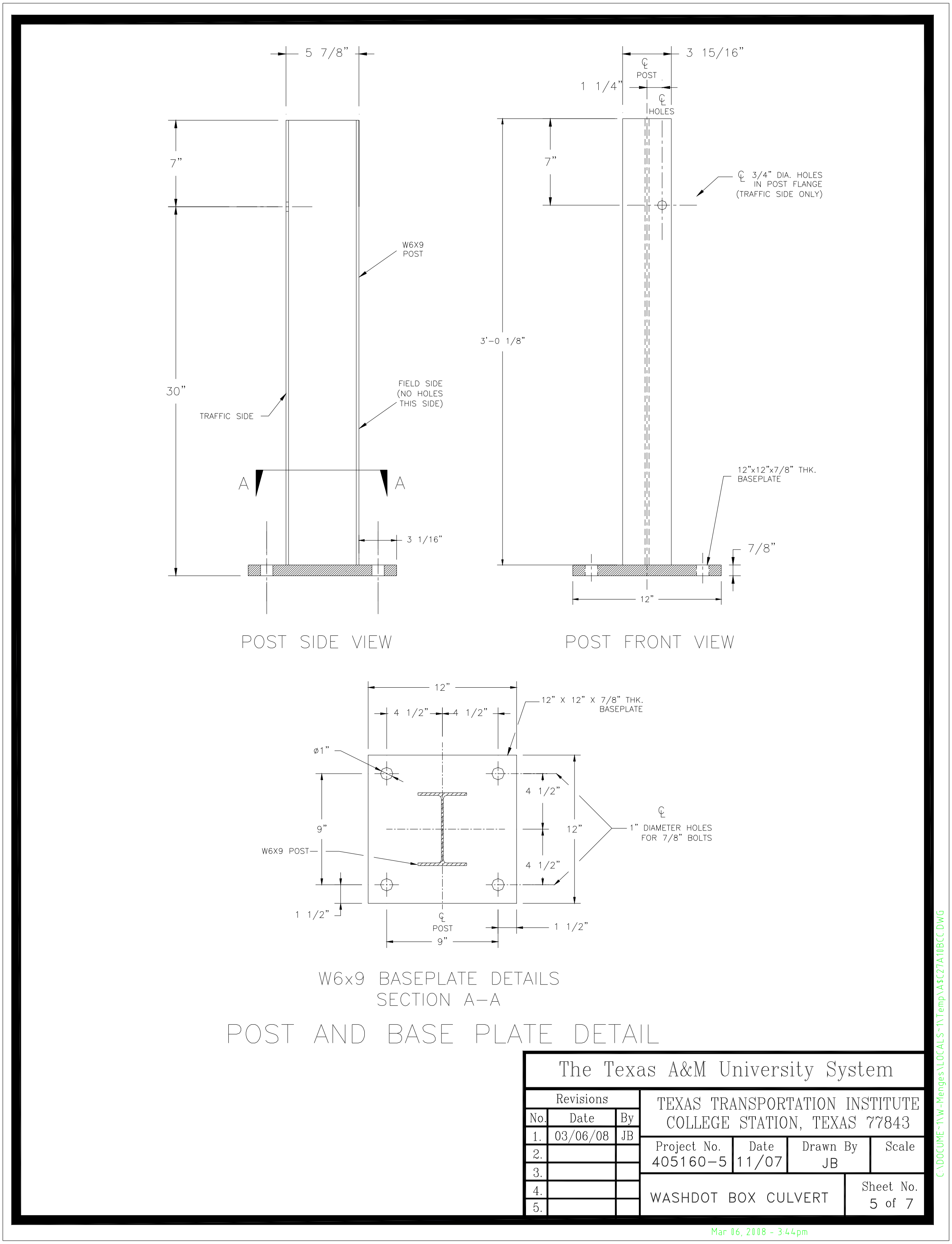


Figure 5. Post and base plate details for the W-Beam Guardrail on Box Culvert installation.

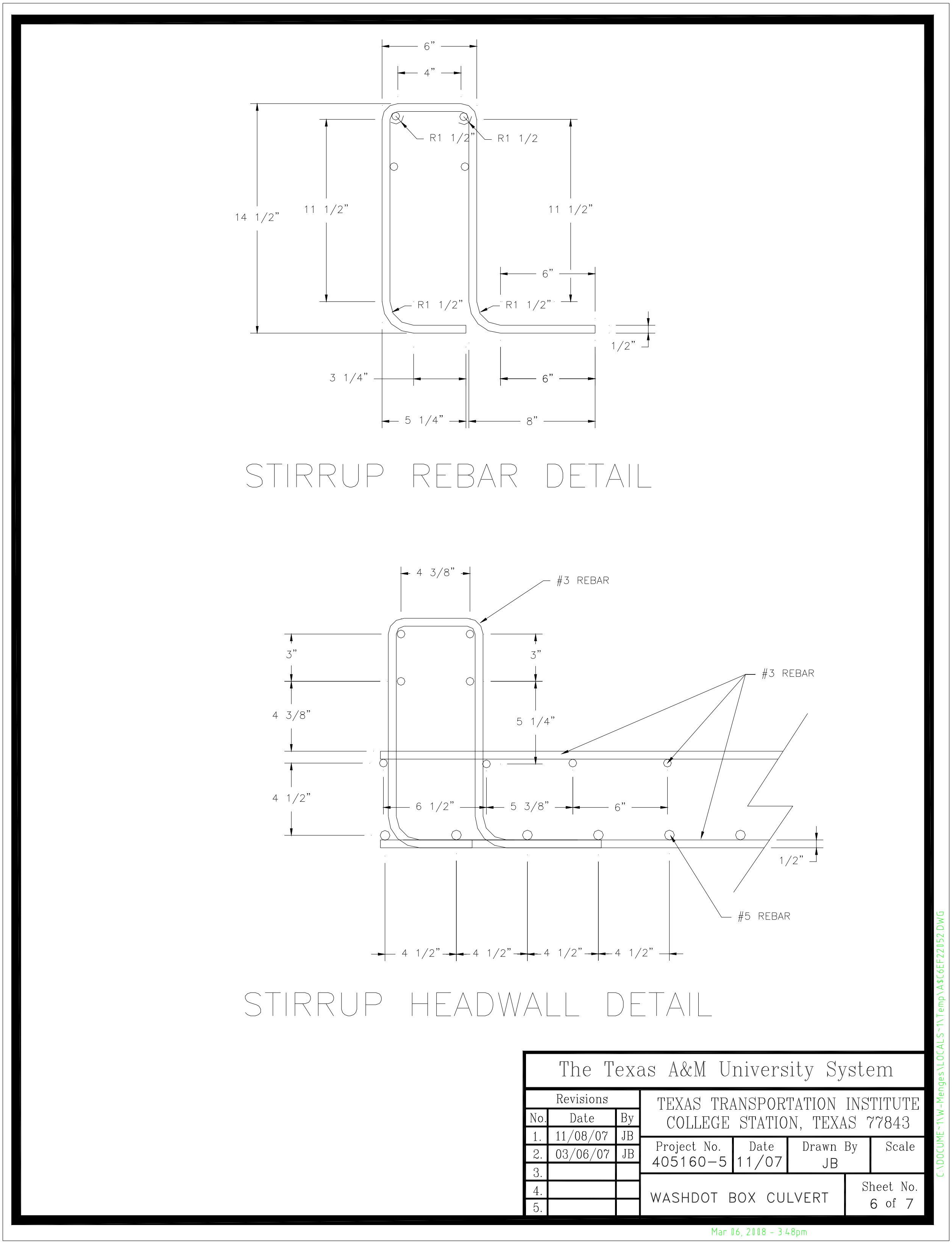


Figure 6. Headwall stirrup details for the W-Beam Guardrail on Box Culvert installation.

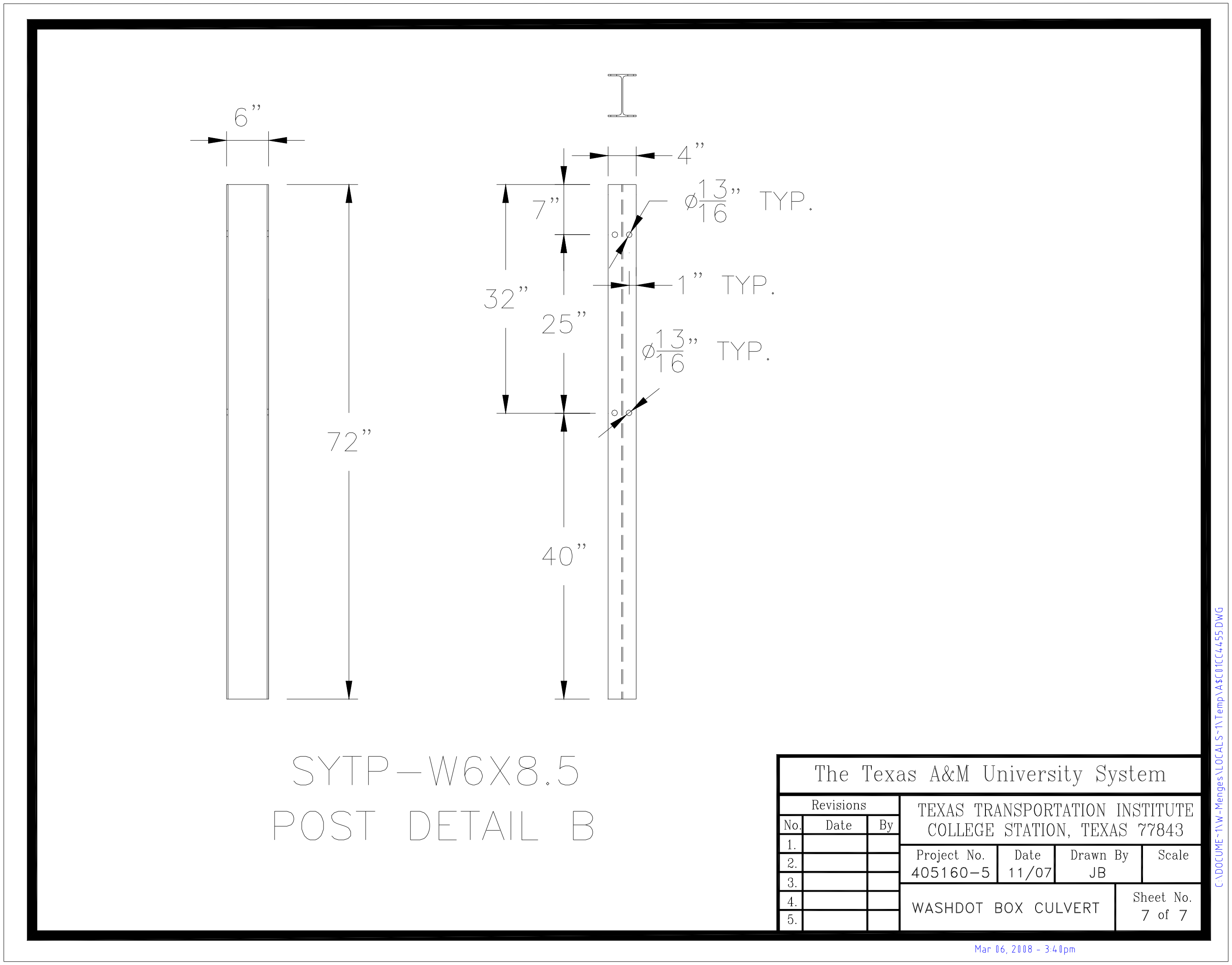


Figure 7. SYTP details for the W-Beam Guardrail on Box Culvert installation.

Figure 8. Box Culvert installation prior to testing.

Test Conditions

According to *NCHRP Report 350*, two tests are recommended to evaluate longitudinal barriers to test level three (TL-3) and are as described below.

> ***NCHRP Report 350* Test Designation 3-10:** An 1808 lb vehicle impacting the length of need section at a speed of 62 mi/h and an angle of 20 degrees.
>
> ***NCHRP Report 350* Test Designation 3-11:** A 4409 lb pickup truck impacting the length of need section at a speed of 62 mi/h and an angle of 25 degrees.

NCHRP Report 350 test 3-11 was performed and is reported herein. This is the critical test for this design.

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 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.

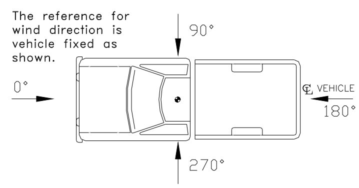
CRASH TEST 405160-5-1 (*NCHRP REPORT 350* TEST NO. 3-11)

Test Vehicle

A 1998 Chevrolet C2500 pickup truck, shown in figures 9 and 10, was used for the crash test. Test inertia weight of the vehicle was 4614 lb, and its gross static weight was 4614 lb. The height to the lower edge of the vehicle front bumper was 16.25 inches, and the height to the upper edge of the front bumper was 25.0 inches. Additional dimensions and information on the vehicle are given in appendix D, figure D1. 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.

Soil and Weather Conditions

The crash test was performed the afternoon of December 6, 2007. No rainfall was recorded for the ten days prior to the test. Moisture content of the *NCHRP Report 350* soil in which the test article was installed was 6 percent. Weather conditions at the time of testing were: Wind speed: 14 mi/h; wind direction: 335 degrees with respect to the vehicle (vehicle was traveling in a southwesterly direction); temperature: 68 ºF; relative humidity: 64 percent.



Impact Description

The pickup truck, traveling at an impact speed of 62.9 mi/h, impacted the W-Beam Guardrail on Box Culvert installation just downstream of post 13 at an impact angle of 23.9 degrees. At 0.024 s, post 13 began to rotate, and at 0.044 s, posts 11 and 12 began to deflect toward traffic lanes. Post 12 began to rotate at 0.046 s, and the vehicle began to redirect at 0.048 s. At 0.049 s, the blockout at post 14 began to rotate, and at 0.056 s, the W-beam began to deform near post 14. Post 14 began to deflect toward the field side at 0.063 s, and the vehicle contacted the post at 0.073 s. At 0.083 s, post 15 began to rotate and deflect toward the field side, and at 0.085 s, the W-beam began to deform near post 15. Post 16 began to rotate and deflect toward the field side at 0.127 s, and the vehicle contacted post 15 at 0.134 s. At 0.156 s, the W-beam began to deform near post 16, and at 0.205 s, the vehicle contacted post 16 and the W-beam began to deform at post 17. Post 17 began to rotate and deflect toward the field side at 0.256 s. The W-beam rail element began to tear as the vehicle had yawed 21 degrees at 0.306 s. At 0.315 s, the vehicle was traveling parallel with the guardrail, and the pickup was traveling at a speed of 40.7 mi/h. The rail ruptured as the vehicle had yawed 24 degrees at 0.352 s. The vehicle exited the view of the overhead camera, while traveling at a speed of 33.7 mi/h and 31.7 degrees. Sequential photographs of the test period are shown in appendix E, figure E1.

Figure 9. Vehicle/installation geometrics for test 405160-5-1.

Figure 10. Vehicle before test 405160-5-1.

Damage to Test Article

Damage to the W-Beam Guardrail on Box Culvert installation is shown in figures 11 and 12. The W-beam rail element ruptured 6 inches downstream of the splice at post 15, and the rail element was separated from posts 14-18 and 20-22. Posts 7-10 rotated clockwise 0.08 inch, post 11 rotated clockwise 0.16 inch, and post 12 rotated clockwise 0.39 inch. Post 13 rotated clockwise 1.5 inches, leaned toward field side 10 degrees, and the soil was disturbed around the base. Post 14 was laid over on the ground in the downstream direction. Post 15 rotated counterclockwise 90 degrees and laid over on the ground in the downstream direction. Post 16 rotated counterclockwise 140 degrees and laid over in the downstream direction 45 degrees. Post 17 rotated clockwise 30 degrees and was leaning downstream 15 degrees. No damage to posts 18 and 19. Post 20 was laid over in the downstream direction 70 degrees. Post 21 rotated clockwise 30 degrees and was laid over downstream 70 degrees. Post 22 rotated clockwise 25 degrees.

Vehicle Damage

Damage to the 1998 Chevrolet C2500 pickup truck is shown in figure 13. The vehicle received structural damage to the right upper and lower ball joints, right outer tie rod ends, right front upper and lower A-arms, sway bar, and right frame rail. The right wheel assembly separated at the upper and lower ball joint and tie rod end. Also damaged were the front bumper, radiator and support, right front fender, right door, right side floor pan, and right rear bumper. Maximum exterior crush to the vehicle was 17.75 inches in the frontal plane at the right front corner at bumper height. Maximum occupant compartment deformation was 0.71 inch in the kickpanel area in the lateral area across the cab. Photographs of the interior of the vehicle are shown in figure 14. Exterior vehicle crush and occupant compartment measurements are shown in appendix D, tables D1 and D2.

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 occupant impact velocity and ridedown accelerations in the longitudinal axis are required from these data for evaluation of criterion L of *NCHRP Report 350*. In the longitudinal direction, occupant impact velocity was 5.6 m/s at 0.138 s, maximum 0.010-s ridedown acceleration was -15.6 g's from 0.239 to 0.249 s, and the maximum 0.050-s average was -7.6 g's between 0.199 and 0.249 s. In the lateral direction, the occupant impact velocity was 4.5 m/s at 0.138 s, the highest 0.010-s occupant ridedown acceleration was -20.6 g's from 0.239 to 0.249 s, and the maximum 0.050-s average was -5.9 g's between 0.142 and 0.192 s. These data and other information pertinent to the test are presented in figure 15. Vehicle angular displacements and accelerations versus time traces are shown in appendix F, figures F1 through F7.

Figure 11. Vehicle trajectory path after test 405160-5-1.

Figure 12. Installation after test 405160-5-1.

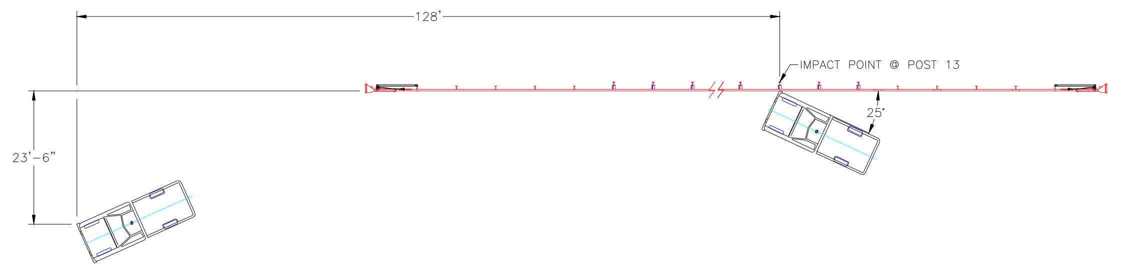
Figure 13. Vehicle after test 405160-5-1.

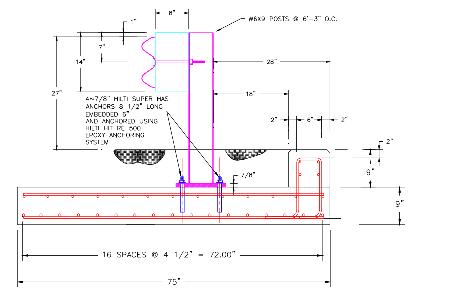

Before Test


After Test

Figure 14. Interior of vehicle for test 405160-5-1.

0.000 s | 0.122 s | 0.244 s | 0.366 s





General Information	
Test Agency	Texas Transportation Institute
Test No.	405160-5-1
Date	12-06-2007
Test Article	
Type	Shallow Mount Guardrail
Name	WSDOT Box Culvert
Installation Length (ft)	175
Material or Key Elements	12 gauge W-beam guardrail system supported by W6x9 steel posts anchored to a simulated box culvert
Soil Type and Condition	Crushed Limestone, Dry
Test Vehicle	
Designation	2000P
Model	1998 Chevrolet C2500 Pickup
Mass (lb)	
Curb	4753
Test Inertial	4614
Dummy	No dummy
Gross Static	4614

Impact Conditions	
Speed (mi/h)	62.9
Angle (deg)	23.9
Exit Conditions	
Speed (mi/h)	33.7
Angle (deg)	34.7
Occupant Risk Values	
Impact Velocity (m/s)	
Longitudinal	5.6
Lateral	4.5
THIV (km/h)	24.5
Ridedown Accelerations (g's)	
Longitudinal	-15.6
Lateral	-20.6
PHD (g's)	25.8
ASI	0.80
Max. 0.050-s Average (g's)	
Longitudinal	-7.6
Lateral	-5.9
Vertical	5.2

Test Article Deflections (ft)	
Dynamic	Ruptured
Permanent	Ruptured
Working Width	5.6
Vehicle Damage	
Exterior	
VDS	01RFQ4
CDC	01RFEW4
Max. Exterior Vehicle Crush (inch)	17.75
Interior	
OCDI	RF0002000
Max. Occupant Compartment Deformation (inch)	0.75
Post-Impact Behavior (during 1.0 sec after impact)	
Max. Yaw Angle (deg)	-75
Max. Pitch Angle (deg)	-15
Max. Roll Angle (deg)	10

Figure 15. Summary of results for *NCHRP Report 350* test 3-11 on W-Beam Guardrail on Box Culvert.

SUMMARY AND CONCLUSIONS

ASSESSMENT OF TEST RESULTS

An assessment of the test based on the following applicable *NCHRP Report 350* safety evaluation criteria for test designation 3-11 is as follows.

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 W-Beam Guardrail on Box Culvert contained and redirected the 2000P vehicle. The W-beam rail element ruptured, however, the 2000P vehicle did not penetrate the rail. (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: Although the rail element ruptured and separated from the posts, the rail element did not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to others. Maximum occupant compartment deformation was 0.71 inch in the lateral area across the floor pan of the vehicle. (PASS)

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

Results: The 2000P vehicle remained upright during and after the collision event. (PASS)

Vehicle Trajectory

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

Result: The 2000P vehicle subsequently came to rest 128 ft downstream from impact and 13.5 ft toward traffic lanes. (FAIL)

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.*

Result: Longitudinal impact velocity was 5.6 m/s, and longitudinal ridedown acceleration was -15.6 g's. (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 at loss of contact with the guardrail was 31.7 degrees, which was 133 percent of the impact angle. (FAIL)

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: [5]

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*

Although the rail element ruptured and separated from the posts, the rail element did not present undue hazard to others.

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*
   - *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

NCHRP Report 350 test 3-11 was performed to evaluate a guardrail system across low-fill culvert. The W-beam rail element was ruptured by the impact from the vehicle. Even though the rail element was ruptured, the vehicle was contained and redirected without penetrating, underriding, or overriding the installation. The rail element ruptured after the vehicle was redirected and while it was exiting out of the barrier system. The occupant risk values recorded for this test were acceptable with respect to *NCHRP Report 350* criteria. Based on the review of all available test data, the W-Beam Guardrail on Box Culvert met the required criteria for TL-3 according to the specifications for *NCHRP Report 350* test 3-11, as shown in table 1.

The W6x9 post and anchorage details developed under this project demonstrated satisfactory performance. No damage to the deck or failure of the adhesive anchors was observed in the full-scale testing. The W6x9 post and anchorage details tested for this project can be used in lieu of the conventional through-bolt design for this and other box culvert guardrail design that meet *NCHRP Report 350*, including the half-post spacing system previously tested.[3]

Table 1. Performance evaluation summary for *NCHRP Report 350* test 3-11 on the W-Beam Guardrail on Box Culvert.

Test Agency: Texas Transportation Institute | Test No.: 405160-5-1 | Test Date: 12-06-2007

NCHRP Report 350 **Test 3-11 Evaluation Criteria**	**Test Results**	**Assessment**
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*	The W-Beam Guardrail on Box Culvert contained and redirected the 2000P vehicle. The W-beam rail element ruptured, however, the 2000P vehicle did not penetrate the rail.	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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.*	Although the rail element ruptured and separated from the posts, the rail element did not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to others. Maximum occupant compartment deformation was 0.71 inch in the lateral area across the floor pan of the vehicle.	Pass
F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	The 2000P vehicle remained upright during and after the collision event.	Pass
Vehicle Trajectory *K. After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.*	The 2000P vehicle subsequently came to rest 128 ft downstream from impact and 13.5 ft toward traffic lanes.	Fail*
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.	Longitudinal impact velocity was 5.6 m/s, and longitudinal ridedown acceleration was -15.6 g's.	Pass
M. 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.	Exit angle at loss of contact with the guardrail was 31.7 degrees, which was 133 percent of the impact angle.	Fail*

*Criterion K and M are preferable, not required.

REFERENCES

1. T. J. Hirsch and D. Beggs, "Use of Guardrails on Low Fill Bridge Length Culverts," *Research Report 405-2F*, Texas Transportation Institute, Texas A&M University, College Station, TX, 1987.

2. J. D. Michie, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program Report 230, Transportation Research Board, National Research Council, Washington, D.C., March 1981.

3. K. A. Polivka, D. L. Sicking, J. D. Reid, R. K. Faller, J. R. Rohde, and J. C. Holloway, "NCHRP 350 Development and Testing of a Guardrail Connection to Low-Fill Culverts," NwRSF Research Report No. TRP-03-114-02, Midwest States' Regional Pooled Fund Program, Midwest Roadside, November 2002.

4. 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.

5. Federal Highway Administration Memorandum, from the Director, Office of Engineering, entitled: "ACTION: Identifying Acceptable Highway Safety Features," dated July 25, 1997.

APPENDIX A. STRENGTH ANALYSES ON DESIGN POSTS

W6x9 POST

Texas Transportation Institute

Project #: 405160-00005

W6x9 Design

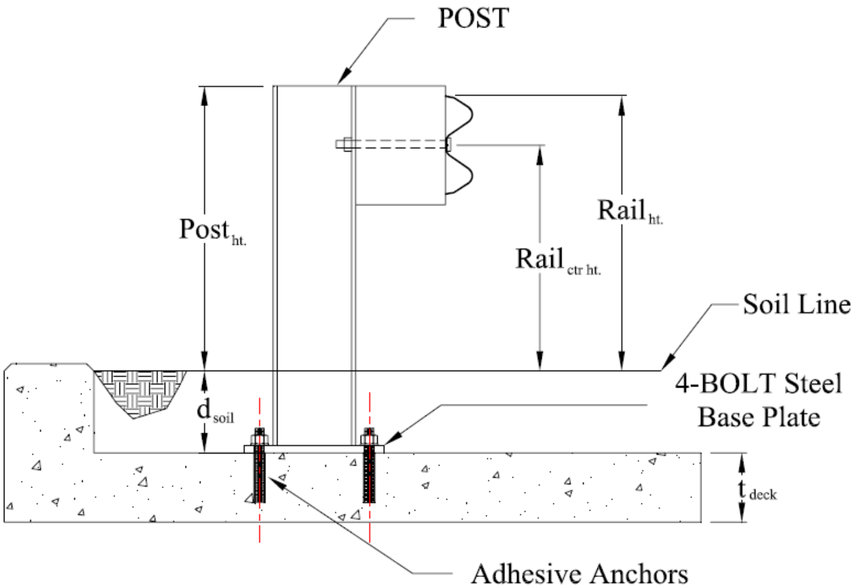
Subject: Box Culvert Guardrail - Task AE Calculations

Hilti RE 500 Anchor System

Sponsor: Washington DOT Pooled Fund

7/8" Dia. Anchors Embed. 6" Max

Given the following general latout of a box culvert guardrail post anchored to a concrete box culvert section using an epoxy adhesive anchoring system. Find the limiting ultimate strength of the post design considering the different variables used in the design.



GUARDRAIL ON BOX CULVERT TYPICAL CROSS-SECTION

depth of soil (in.)

$d_{soil} := 0in$

Thickness of Deck (in.)

$t_{deck} := 9in$

1.) Design Information:

****** Rail Geometry ******

$Rail_{ctrht} := 21in$ Center Height of Rail (in.)

$Rail_{ht} := Rail_{ctrht} + 6.125in$ Height to top of rail (in.)

$Post_{ht} := 27in$ Height of Post above grade (in.)

$Post_{load} := 12kips$ Load applied to Rail center (kips) $M_{load} := Post_{load} \cdot (Rail_{ht} + d_{soil})$

Texas Transportation Institute

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Define Mathcad units ORIGIN := 1

kips ≡ kip $ksi \equiv \frac{kips}{in^2}$

Steel Beam Yield Strength: $F_y := (50) \cdot ksi$
Beam Nominal Depth: NOMINAL_DEPTH := (6)
Beam weight per foot: WEIGHT_PER_FOOT := (9)

Beam Data - Fri Sep 15 09:13:04 2006

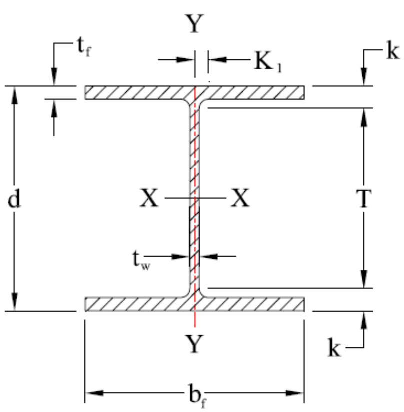
***** **Post Information** *****

$Wt\_per\_foot = 9\,ft^{-1} \cdot lb$ $F_y = 50 \cdot ksi$

Post Data for: $Nominal\_depth = 6 \cdot in$

$Wt\_per\_foot = 9\,ft^{-1} \cdot lb$ Wt. per foot of length (lb/ft)

$d_n = 6$ Nominal Depth of member



POST DETAILS

$Area = 2.68 \cdot in^2$	Area (in^2)
$d = 5.9 \cdot in$	Actual Depth of Member (in.)
$t_w = 0.17 \cdot in$	Thickness of Web (in.)
$b_f = 3.94 \cdot in$	Width of Flange (in.)
$t_f = 0.215 \cdot in$	Thickness of Flange (in.)
$k = 0.56 \cdot in$	Distance to toe of fillet (in.)
$I_x = 16.4 \cdot in^4$	Moment of Inertia (Stg. Axis (in^4))
$S_x = 5.56 \cdot in^3$	Section Modulus (Stg. Axis (in^3))
$Z_x = 6.23 \cdot in^3$	Plastic Modulus (Strong Axis (in^3))
$Z_y = 1.72 \cdot in^3$	Plastic Modulus (Weak Axis (In^3))
$A_f = 0.85 \cdot in^2$	Area Flange (in^2)
$r_x = 2.47 \cdot in$	radius of gyration with respect to X-X Axis (in.)
$I_y = 2.19 \cdot in^4$	Moment of Inertia (Weak Axis (in^4))
$S_y = 1.11 \cdot in^3$	Section Modulus (Weak Axis (in^3))

Texas Transportation Institute

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

***** Steel & Concrete Material properties *****

$F_{ysteel} := 50ksi$ — Yield Strength of Steel Material (ksi)

$F_{yrebar} := 60ksi$ — Yield Strength of rebar (ksi)

$F_u := 65ksi$ — Rupture Strength of Steel Material (ksi)

$f'_c := 4000psi$ — Compressive Strength of Concrete)psi)

****** Anchor Bolt Properties *******

$F_{ubolts} := 125ksi$ — High Strength Super HAS Rod Material, ASTM A193, Grade B7 Material (ksi)

$Dia_{bolt} := \frac{7}{8} in$ — Dia. of anchor bolts (in.) — $Area_{bolt} := \pi \, Dia_{bolt}^2 \cdot 0.25$ — $Area_{bolt} = 0.6 \cdot in^2$

$\phi_{bolt} := 1.0$ — Strength Reduction Factor For Bolts

$E_s := 29 \cdot 10^6 \cdot psi$ — Modulus of Elasticity (in.) — $N_t := 2$ — 2 bolts on the tension face

$A_s := \frac{\pi \cdot Dia_{bolt}^2}{4} \cdot N_t$ — Area of tension bolts — $A_s = 1.203 \cdot in^2$

$E_c := 57000 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi$ — $E_c = 3604996.533 \cdot psi$ — $n := \frac{E_s}{E_c}$ — $n = 8.04$

***** Weld Properties *****

$F_{EXX} := 70ksi$ — Weld Material Strength (ksi)

$t_{weld} := \frac{1}{4} in$ — Weld Size (in.)

$\phi_{weld} := 1.0$ — Reduction Factor for Weld

Texas Transportation Institute

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

****** **Baseplate Properties** ******

$D := 12\text{in}$ Baseplate Length (in.)

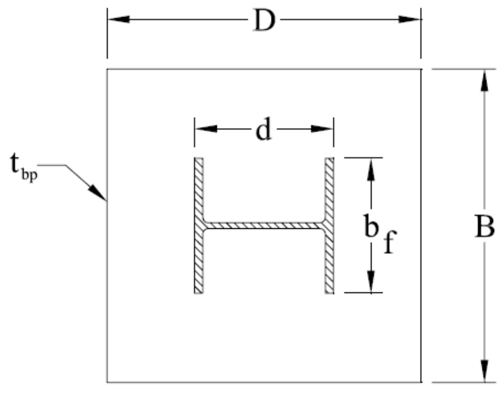
$B := 12\text{in}$ Baseplate width (in.)

$t_p := 1.000\text{in}$ Approx. Baseplate thickness (in.)

$d = 5.9\cdot\text{in}$ Depth of Post (in.)

$b_f = 3.94\cdot\text{in}$ Width of Post (in.)

$Hole_{edgedist} := 1.5\text{in}$ Distance to plate edge to hole center (in.)



BASEPLATE DETAILS

***** Hilti Anchor Properties *****

1.) As per page 163, 2006 Hilti Product Technical Guide,
HIT RE 500 Epoxy System, Average values for 4000 psi concrete:

$$Tension := \begin{pmatrix} 22670 \\ 63495 \\ 64730 \end{pmatrix} \text{lbf} \qquad Shear := \begin{pmatrix} 16365 \\ 48455 \\ 79020 \end{pmatrix} \text{lbf}$$

$$Depth_{embed} := \begin{pmatrix} 4 \\ 7.875 \\ 10.5 \end{pmatrix} \text{in}$$

Actual Embedment Depth (inches)
, see Hilti guide

$h_{ef} := 6.00\text{in}$

Use Hilti Hight Strength Super HAS, 7/8" Dia. Rod:

$HIT_{ultimatetensile} := \text{linterp}(Depth_{embed}, Tension, h_{ef})$

$HIT_{ultimateshear} := \text{linterp}(Depth_{embed}, Shear, h_{ef})$

Interpolate for Embedment Depth, h_{ef}

$HIT_{ultimatetensile} = 43.741\cdot\text{kips}$ Ultimate Bond Strength
(see pg 112 Hilti 2002 Tech. Guide)

$HIT_{ultimateshear} = 32.928\cdot\text{kips}$ Ulitmate shear strength of
anchor (see pg 112)

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Temperature := 110 °F   Max Temperature for Temperature Reduction

Check Load Adjustment Factors for Anchor Spacings & Clearance:

From page 119, Hilti 2002 Technical Guide

$S_{act} := 9.0in$ Actual anchor spacing (inches)

$C_{act} := 24in$ edge distance (inches) from concrete edge to Centerline of bolts

$h_{nom} := 7.875in$ Standard embedment depth (inches), see page 110

$h_{ef} = 6 \cdot in$ Actual embedment depth (in.)

$S_{min} := 0.5 \cdot h_{ef}$ $S_{min} = 3 \cdot in$

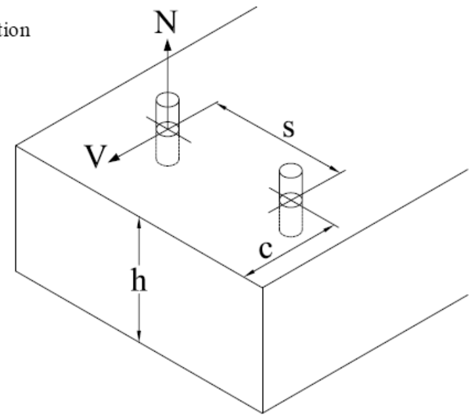
$S_{cr} := 1.5 \cdot h_{ef}$ $S_{cr} = 9 \cdot in$

$C_{min} := 0.5 \cdot h_{ef}$ $C_{min} = 3 \cdot in$

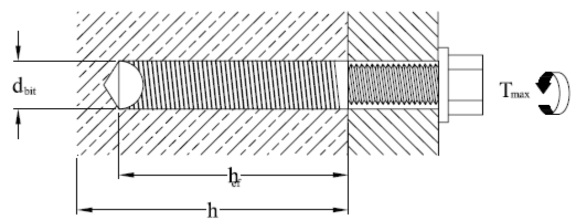
$C_{cr} := 1.5 \cdot h_{ef}$ $C_{cr} = 9 \cdot in$

$h := t_{deck}$ Thickness of slab, (in)

$h = 9 \cdot in$



ANCHOR DETAILS



ANCHOR GEOMETRY

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

**** Calculate Hilti Reduction Factors for Spacing Tension & Shear ******

$$f_A := \begin{vmatrix} f_A \leftarrow 0.3 \cdot \left(\dfrac{S_{act}}{h_{ef}}\right) + 0.55 \quad \text{if } S_{cr} \ge S_{act} \ge S_{min} \\ f_A \leftarrow 1.0 \quad \text{if } S_{act} \ge S_{cr} \\ f_A \leftarrow 0 \quad \text{if } S_{act} < S_{min} \end{vmatrix}$$

$f_A = 1$

***** Calculate Reduction Factors for Edge Distance Tension, "f_{RN}" *******

$$f_{RN} := \begin{vmatrix} f_{RN} \leftarrow 0.3 \cdot \left(\dfrac{C_{act}}{h_{ef}}\right) + 0.55 \quad \text{if } C_{cr} \ge C_{act} \ge C_{min} \\ f_{RN} \leftarrow 1.0 \quad \text{if } C_{act} \ge C_{cr} \\ f_{RN} \leftarrow 0 \quad \text{if } C_{act} < C_{min} \end{vmatrix}$$

$f_{RN} = 1$

5.) Calculate Reduction Factors for Edge Distance Shear, "f_{RVperp}"

$$f_{RVperp} := \begin{vmatrix} f_{RVperp} \leftarrow 0.54 \cdot \left(\dfrac{C_{act}}{h_{ef}}\right) - 0.09 \quad \text{if } C_{cr} \ge C_{act} \ge C_{min} \\ f_{RVperp} \leftarrow 1.0 \quad \text{if } C_{act} \ge C_{cr} \\ f_{RVperp} \leftarrow 0 \quad \text{if } C_{act} < C_{min} \end{vmatrix}$$

$f_{RVperp} = 1$

Texas Transportation Institute

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

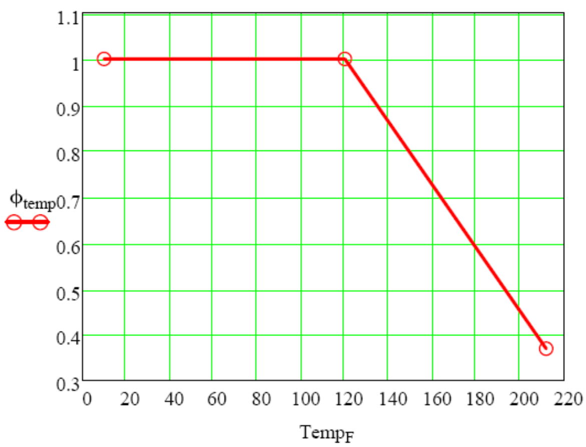
Sponsor: Washington DOT Pooled Fund

6.) Calculate total combined Reduction Factors for tension & shear:

$f_{RVperp} = 1$ $f_A = 1$ $f_{RN} = 1$

$\phi_{temp} := \begin{pmatrix} 1.0 \\ 1.0 \\ 0.37 \end{pmatrix}$ $Temp := \begin{pmatrix} 10 \\ 120 \\ 212 \end{pmatrix} {}^\circ F$ $F := Temp$ $Temp = \begin{pmatrix} 260.93 \\ 322.04 \\ 373.15 \end{pmatrix} K$ $Temp = \begin{pmatrix} 260.93 \\ 322.04 \\ 373.15 \end{pmatrix} K$

$$Temp_F := \frac{\left[(Temp - 273.15K)\cdot\frac{9}{5}\right] + 32K}{K}$$ Temperature conversion



$\phi_{tempreduce} := \mathrm{linterp}(Temp, \phi_{temp}, Temperature)$

$\phi_{tempreduce} = 1$

$\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN} \cdot \phi_{tempreduce})}$ $\phi_{shear} := \overrightarrow{(f_A \cdot f_{RVperp})}$

$\phi_{tension} = 1$ $\phi_{shear} = 1$

$\phi R_{tension} := \phi_{tension} \cdot HIT_{ultimatetensile}$ $\phi R_{shear} := \phi_{shear} \cdot HIT_{ultimateshear}$

$\phi R_{tension} = 43.74 \cdot kips$ $\phi R_{shear} = 32.93 \cdot kips$ Hilti Factored Anchor Strengths for $h_{ef} = 6.00 \cdot in$

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

7. Calculate the Plastice Strength of the Post:

$F_y = 50 \cdot ksi$ Yield Strength of Steel

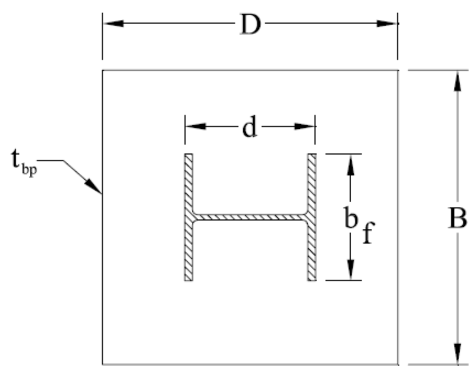
$Z_x = 6.23 \cdot in^3$ Plastic Section Modulus of Post

$M_{xplastic} := F_y \cdot Z_x$

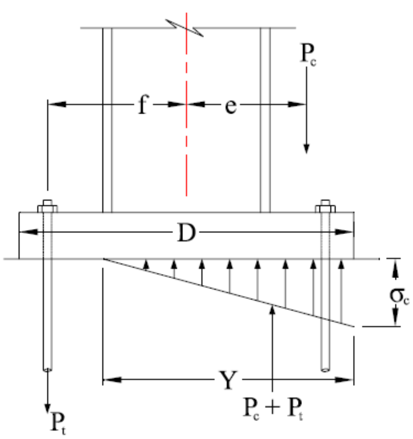
$M_{xplastic} = 25.96 \cdot kip \cdot ft$ Plastic Moment

$M_{load} = 27.12 \cdot kip \cdot ft$ Moment from Post Load

8.) Check Baseplate details & calculate anchor bolt forces:



BASEPLATE DETAILS



Given Basic Uplift Procedure as shown in Blodgett, "Design of Welded Structures" pages 3-3-8 through 10. and sketch w/ nomenclature showing Baseplate Geometry and distribution of force.

Find: Maximum Stress (σ_c), "Y", and force in the bolts (P_t) for applied force as shown.

This basic uplift procedure as shown in Blodget's "Design of Welded Structures" pages 3-3-8 through 10. It solves three equations for three unknowns for any combination of vertical & applied moment to the column. You have to combine the vertical load and moment to a single vertical load at some eccentricity "e". (Input Items in Yellow):

4 Bolts are used in he deign with 2 bolts located on the tension face

$P_c := .10 \cdot kips$ Vertical Load on Column (kips)

Select Design Moment from Above:

$M_1 := M_{xplastic}$ Applied Moment (k-ft.)

$e := \frac{M_1}{P_c}$ $e = 3115 \cdot in$ eccentricity (in.)

Texas Transportation Institute

Project #: 405160-00005

By: William F. Williams, P.E.

Subject: **Box Culvert Guardrail - Task AE Calculations**

$D = 12 \cdot in$ BP Length (in.) $B = 12 \cdot in$ BP Width (in.) $f'_c = 4000 \cdot psi$

$d = 5.9 \cdot in$ Post Depth (in.) $D = 12 \cdot in$ BP Length (in.) $N_t = 2$ # Tension Bolts

$b_f = 0.33\ ft$ Post Flange Width (in.) $Hole_{edgedist} = 1.5\ in$

$f := \frac{D}{2} - Hole_{edgedist}$ Distance from Col. Centerline to tension bolts.

From static, there are Three Equations & Three Unknowns, P_t, "Y", & s_c:

Initial estimates required. Use these estimates to converge on solutions for the three unknowns, s_c, Y, P_t:

Initial Guesses for unknowns: $\sigma_c := 1000 \cdot psi$ $Y := .3 \cdot ft$ $P_t := 10 \cdot kip$

Given

$$\frac{1}{2} \cdot Y \cdot \sigma_c \cdot B - P_t - P_c = 0$$

Equation 1

$$P_t \cdot f + (P_c + P_t) \cdot \left(\frac{D}{2} - \frac{Y}{3}\right) - P_c \cdot e = 0$$

Equation 2

$$\sigma_c = \frac{P_t \cdot Y}{A_s \cdot n \cdot \left(\frac{D}{2} - Y + f\right)}$$

Equation 3

$$\begin{pmatrix} Y \\ \sigma_c \\ P_t \end{pmatrix} := Find(Y, \sigma_c, P_t)$$

$Y = 3.3908 \cdot in$

$\sigma_c = 1636 \cdot psi$ Compressive stress @ the Edge of the Baseplate on Compression side.

$P_t = 33 \cdot kips$ Tension Force in (N_t) Anchor Bolts

$P_{Bolt} := \frac{P_t}{N_t}$ $P_{Bolt} = 16.6 \cdot kips$ Tension per Bolt (kips)

... o.k. less than Factored Hilti Ultimate for $h_{ef} = 6 \cdot in$ $\phi R_{tension} = 43.74 \cdot kips$

9.) Check Baseplate bending/thickness using forces & stress above separately.

Calculate moment in baseplate on bearing side:

$Y = 3.39 \cdot in$ $\quad d_{edge} := \frac{D}{2} - \frac{b_f}{2}$ $\quad d_{edge} = 4.03 \cdot in$

$$M_{plate1} := \frac{\sigma_c \cdot Y}{2} \cdot \left[\left(d_{edge} + \frac{t_f}{2} \right) - \frac{Y}{3} \right]$$

$$M_{plate1} = 8.34 \cdot \frac{kip \cdot in}{in}$$

Calculate moment in baseplate on Tension Bolt Side:

$P_{Bolt} = 16.6 \cdot kips$

$Hole_{edgedist} = 1.5 \cdot in$

$d_{edge} = 4.03 \cdot in$ Distance from Baseplate Edge to Post Edge

$$Bolt_{dist} := d_{edge} - Hole_{edgedist} + \frac{t_f}{2}$$

$Bolt_{dist} = 2.64 \cdot in$ Distance from center of bolt to centerline of post flange

$$M_{plate2} := \frac{P_{Bolt} \cdot Bolt_{dist}}{Bolt_{dist} \cdot 2} \qquad M_{plate2} = 8.3 \cdot \frac{kip \cdot in}{in}$$

$$M_{plate} := \begin{cases} M_{plate1} & \text{if } M_{plate1} > M_{plate2} \\ M_{plate2} & \text{otherwise} \end{cases}$$

Select worst case bending moment in plate bearing or anchor bolt tension

$M_{plate} = 8.34 \cdot \frac{kip \cdot in}{in}$ Design moment in the baseplate for thickness calculations

Substract 1/8" since procedure is little conservative

Therefore: $t_{prequired} := \sqrt{\frac{4 \cdot M_{plate}}{F_y}}$ $\quad t_{prequired} = 0.82 \cdot in$ $\quad t_{plate} := (t_{prequired} - 0.125in)$

$t_{bp} := \text{Round}(t_{plate}, 0.125in)$ $\quad t_{bp} = 0.75 \cdot in$ Final Baseplate Design Thickness (in.)

Texas Transportation Institute

Project #: 405160-00005

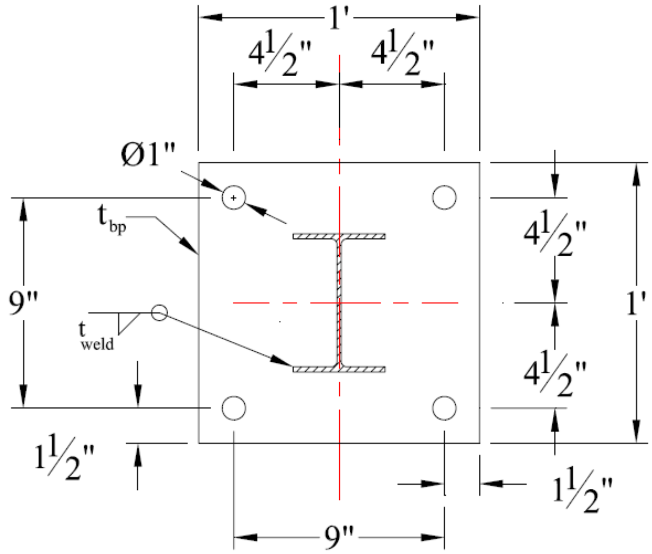
Subject: Box Culvert Guardrail - Task AE Calculations

$t_{bp} = 0.75 \cdot in$

$F_y = 50 \cdot ksi$

$t_{weld} = 0.25 \cdot in$

RECOMMENDED BASEPLATE DETAILS



W6x8.5 & 9
BASEPLATE DETAILS

Anchor Bolts: 7/8" Dia. A193 Threaded Rods 8 inches long, embedded 6 inches minimum

Anchorage System: Hilti RE 500 Anchoring System

W8x21 POST

Texas Transportation Institute

Project #: 405160-00005

W8x21 Design

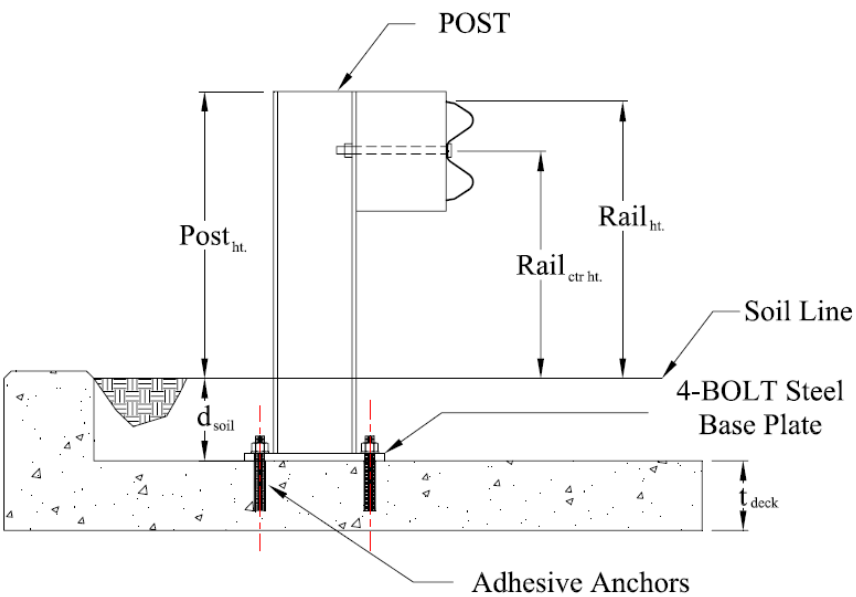
Hilti RE 500 Anchor System

7/8" Dia. Anchors Embed. 10" Max

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

Given the following general latout of a box culvert guardrail post anchored to a concrete box culvert section using an epoxy adhesive anchoring system. Find the limiting ultimate strength of the post design considering the different variables used in the design.



GUARDRAIL ON BOX CULVERT TYPICAL CROSS-SECTION

depth of soil (in.)

$d_{soil} := 18in$

Thickness of Deck, Slab or Footing (in.)

$t_{deck} := 14in$

1.) Design Information:

****** Rail Geometry ******

$Rail_{ctrht} := 21in$ Center Height of Rail (in.)

$Rail_{ht} := Rail_{ctrht} + 6.125in$ Height to top of rail (in.)

$Post_{ht} := 27in$ Height of Post above grade (in.)

$Post_{load} := 20kips$ Load applied to Rail center (kips) $M_{load} := Post_{load} \cdot \left(Rail_{ctrht} + d_{soil}\right)$

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Define Mathcad units ORIGIN := 1

kips ≡ kip $\quad ksi \equiv \frac{kips}{in^2}$

Steel Beam Yield Strength: $F_y := (50) \cdot ksi$

Beam Nominal Depth: NOMINAL_DEPTH := (8)

Beam weight per foot: WEIGHT_PER_FOOT := (21)

Beam Data - Fri Sep 15 09:13:04 2006

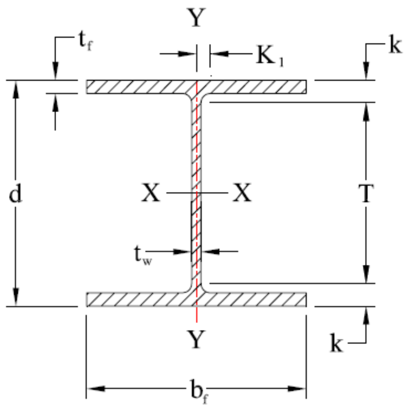
***** **Post Information** *****

Wt_per_foot = $21\,ft^{-1} \cdot lb$ $\quad F_y = 50 \cdot ksi$

Post Data for: Nominal_depth = $8 \cdot in$

Wt_per_foot = $21\,ft^{-1} \cdot lb$ Wt. per foot of length (lb/ft)

$d_n = 8$ Nominal Depth of member



POST DETAILS

Area = $6.16 \cdot in^2$	Area (in^2)
d = $8.28 \cdot in$	Actual Depth of Member (in.)
$t_w = 0.25 \cdot in$	Thickness of Web (in.)
$b_f = 5.27 \cdot in$	Width of Flange (in.)
$t_f = 0.4 \cdot in$	Thickness of Flange (in.)
$k = 0.81 \cdot in$	Distance to toe of fillet (in.)
$I_x = 75.3 \cdot in^4$	Moment of Inertia (Stg. Axis (in^4))
$S_x = 18.2 \cdot in^3$	Section Modulus (Stg. Axis (in^3))
$Z_x = 20.4 \cdot in^3$	Plastic Modulus (Strong Axis (in^3))
$Z_y = 5.69 \cdot in^3$	Plastic Modulus (Weak Axis (In^3))
$A_f = 2.11 \cdot in^2$	Area Flange (in^2)
$r_x = 3.49 \cdot in$	radius of gyration with respect to X-X Axis (in.)
$I_y = 9.77 \cdot in^4$	Moment of Inertia (Weak Axis (in^4))
$S_y = 3.71 \cdot in^3$	Section Modulus (Weak Axis (in^3))

Texas Transportation Institute

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

***** Steel & Concrete Material properties *****

$F_{ysteel} := 50ksi$ Yield Strength of Steel Material (ksi)

$F_{yrebar} := 60ksi$ Yield Strength of rebar (ksi)

$F_u := 65ksi$ Rupture Strength of Steel Material (ksi)

$f'_c := 4000psi$ Compressive Strength of Concrete)psi)

****** Anchor Bolt Properties *******

$F_{ubolts} := 125ksi$ High Strength Super HAS Rod Material, ASTM A193, Grade B7 Material (ksi)

$Dia_{bolt} := \frac{7}{8}in$ Dia. of anchor bolts (in.) $Area_{bolt} := \pi\, Dia_{bolt}^2 \cdot 0.25$ $Area_{bolt} = 0.6 \cdot in^2$

$\phi_{bolt} := 1.0$ Strength Reduction Factor For Bolts

$E_s := 29 \cdot 10^6 \cdot psi$ Modulus of Elasticity (in.) $N_t := 2$ 2 bolts on the tension face

$A_s := \frac{\pi \cdot Dia_{bolt}^2}{4} \cdot N_t$ Area of tension bolts $A_s = 1.203 \cdot in^2$

$E_c := 57000 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi$ $E_c = 3604996.533 \cdot psi$ $n := \frac{E_s}{E_c}$ $n = 8.04$

***** Weld Properties *****

$F_{EXX} := 70ksi$ Weld Material Strength (ksi)

$t_{weld} := \frac{1}{4}in$ Weld Size (in.)

$\phi_{weld} := 1.0$ Reduction Factor for Weld

Texas Transportation Institute

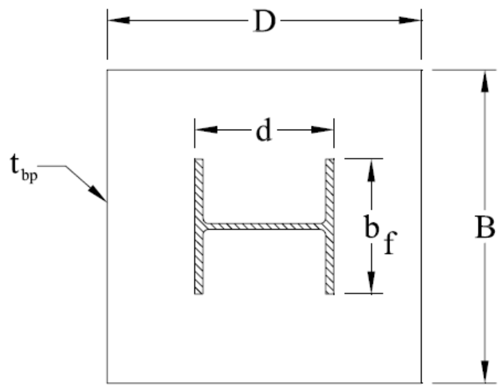
Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

****** **Baseplate Properties** ******

$D := 14in$	Baseplate Length (in.)
$B := 14in$	Baseplate width (in.)
$t_p := 1.000in$	Baseplate thickness (in.)
$d = 8.28 \cdot in$	Depth of Post (in.)
$b_f = 5.27 \cdot in$	Width of Post (in.)
$Hole_{edgedist} := 1.5in$	Distance to plate edge to hole center (in.)



BASEPLATE DETAILS

***** **Hilti Anchor Properties** *****

1.) As per page 112, 2002 Hilti Product Technical Guide,
HIT RE 500 Epoxy System, Average values for 4000 psi concrete:

$$Tension := \begin{pmatrix} 22670 \\ 63495 \\ 64730 \end{pmatrix} lbf \qquad Shear := \begin{pmatrix} 16365 \\ 48455 \\ 79020 \end{pmatrix} lbf$$

$$Depth_{embed} := \begin{pmatrix} 4 \\ 7.875 \\ 10.5 \end{pmatrix} in$$

Actual Embedment Depth (inches)
, see Hilti guide

$h_{ef} := 10.5000in$

Use Hilti Hight Strength Super HAS, 7/8" Dia. Rod:

$$HIT_{ultimatetensile} := linterp(Depth_{embed}, Tension, h_{ef})$$

$$HIT_{ultimateshear} := linterp(Depth_{embed}, Shear, h_{ef})$$

Interpolate for Embedment Depth, h_{ef}

$HIT_{ultimatetensile} = 64.73 \cdot kips$ Ultimate Bond Strength (see pg 112 Hilti 2002 Tech. Guide)

$HIT_{ultimateshear} = 79.02 \cdot kips$ Ulitmate shear strength of anchor (see pg 112)

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Temperature := 110 °F   Max Temperature for Temperature Reduction

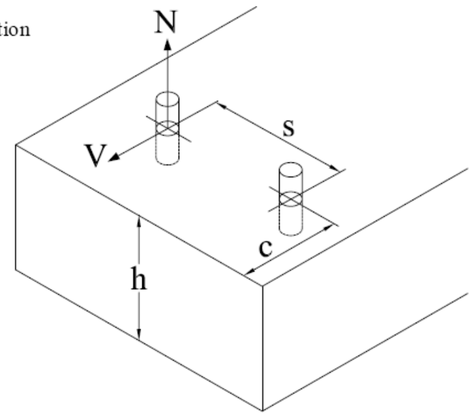
Check Load Adjustment Factors for Anchor Spacings & Clearance:

From page 119, Hilti 2002 Technical Guide

$S_{act} := 11.0in$ Actual anchor spacing (inches)

$C_{act} := 12in$ edge distance (inches) from concrete edge to Centerline of bolts

$h_{nom} := 7.875in$ Standard embedment depth (inches), see page 110



ANCHOR DETAILS

$S_{min} := 0.5 \cdot h_{ef}$ $S_{min} = 5.25 \cdot in$

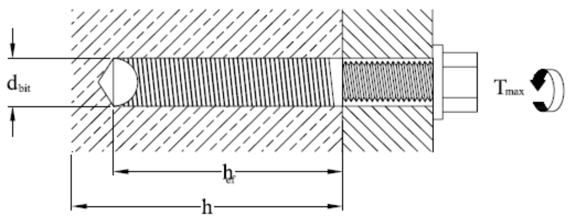
$S_{cr} := 1.5 \cdot h_{ef}$ $S_{cr} = 15.75 \cdot in$

$C_{min} := 0.5 \cdot h_{ef}$ $C_{min} = 5.25 \cdot in$

$C_{cr} := 1.5 \cdot h_{ef}$ $C_{cr} = 15.75 \cdot in$

$h := t_{deck}$ Thickness of slab, (in)

$h = 14 \cdot in$



ANCHOR GEOMETRY

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Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

$S_{act} = 11 \cdot in$

$h_{ef} = 10.5 \cdot in$

$S_{cr} = 15.75 \cdot in$

**** Calculate Hilti Reduction Factors Spacing Tension & Shear ******

$$f_A := \left| \begin{array}{l} f_A \leftarrow 0.3 \cdot \left(\dfrac{S_{act}}{h_{ef}} \right) + 0.55 \quad \text{if } S_{cr} \geq S_{act} \geq S_{min} \\ f_A \leftarrow 1.0 \quad \text{if } S_{act} \geq S_{cr} \\ f_A \leftarrow 0 \quad \text{if } S_{act} < S_{min} \end{array} \right.$$

$f_A = 0.864$

***** Calculate Reduction Factors for Edge Distance Tension, "f_{RN}" *******

$$f_{RN} := \left| \begin{array}{l} f_{RN} \leftarrow 0.3 \cdot \left(\dfrac{C_{act}}{h_{ef}} \right) + 0.55 \quad \text{if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RN} \leftarrow 1.0 \quad \text{if } C_{act} \geq C_{cr} \\ f_{RN} \leftarrow 0 \quad \text{if } C_{act} < C_{min} \end{array} \right.$$

$f_{RN} = 0.89$

5.) Calculate Reduction Factors for Edge Distance Shear, "f_{RVperp}"

$$f_{RVperp} := \left| \begin{array}{l} f_{RVperp} \leftarrow 0.7 \cdot \left(\dfrac{C_{act}}{h_{ef}} \right) - 0.05 \quad \text{if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RVperp} \leftarrow 1.0 \quad \text{if } C_{act} \geq C_{cr} \\ f_{RVperp} \leftarrow 0 \quad \text{if } C_{act} < C_{min} \end{array} \right.$$

$f_{RVperp} = 0.75$

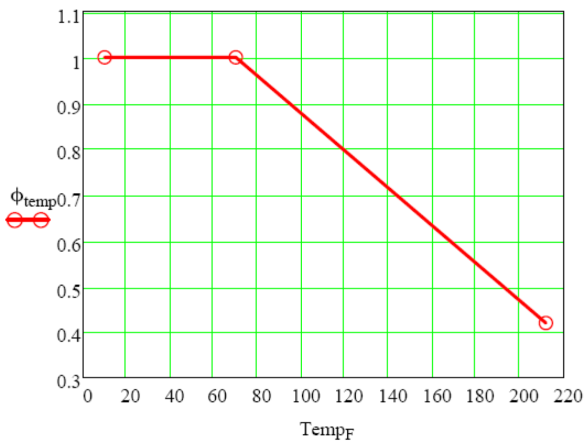
6.) Calculate total combined Reduction Factors for tension & shear:

$f_{RVperp} = 0.75$ $\quad f_A = 0.86$ $\quad f_{RN} = 0.89$

$\phi_{temp} := \begin{pmatrix} 1.0 \\ 1.0 \\ 0.42 \end{pmatrix}$ $\quad Temp := \begin{pmatrix} 10 \\ 70 \\ 212 \end{pmatrix} {}^\circ F$ $\quad F := Temp$ $\quad Temp = \begin{pmatrix} 260.93 \\ 294.26 \\ 373.15 \end{pmatrix} K$ $\quad Temp = \begin{pmatrix} 260.93 \\ 294.26 \\ 373.15 \end{pmatrix} K$

$$Temp_F := \frac{\left[(Temp - 273.15K)\cdot\frac{9}{5}\right] + 32K}{K}$$

Temperature conversion



$\phi_{tempreduce} := \text{linterp}(Temp, \phi_{temp}, Temperature)$

$\phi_{tempreduce} = 0.84$

$\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN} \cdot \phi_{tempreduce})}$ $\qquad \phi_{shear} := \overrightarrow{(f_A \cdot f_{RVperp})}$

$\phi_{tension} = 0.65$ $\qquad \phi_{shear} = 0.65$

$\phi R_{tension} := \phi_{tension} \cdot HIT_{ultimatetensile}$ $\qquad \phi R_{shear} := \phi_{shear} \cdot HIT_{ultimateshear}$

$\phi R_{tension} = 41.79 \cdot kips$ $\qquad \phi R_{shear} = 51.22 \cdot kips$

Hilti Factored Anchor Strengths for $h_{ef} = 10.50 \cdot in$

Texas Transportation Institute

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

7. Calculate the Plastice Strength of the Post:

$F_y = 50 \cdot ksi$ Yield Strength of Steel

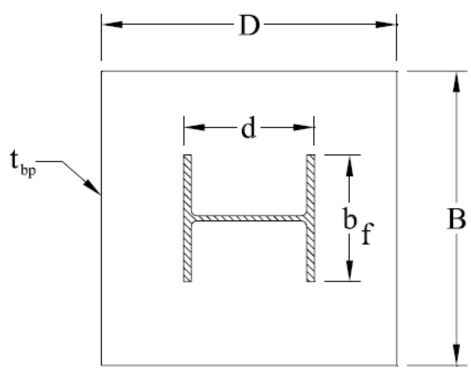
$Z_x = 20.4 \cdot in^3$ Plastic Section Modulus of Post

$M_{xplastic} := F_y \cdot Z_x$

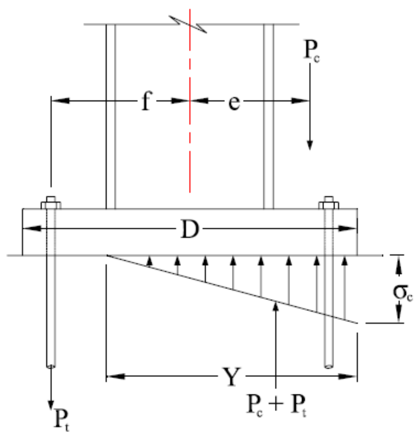
$M_{xplastic} = 85 \cdot kip \cdot ft$ Plastic Moment

$M_{load} = 65 \cdot kip \cdot ft$ Moment from Post Load

8.) Check Baseplate details & calculate anchor bolt forces:



BASEPLATE DETAILS



Given Basic Uplift Procedure as shown in Blodgett, "Design of Welded Structures" pages 3-3-8 through 10. and sketch w/ nomenclature showing Baseplate Geometry and distribution of force.

Find: Maximum Stress (σ_c), "Y", and force in the bolts (P_t) for applied force as shown.

This basic uplift procedure as shown in Blodget's "Design of Welded Structures" pages 3-3-8 through 10. It solves three equations for three unknowns for any combination of vertical & applied moment to the column. You have to combine the vertical load and moment to a single vertical load at some eccentricity "e". (Input Items in Yellow):

4 Bolts are used in he deign with 2 bolts located on the tension face

$P_c := .10 \cdot kips$ Vertical Load on Column (kips)

Select Design Moment from Above:

$M_1 := M_{xplastic}$ Applied Moment (k-ft.) (Use Plastic Strength of Post)

$e := \frac{M_1}{P_c}$ $e = 10200 \cdot in$ eccentricity (in.)

Texas Transportation Institute

Project #: 405160-00005

By: William F. Williams, P.E.

Subject: **Box Culvert Guardrail - Task AE Calculations**

$D = 14 \cdot in$ BP Length (in.) $B = 14 \cdot in$ BP Width (in.) $f'_c = 4000 \cdot psi$

$d = 8.28 \cdot in$ Post Depth (in.) $D = 14 \cdot in$ BP Length (in.) $N_t = 2$ # Tension Bolts

$b_f = 5.27 \cdot in$ Post Flange Width (in.) $Hole_{edgedist} = 1.5\,in$

$f := \frac{D}{2} - Hole_{edgedist}$ Distance from Col. Centerline to tension bolts.

From static, there are Three Equations & Three Unknowns, P_t, "Y", & s_c:

Initial estimates required. Use these estimates to converge on solutions for the three unknowns, s_c, Y, P_t:

Initial Estimates for unknowns: $\sigma_c := 1000 \cdot psi$ $Y := .3 \cdot ft$ $P_t := 10 \cdot kip$

Given

$$\frac{1}{2} \cdot Y \cdot \sigma_c \cdot B - P_t - P_c = 0$$

Equation 1

$$P_t \cdot f + (P_c + P_t) \cdot \left(\frac{D}{2} - \frac{Y}{3}\right) - P_c \cdot e = 0$$

Equation 2

$$\sigma_c = \frac{P_t \cdot Y}{A_s \cdot n \cdot \left(\frac{D}{2} - Y + f\right)}$$

Equation 3

$$\begin{pmatrix} Y \\ \sigma_c \\ P_t \end{pmatrix} := Find(Y, \sigma_c, P_t)$$

$Y = 3.5241 \cdot in$

$\sigma_c = 3653 \cdot psi$ Compressive stress @ the Edge of the Baseplate on Compression side.

$P_t = 90 \cdot kips$ Tension Force in (N_t) Anchor Bolts

$P_{Bolt} := \frac{P_t}{N_t}$ $P_{Bolt} = 45.01 \cdot kips$ Tension per Bolt (kips) ... o.k.. close to $\phi R_{tension\ per\ bolt}$

$h_{ef} = 10.5 \cdot in$ $\phi R_{tension} = 41.79 \cdot kips$

9.) Check Baseplate bending/thickness using forces & stress above separately.

Calculate moment in baseplate on bearing side:

$Y = 3.52 \cdot in \qquad d_{edge} := \frac{D}{2} - \frac{b_f}{2} \qquad d_{edge} = 4.37 \cdot in$

$$M_{plate1} := \frac{\sigma_c \cdot Y}{2} \cdot \left[\left(d_{edge} + \frac{t_f}{2} \right) - \frac{Y}{3} \right]$$

$$M_{plate1} = 21.82 \cdot \frac{kip \cdot in}{in}$$

Calculate moment in baseplate on Tension Bolt Side:

$P_{Bolt} = 45.01 \cdot kips$

$Hole_{edgedist} = 1.5 \cdot in$

$d_{edge} = 4.37 \cdot in$ Distance from Baseplate Edge to Post Edge

$$Bolt_{dist} := d_{edge} - Hole_{edgedist} + \frac{t_f}{2}$$

$Bolt_{dist} = 3.07 \cdot in$ Distance from center of bolt to centerline of post flange

$$M_{plate2} := \frac{P_{Bolt} \cdot Bolt_{dist}}{Bolt_{dist} \cdot 2} \qquad M_{plate2} = 22.5 \cdot \frac{kip \cdot in}{in}$$

$$M_{plate} := \begin{cases} M_{plate1} & \text{if } M_{plate1} > M_{plate2} \\ M_{plate2} & \text{otherwise} \end{cases}$$

Select worst case bending moment in plate bearing or anchor bolt tension

$$M_{plate} = 22.5 \cdot \frac{kip \cdot in}{in}$$

Design moment in the baseplate for thickness calculations

Substract 1/8" since procedure is little conservative

Therefore: $t_{prequired} := \sqrt{\frac{4 \cdot M_{plate}}{F_y}} \qquad t_{prequired} = 1.34 \cdot in \qquad t_{plate} := (t_{prequired} - 0.125in)$

$t_{bp} := Round(t_{plate}, 0.125in) \qquad t_{bp} = 1.25 \cdot in$ Final Baseplate Design Thickness (in.)

Texas Transportation Institute

Project #: 405160-00005

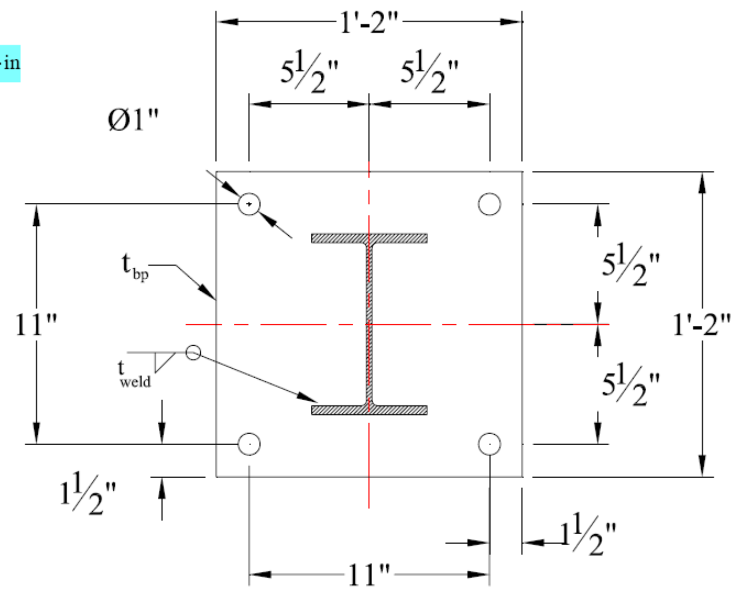
Subject: Box Culvert Guardrail - Task AE Calculations

RCOMMENDED BASEPLATE DETAILS

$t_{bp} = 1.25 \cdot in$

$F_y = 50 \cdot ksi$

$t_{weld} = 0.25 \cdot in$



W8x21
BASEPLATE DETAILS

Anchor Bolts: 7/8" Dia. A193 Threaded Rods, 14 inches Long, embedded 10.0 inches minimum

Anchorage System: Hilti RE 500 Anchoring System

APPENDIX B. PENDULUM TESTING OF GUARDRAIL POSTS ON BOX CULVERTS

INTRODUCTION

The objective of this project was to develop a guardrail design for typical box culverts that will meet the safety performance guidelines set forth in National Cooperative Highway Research Program (NCHRP) *Report 350*. Low-speed pendulum tests were performed on a prototype guardrail post on a simulated box culvert as a surrogate for full-scale crash testing.

PENDULUM FACILITY

The guardrail post on box culvert was tested at Texas Transportation Institute (TTI) outdoor pendulum testing facility. The pendulum bogie, built according the specifications of the Federal Outdoor Impact Laboratory's (FOIL) pendulum, and the testing area are shown in the adjacent figure. Frontal crush of the aluminum honeycomb nose of the bogie simulates the crush of an actual vehicle and the sweeper plate, constructed of steel angles and a steel plate, is attached to the body of the pendulum with a ground clearance of 4 inches to replicate roughly an automobile's undercarriage. The crushable nose configuration is the FOIL ten stage bogie nose. Cartridges of expendable aluminum honeycomb material of differing densities are placed in a sliding nose. The pendulum impacts the guardrail post on box culvert at a target speed of 22 mph and at a height of 21 inches above the ground, which represents the bumper height of a pickup truck. After a test, the honeycomb material is replaced and the bogie is reused. A sketch of the honeycomb configuration used for the pendulum bogie is shown in Attachment A. Testing was performed in accordance with *NCHRP Report 350* and a brief description of the procedures is presented in Attachment B.

TEST INSTALLATION

TTI received simulated concrete box culvert details from Michael Elle of Minnesota Department of Transportation (Mn/DOT). Two W6x9 guardrail post were anchored to two simulated concrete deck specimens. Each specimen was crash tested using a dynamic pendulum surrogate vehicle. Each post was anchored to a 9-inch thick concrete deck to simulate a typical box culvert installation. The concrete deck specimens were 8 feet-3½ inches wide and 8 feet-4½ inches long. The concrete decks constructed and tested for this project were 9 inches thick. Reinforcement in the top of each deck consisted of #3 transverse bars spaced on 12-inch centers. Longitudinal reinforcement in each deck consisted of #3 bars spaced on 6-inch centers. Reinforcement in the bottom layer consisted also of #3 bars spaced on 12-inch centers with #5 bars spaced on 4½-inch centers in the longitudinal direction. To further simulate the anchorage to a typical concrete box culvert installation, the posts were anchored 2 ft-4 inches from the edge of the culvert. Additional details are shown in Attachment C.

A detailed design of the W6x9 post anchorage and base plate tested was performed. A second design utilizing W8x21 posts was also performed. However, based on the proposed frequent use, only the system utilizing W6x9 posts was tested. Based on the information provided by the participating states in this pooled fund project, the preferred anchoring system for post anchorage to the top of the box culvert system was Hilti's RE 500 Adhesive Anchoring System. The W6x9 posts were welded to 12 inch x 12 inch x 7/8-inch thick base plates and anchored to the 9-inch thick concrete box culvert decks utilizing 7/8-inch diameter super Hilti Anchoring System (HAS) rods. These rods were embedded a minimum of 6 inches into 1-inch diameter drilled holes in the concrete decks and anchored to the deck using Hilti RE 500 Epoxy Anchoring System. A larger base plate utilizing deeper adhesive anchors was designed for the W8x21 posts to simulate anchorage to the top of a concrete footing. The base plate and anchorage designs were based on the minimum strengths to cause plastic failure in the posts. These designs can be utilized for the direct anchorage to either the box culvert or concrete footing without any contribution from soil embedment above the box culvert or footing. The anchorage and base plate designs for both the W6x9 and the W8x21 posts are provided in Attachment D.

TEST RESULTS

Test P1

The pendulum bogie, traveling at an impact speed of 21.7 mi/h, impacted the guardrail post at a height of 21 inches. At 0.012 s, the post began to deflect toward the field side, and at 0.017 s, the post returned to its upright position. The post began to deflect toward the field side again at 0.022 s, and the pendulum began to ride up the face of the post at 0.091 s. Forward motion of the pendulum stopped at 0.157 s.

The top of the post was deformed toward field side 10.8 inches. Total crush of the honeycomb nose was 14.0 inches. Photographs of the post before and after the test are shown in Attachment E.

Longitudinal occupant impact velocity was 8.9 m/s, longitudinal occupant ridedown acceleration was -3.9 g's, and the maximum 50-ms average acceleration was -10.0 g's. Graphs for this test are shown in Attachment F.

Test P2

The pendulum bogie, traveling at an impact speed of 21.1 mi/h, impacted the guardrail post at a height of 21 inches. At 0.010 s, the post began to deflect toward the field side, and at 0.015 s, the post returned to its upright position. The post began to deflect toward the field side again at 0.020 s, and the pendulum began to ride up the face of the post at 0.067 s. The post began to shear at the front of the base at 0.106 s.

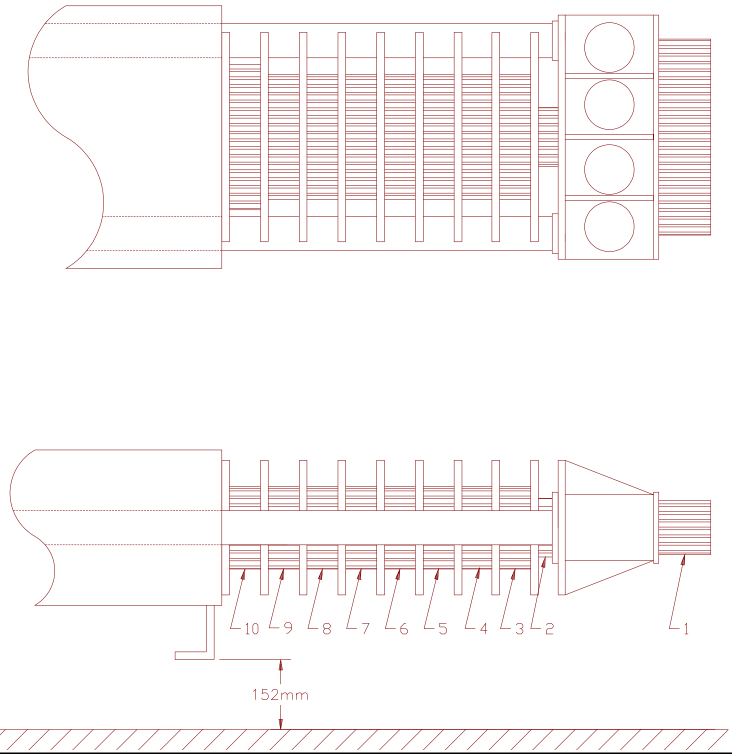
The top of the post was deformed toward field side 10.8 inches. Total crush of the honeycomb nose was 13.7 inches. Photographs of the post before and after the test are shown in Attachment E.

Longitudinal occupant impact velocity was 6.3 m/s, longitudinal occupant ridedown acceleration was -0.6 g's, and the maximum 50-ms average acceleration was -9.6 g's. Graphs for this test are shown in Attachment F.

CONCLUSIONS

TTI performed low-speed pendulum tests as a surrogate for full-scale crash testing. The W6x9 post and baseplate design using 7/8-inch high strength anchor rods and anchored using the Hilti RE 500 Adhesive System and presented herein performed well in the full scale tests. Based on the testing results, the W6x9 post and anchorage details presented in this report are recommended for full-scale crash testing.

ATTACHMENT A. PENDULUM BOGIE DETAILS



Cartridge Number	Size (mm)	Area Effectively Removed by Pre-Crushing (mm^2)	Static Crush Strength (kPa)	Total Crush Force for Each Cartridge (kN)
1	69.9 × 406 × 76		896.3	25.4
2	102 × 127 × 51		172.4	2.2
3	203 × 203 × 76	13549	896.3	24.8
4	203 × 203 × 76	9678	1585.8	50.0
5	203 × 203 × 76	3871	1585.8	59.2
6	203 × 203 × 76		1585.8	65.3
7	203 × 203 × 76	13549	2757.9	76.3
8	203 × 203 × 76	7742	2757.9	92.3
9	203 × 203 × 76		2757.9	113.6
10	203 × 254 × 76		2757.9	142.3

Configuration of pendulum nose and honeycomb.

ATTACHMENT B. PENDULUM TEST PROCEDURES AND DATA ANALYSIS

The pendulum 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 bogie was instrumented with two accelerometers mounted at the rear of the bogie to measure longitudinal acceleration levels. The accelerometers were strain gage type with a linear millivolt output proportional to acceleration.

The electronic signals from the accelerometers were amplified and transmitted to a base station by means of constant bandwidth FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Calibration signals were recorded before and after the test and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive switches on the nose of the bogie were actuated by wooden dowel rods and initial contact to produce speed trap and "event" marks on the data record to establish the exact instant of contact with the installation, as well as impact velocity.

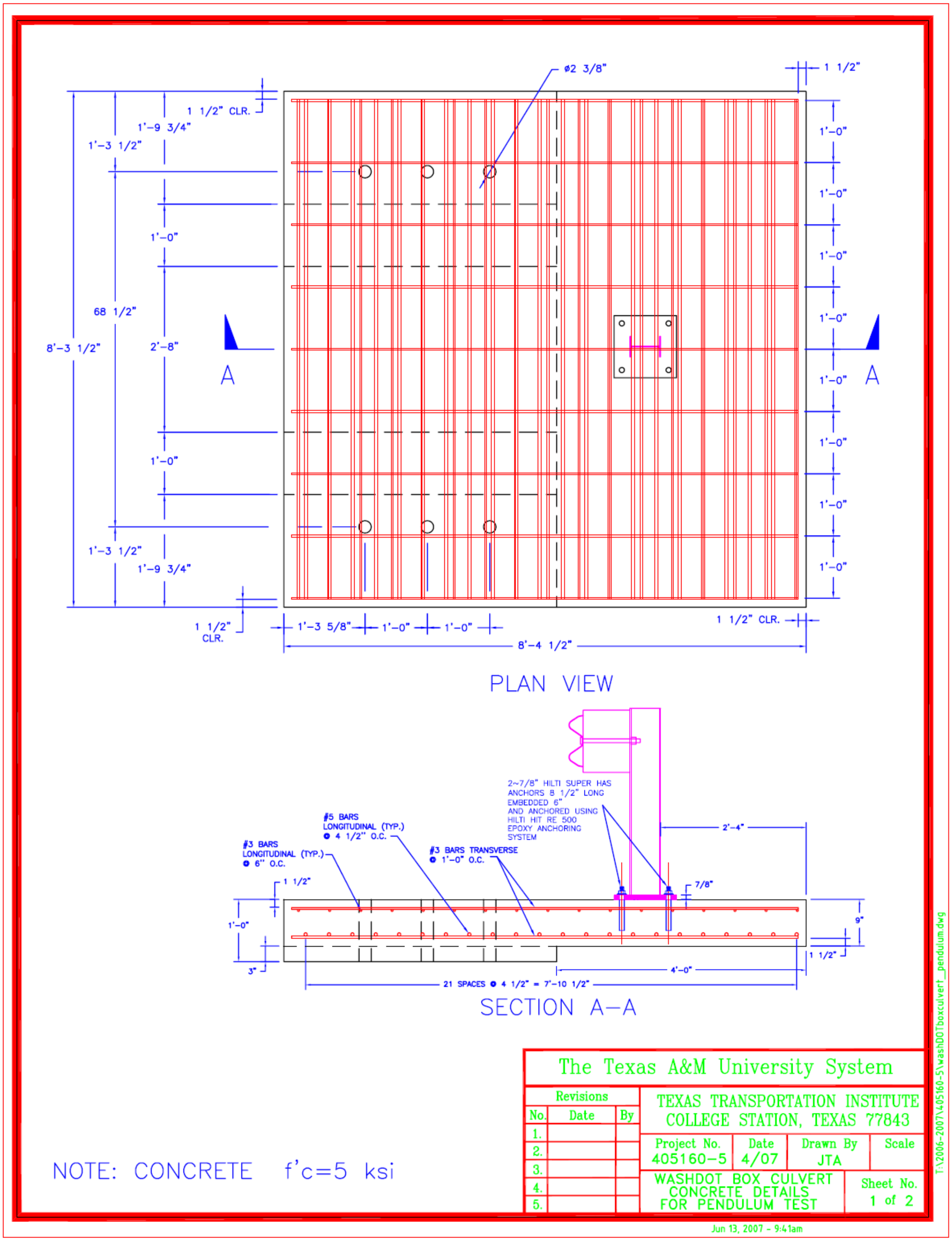
The multiplex of data channels, transmitted on one radio frequency, is received and demultiplexed onto TEAC® instrumentation data recorder. After the test, the data are played back from the TEAC® recorder and digitized. A proprietary software program (WinDigit) converts the analog data from each transducer 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 bogie impact velocity.

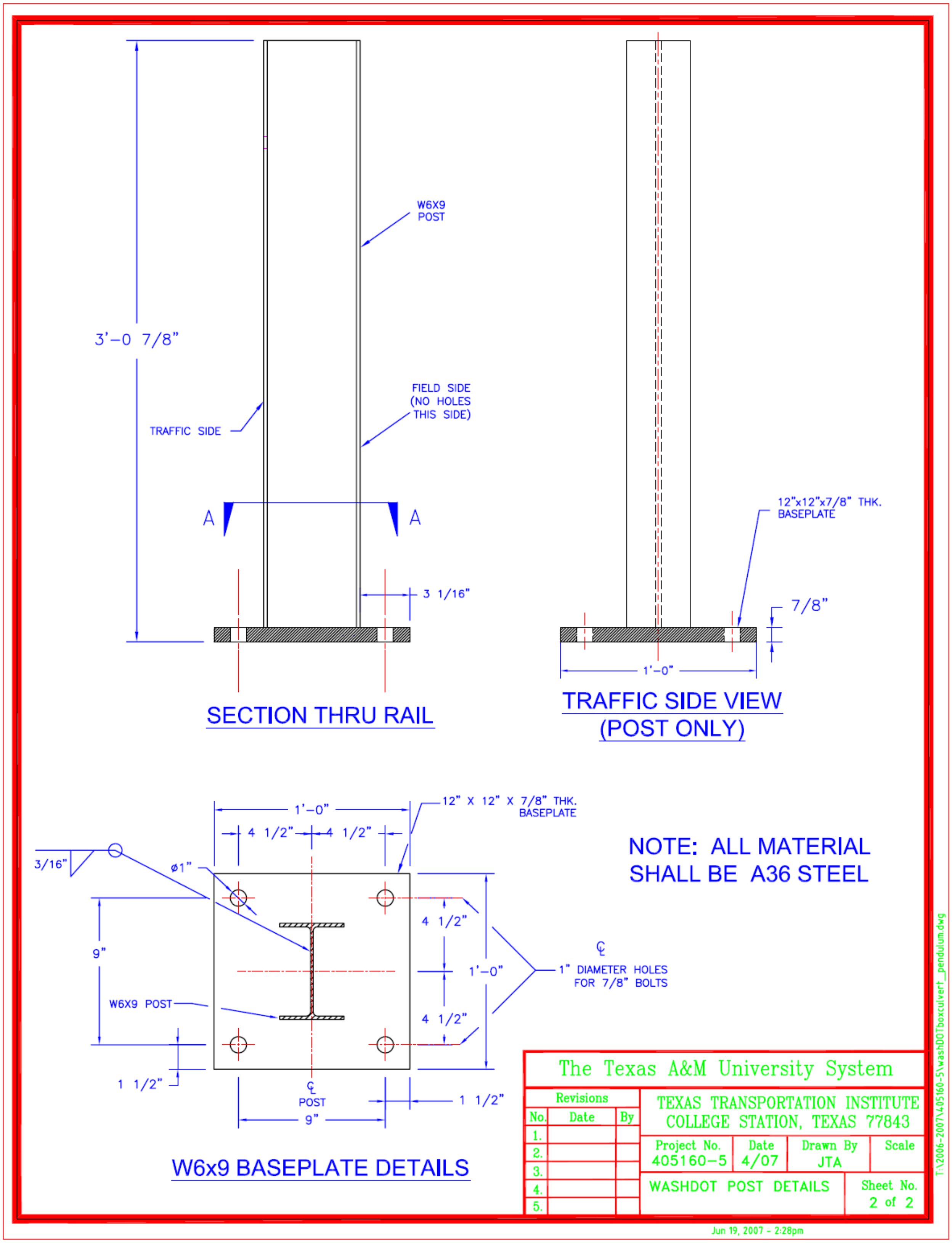
The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartment impact velocities, time of occupant/compartment impact after bogie impact, and the highest 10-ms average ridedown acceleration. WinDigit calculates change in bogie velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms are computed. For reporting purposes, the data from the bogie-mounted accelerometers were then filtered with a 180 Hz digital filter and plotted using a commercially available software package (Microsoft EXCEL).

PHOTOGRAPHIC INSTRUMENTATION

A high-speed digital camera, positioned perpendicular to the path of the pendulum bogie and the test article, was used to record the collision period. The film from this high-speed camera was analyzed on a computer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A Betacam camera and still cameras were used to document the crushable pendulum nose and the test article before and after the test.

ATTACHMENT C. DETAILS OF TEST ARTICLES





3'-0 7/8"
W6X9
POST
FIELD SIDE
(NO HOLES
THIS SIDE)
TRAFFIC SIDE
A
A
3 1/16"
SECTION THRU RAIL
12"x12"x7/8" THK.
BASEPLATE
7/8"
1'-0"
TRAFFIC SIDE VIEW
(POST ONLY)
1'-0"
12" X 12" X 7/8" THK.
BASEPLATE
4 1/2"
4 1/2"
3/16"
ø1"
NOTE: ALL MATERIAL
SHALL BE A36 STEEL
9"
4 1/2"
1'-0"
1" DIAMETER HOLES
FOR 7/8" BOLTS
W6X9 POST
4 1/2"
1 1/2"
POST
9"
1 1/2"
W6x9 BASEPLATE DETAILS
The Texas A&M University System
Revisions
No.
Date
By
1.
2.
3.
4.
5.
TEXAS TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS 77843
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ATTACHMENT D. DESIGN CALCULATIONS

W6x9 DESIGN

Texas Transportation Institute

Project #: 405160-00005

W6x9 Design

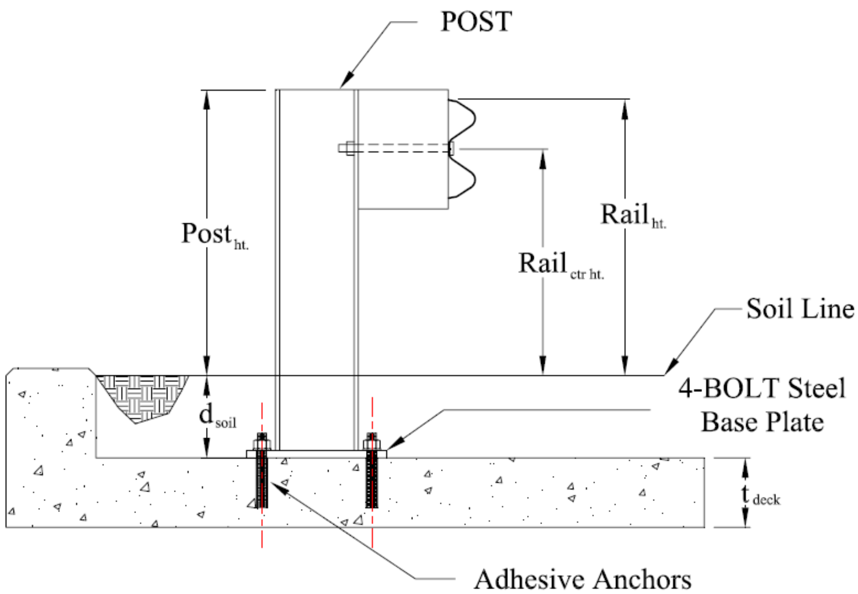
Subject: Box Culvert Guardrail - Task AE Calculations

Hilti RE 500 Anchor System

Sponsor: Washington DOT Pooled Fund

7/8" Dia. Anchors Embed. 6" Max

Given the following general latout of a box culvert guardrail post anchored to a concrete box culvert section using an epoxy adhesive anchoring system. Find the limiting ultimate strength of the post design considering the different variables used in the design.



GUARDRAIL ON BOX CULVERT TYPICAL CROSS-SECTION

depth of soil (in.)

$d_{soil} := 0in$

Thickness of Deck (in.)

$t_{deck} := 9in$

1.) Design Information:

****** Rail Geometry ******

$Rail_{ctrht} := 21in$ Center Height of Rail (in.)

$Rail_{ht} := Rail_{ctrht} + 6.125in$ Height to top of rail (in.)

$Post_{ht} := 27in$ Height of Post above grade (in.)

$Post_{load} := 12kips$ Load applied to Rail center (kips) $M_{load} := Post_{load} \cdot (Rail_{ht} + d_{soil})$

Texas Transportation Institute

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

Define Mathcad units ORIGIN := 1

$kips \equiv kip$ $ksi \equiv \frac{kips}{in^2}$

Steel Beam Yield Strength: $F_y := (50) \cdot ksi$

Beam Nominal Depth: NOMINAL_DEPTH := (6)

Beam weight per foot: WEIGHT_PER_FOOT := (9)

Beam Data - Fri Sep 15 09:13:04 2006

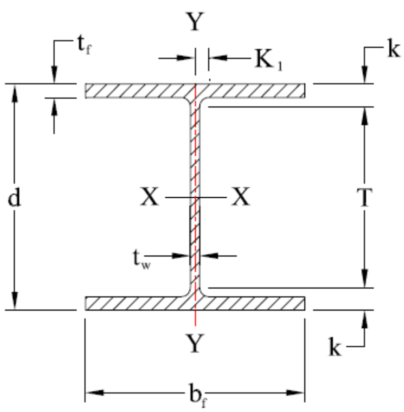
******* Post Information *******

$Wt\_per\_foot = 9\,ft^{-1} \cdot lb$ $F_y = 50 \cdot ksi$

Post Data for: $Nominal\_depth = 6 \cdot in$

$Wt\_per\_foot = 9\,ft^{-1} \cdot lb$ Wt. per foot of length (lb/ft)

$d_n = 6$ Nominal Depth of member



POST DETAILS

$Area = 2.68 \cdot in^2$ Area (in^2)

$d = 5.9 \cdot in$ Actual Depth of Member (in.)

$t_w = 0.17 \cdot in$ Thickness of Web (in.)

$b_f = 3.94 \cdot in$ Width of Flange (in.)

$t_f = 0.215 \cdot in$ Thickness of Flange (in.)

$k = 0.56 \cdot in$ Distance to toe of fillet (in.)

$I_x = 16.4 \cdot in^4$ Moment of Inertia (Stg. Axis (in^4))

$S_x = 5.56 \cdot in^3$ Section Modulus (Stg. Axis (in^3))

$Z_x = 6.23 \cdot in^3$ Plastic Modulus (Strong Axis (in^3))

$Z_y = 1.72 \cdot in^3$ Plastic Modulus (Weak Axis (In^3))

$A_f = 0.85 \cdot in^2$ Area Flange (in^2)

$r_x = 2.47 \cdot in$ radius of gyration with respect to X-X Axis (in.)

$I_y = 2.19 \cdot in^4$ Moment of Inertia (Weak Axis (in^4))

$S_y = 1.11 \cdot in^3$ Section Modulus (Weak Axis (in^3))

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

***** Steel & Concrete Material properties *****

$F_{ysteel} := 50ksi$ Yield Strength of Steel Material (ksi)

$F_{yrebar} := 60ksi$ Yield Strength of rebar (ksi)

$F_u := 65ksi$ Rupture Strength of Steel Material (ksi)

$f'_c := 4000psi$ Compressive Strength of Concrete)psi)

****** Anchor Bolt Properties *******

$F_{ubolts} := 125ksi$ High Strength Super HAS Rod Material, ASTM A193, Grade B7 Material (ksi)

$Dia_{bolt} := \frac{7}{8} in$ Dia. of anchor bolts (in.) $Area_{bolt} := \pi\, Dia_{bolt}^2 \cdot 0.25$ $Area_{bolt} = 0.6 \cdot in^2$

$\phi_{bolt} := 1.0$ Strength Reduction Factor For Bolts

$E_s := 29 \cdot 10^6 \cdot psi$ Modulus of Elasticity (in.) $N_t := 2$ 2 bolts on the tension face

$A_s := \frac{\pi \cdot Dia_{bolt}^2}{4} \cdot N_t$ Area of tension bolts $A_s = 1.203 \cdot in^2$

$E_c := 57000 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi$ $E_c = 3604996.533 \cdot psi$ $n := \frac{E_s}{E_c}$ $n = 8.04$

***** Weld Properties *****

$F_{EXX} := 70ksi$ Weld Material Strength (ksi)

$t_{weld} := \frac{1}{4} in$ Weld Size (in.)

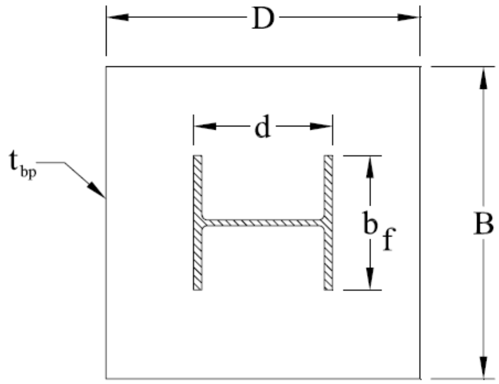
$\phi_{weld} := 1.0$ Reduction Factor for Weld

Texas Transportation Institute

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**



BASEPLATE DETAILS

****** **Baseplate Properties** ******

$D := 12in$ Baseplate Length (in.)

$B := 12in$ Baseplate width (in.)

$t_p := 1.000in$ Approx. Baseplate thickness (in.)

$d = 5.9 \cdot in$ Depth of Post (in.)

$b_f = 3.94 \cdot in$ Width of Post (in.)

$Hole_{edgedist} := 1.5in$ Distance to plate edge to hole center (in.)

***** **Hilti Anchor Properties** *****

1.) As per page 163, 2006 Hilti Product Technical Guide,
HIT RE 500 Epoxy System, Average values for 4000 psi concrete:

$$Tension := \begin{pmatrix} 22670 \\ 63495 \\ 64730 \end{pmatrix} lbf \qquad Shear := \begin{pmatrix} 16365 \\ 48455 \\ 79020 \end{pmatrix} lbf$$

$$Depth_{embed} := \begin{pmatrix} 4 \\ 7.875 \\ 10.5 \end{pmatrix} in$$

Actual Embedment Depth (inches)
, see Hilti guide

$h_{ef} := 6.00in$

Use Hilti Hight Strength Super HAS, 7/8" Dia. Rod:

$$HIT_{ultimatetensile} := linterp(Depth_{embed}, Tension, h_{ef})$$

$$HIT_{ultimateshear} := linterp(Depth_{embed}, Shear, h_{ef})$$

Interpolate for Embedment Depth, h_{ef}

$HIT_{ultimatetensile} = 43.741 \cdot kips$ Ultimate Bond Strength (see pg 112 Hilti 2002 Tech. Guide)

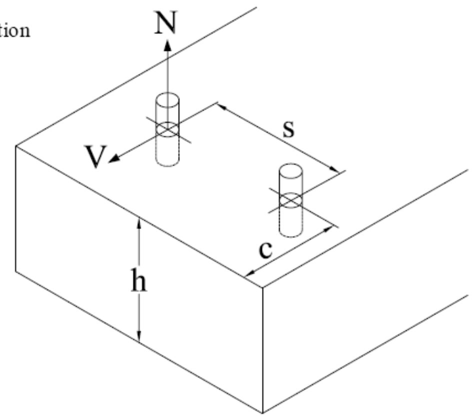
$HIT_{ultimateshear} = 32.928 \cdot kips$ Ulitmate shear strength of anchor (see pg 112)

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

$Temperature := 110\,°F$ Max Temperature for Temperature Reduction



ANCHOR DETAILS

Check Load Adjustment Factors for Anchor Spacings & Clearance:

From page 119, Hilti 2002 Technical Guide

$S_{act} := 9.0in$ Actual anchor spacing (inches)

$C_{act} := 24in$ edge distance (inches) from concrete edge to Centerline of bolts

$h_{nom} := 7.875in$ Standard embedment depth (inches), see page 110

$h_{ef} = 6 \cdot in$ Actual embedment depth (in.)

$S_{min} := 0.5 \cdot h_{ef}$ $S_{min} = 3 \cdot in$

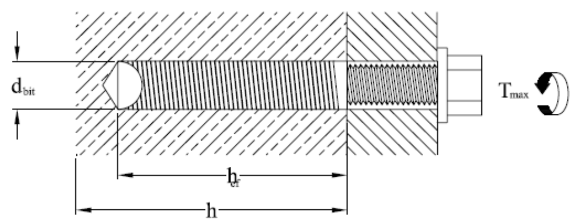
$S_{cr} := 1.5 \cdot h_{ef}$ $S_{cr} = 9 \cdot in$

$C_{min} := 0.5 \cdot h_{ef}$ $C_{min} = 3 \cdot in$

$C_{cr} := 1.5 \cdot h_{ef}$ $C_{cr} = 9 \cdot in$

$h := t_{deck}$ Thickness of slab, (in)

$h = 9 \cdot in$



ANCHOR GEOMETRY

**** Calculate Hilti Reduction Factors for Spacing Tension & Shear ******

$$f_A := \left| \begin{array}{l} f_A \leftarrow 0.3\cdot\left(\frac{S_{act}}{h_{ef}}\right) + 0.55 \ \text{ if } \ S_{cr} \geq S_{act} \geq S_{min} \\ f_A \leftarrow 1.0 \ \text{ if } \ S_{act} \geq S_{cr} \\ f_A \leftarrow 0 \ \text{ if } \ S_{act} < S_{min} \end{array} \right.$$

$f_A = 1$

***** Calculate Reduction Factors for Edge Distance Tension, "f_{RN}" *******

$$f_{RN} := \left| \begin{array}{l} f_{RN} \leftarrow 0.3\cdot\left(\frac{C_{act}}{h_{ef}}\right) + 0.55 \ \text{ if } \ C_{cr} \geq C_{act} \geq C_{min} \\ f_{RN} \leftarrow 1.0 \ \text{ if } \ C_{act} \geq C_{cr} \\ f_{RN} \leftarrow 0 \ \text{ if } \ C_{act} < C_{min} \end{array} \right.$$

$f_{RN} = 1$

5.) Calculate Reduction Factors for Edge Distance Shear, "f_{RVperp}"

$$f_{RVperp} := \left| \begin{array}{l} f_{RVperp} \leftarrow 0.54\cdot\left(\frac{C_{act}}{h_{ef}}\right) - 0.09 \ \text{ if } \ C_{cr} \geq C_{act} \geq C_{min} \\ f_{RVperp} \leftarrow 1.0 \ \text{ if } \ C_{act} \geq C_{cr} \\ f_{RVperp} \leftarrow 0 \ \text{ if } \ C_{act} < C_{min} \end{array} \right.$$

$f_{RVperp} = 1$

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

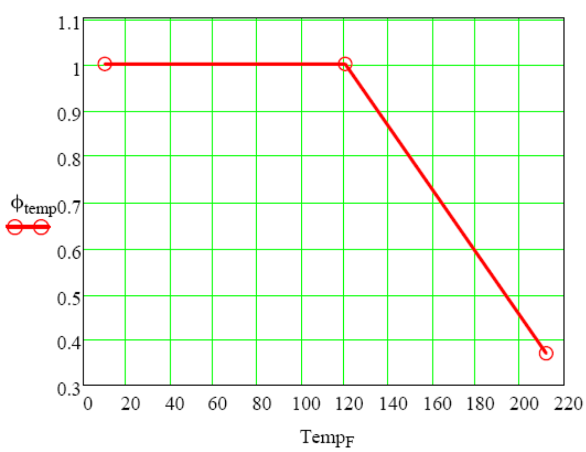
Sponsor: Washington DOT Pooled Fund

6.) Calculate total combined Reduction Factors for tension & shear:

$f_{RVperp} = 1$ $f_A = 1$ $f_{RN} = 1$

$\phi_{temp} := \begin{pmatrix} 1.0 \\ 1.0 \\ 0.37 \end{pmatrix}$ $Temp := \begin{pmatrix} 10 \\ 120 \\ 212 \end{pmatrix} {}^\circ F$ $F := Temp$ $Temp = \begin{pmatrix} 260.93 \\ 322.04 \\ 373.15 \end{pmatrix} K$ $Temp = \begin{pmatrix} 260.93 \\ 322.04 \\ 373.15 \end{pmatrix} K$

$$Temp_F := \frac{\left[(Temp - 273.15K)\cdot\frac{9}{5}\right] + 32K}{K}$$ Temperature conversion



$\phi_{tempreduce} := \text{linterp}(Temp, \phi_{temp}, Temperature)$

$\phi_{tempreduce} = 1$

$\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN} \cdot \phi_{tempreduce})}$ $\phi_{shear} := \overrightarrow{(f_A \cdot f_{RVperp})}$

$\phi_{tension} = 1$ $\phi_{shear} = 1$

$\phi R_{tension} := \phi_{tension} \cdot HIT_{ultimatetensile}$ $\phi R_{shear} := \phi_{shear} \cdot HIT_{ultimateshear}$

$\phi R_{tension} = 43.74 \cdot kips$ $\phi R_{shear} = 32.93 \cdot kips$ Hilti Factored Anchor Strengths for

$h_{ef} = 6.00 \cdot in$

Texas Transportation Institute

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

7. Calculate the Plastice Strength of the Post:

$F_y = 50 \cdot ksi$ Yield Strength of Steel

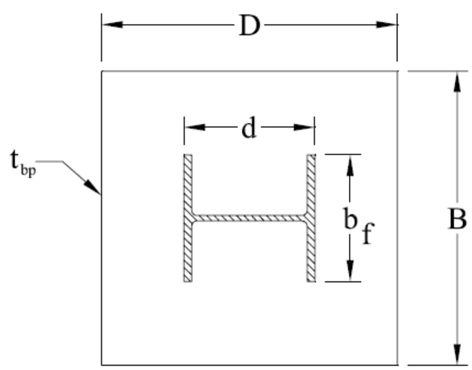
$Z_x = 6.23 \cdot in^3$ Plastic Section Modulus of Post

$M_{xplastic} := F_y \cdot Z_x$

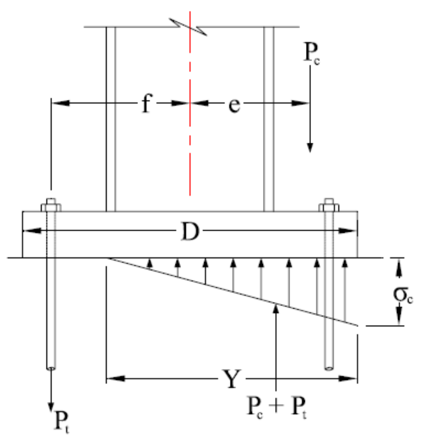
$M_{xplastic} = 25.96 \cdot kip \cdot ft$ Plastic Moment

$M_{load} = 27.12 \cdot kip \cdot ft$ Moment from Post Load

8.) Check Baseplate details & calculate anchor bolt forces:



BASEPLATE DETAILS



Given Basic Uplift Procedure as shown in Blodgett, "Design of Welded Structures" pages 3-3-8 through 10. and sketch w/ nomenclature showing Baseplate Geometry and distribution of force.

Find: Maximum Stress (σ_c), "Y", and force in the bolts (P_t) for applied force as shown.

This basic uplift procedure as shown in Blodget's "Design of Welded Structures" pages 3-3-8 through 10. It solves three equations for three unknowns for any combination of vertical & applied moment to the column. You have to combine the vertical load and moment to a single vertical load at some eccentricity "e". (Input Items in Yellow):

4 Bolts are used in he deign with 2 bolts located on the tension face

$P_c := .10 \cdot kips$ Vertical Load on Column (kips)

Select Design Moment from Above:

$M_1 := M_{xplastic}$ Applied Moment (k-ft.)

$e := \frac{M_1}{P_c}$ $e = 3115 \cdot in$ eccentricity (in.)

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Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

$D = 12 \cdot in$ BP Length (in.) $B = 12 \cdot in$ BP Width (in.) $f'_c = 4000 \cdot psi$

$d = 5.9 \cdot in$ Post Depth (in.) $D = 12 \cdot in$ BP Length (in.) $N_t = 2$ # Tension Bolts

$b_f = 0.33\ ft$ Post Flange Width (in.)

$f := \frac{d}{2} - Hole_{edgedist}$ Distance from Col. Centerline to tension bolts.

From static, there are Three Equations & Three Unknowns, P_t, "Y", & s_c:

Use Mathcad's Solve Block to find solutions. Solve Block requires "Initial guesses and uses these guesses to converge on solutions for the three unknowns, s_c, Y, P_t:

Initial Guesses for unknowns: $\sigma_c := 1000 \cdot psi$ $Y := .3 \cdot ft$ $P_t := 10 \cdot kip$

Given

$$\frac{1}{2} \cdot Y \cdot \sigma_c \cdot B - P_t - P_c = 0$$

Equation 1

$$P_t \cdot f + (P_c + P_t) \cdot \left(\frac{D}{2} - \frac{Y}{3}\right) - P_c \cdot e = 0$$

Equation 2

$$\sigma_c = \frac{P_t \cdot Y}{A_s \cdot n \cdot \left(\frac{D}{2} - Y + f\right)}$$

Equation 3

$$\begin{pmatrix} Y \\ \sigma_c \\ P_t \end{pmatrix} := Find(Y, \sigma_c, P_t)$$

$Y = 2.7545 \cdot in$

$\sigma_c = 2887 \cdot psi$ Compressive stress @ the Edge of the Baseplate on Compression side.

$P_t = 48 \cdot kips$ Tension Force in (N_t) Anchor Bolts

$P_{Bolt} := \frac{P_t}{N_t}$ $P_{Bolt} = 23.81 \cdot kips$ Tension per Bolt (kips)

... o.k. less than Factored Hilti Ultimate for $h_{ef} = 6 \cdot in$ $\phi R_{tension} = 43.74 \cdot kips$

9.) Check Baseplate bending/thickness using forces & stress above separately.

Calculate moment in baseplate on bearing side:

$Y = 2.75 \cdot in$ $\quad d_{edge} := \frac{D}{2} - \frac{b_f}{2}$ $\quad d_{edge} = 4.03 \cdot in$

$$M_{plate1} := \frac{\sigma_c \cdot Y}{2} \cdot \left[\left(d_{edge} + \frac{t_f}{2}\right) - \frac{Y}{3}\right]$$

$$M_{plate1} = 12.8 \cdot \frac{kip \cdot in}{in}$$

Calculate moment in baseplate on Tension Bolt Side:

$P_{Bolt} = 23.81 \cdot kips$

$Hole_{edgedist} = 1.5 \cdot in$

$d_{edge} = 4.03 \cdot in$ Distance from Baseplate Edge to Post Edge

$$Bolt_{dist} := d_{edge} - Hole_{edgedist} + \frac{t_f}{2}$$

$Bolt_{dist} = 2.64 \cdot in$ Distance from center of bolt to centerline of post flange

$M_{plate2} := \frac{P_{Bolt} \cdot Bolt_{dist}}{Bolt_{dist} \cdot 2}$ $\quad M_{plate2} = 11.9 \cdot \frac{kip \cdot in}{in}$

$$M_{plate} := \begin{cases} M_{plate1} & \text{if } M_{plate1} > M_{plate2} \\ M_{plate2} & \text{otherwise} \end{cases}$$

Select worst case bending moment in plate bearing or anchor bolt tension

$M_{plate} = 12.8 \cdot \frac{kip \cdot in}{in}$ Design moment in the baseplate for thickness calculations

Substract 1/8" since procedure is little conservative

Therefore: $t_{prequired} := \sqrt{\frac{4 \cdot M_{plate}}{F_y}}$ $\quad t_{prequired} = 1.01 \cdot in$ $\quad t_{plate} := (t_{prequired} - 0.125in)$

$t_{bp} := Round(t_{plate}, 0.125in)$ $\quad t_{bp} = 0.875 \cdot in$ Final Baseplate Design Thickness (in.)

Project #: 405160-00005

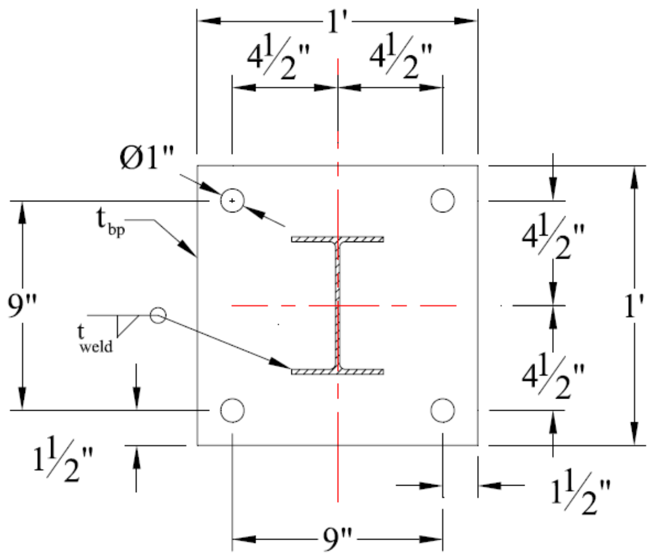
Subject: Box Culvert Guardrail - Task AE Calculations

$t_{bp} = 0.875 \cdot in$

$F_y = 50 \cdot ksi$

$t_{weld} = 0.25 \cdot in$

RECOMMENDED BASEPLATE DETAILS



W6x8.5 & 9
BASEPLATE DETAILS

Anchor Bolts: 7/8" Dia. A193 Threaded Rods 8 inches long, embedded 6 inches minimum

Anchorage System: Hilti RE 500 Anchoring System

W8x21 DESIGN

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

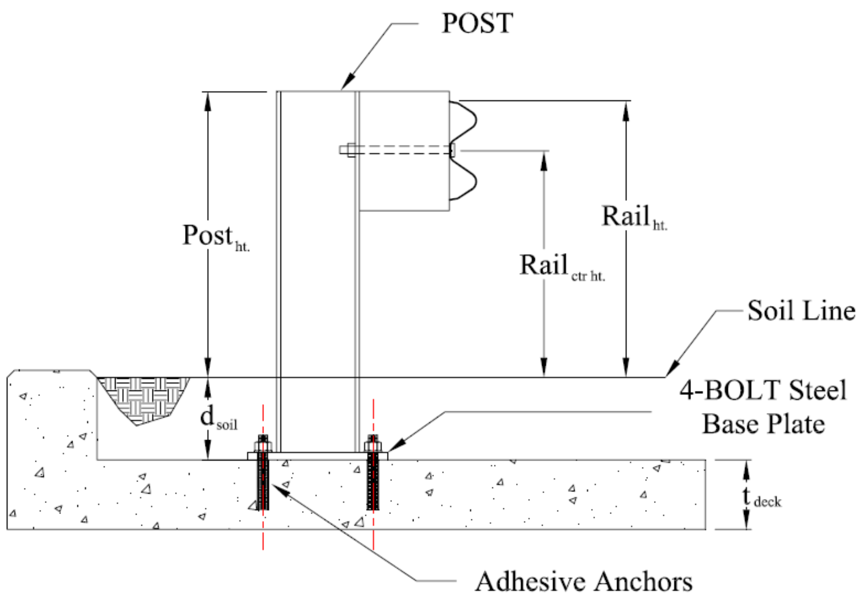
Sponsor: Washington DOT Pooled Fund

W8x21 Design

Hilti RE 500 Anchor System

7/8" Dia. Anchors Embed. 10" Max

Given the following general latout of a box culvert guardrail post anchored to a concrete box culvert section using an epoxy adhesive anchoring system. Find the limiting ultimate strength of the post design considering the different variables used in the design.



GUARDRAIL ON BOX CULVERT TYPICAL CROSS-SECTION

depth of soil (in.)

$d_{soil} := 18in$

Thickness of Deck, Slab or Footing (in.)

$t_{deck} := 14in$

1.) Design Information:

****** Rail Geometry ******

$Rail_{ctrht} := 21in$ Center Height of Rail (in.)

$Rail_{ht} := Rail_{ctrht} + 6.125in$ Height to top of rail (in.)

$Post_{ht} := 27in$ Height of Post above grade (in.)

$Post_{load} := 20kips$ Load applied to Rail center (kips) $M_{load} := Post_{load} \cdot (Rail_{ctrht} + d_{soil})$

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Define Mathcad units ORIGIN := 1

$kips \equiv kip$ $ksi \equiv \frac{kips}{in^2}$

Steel Beam Yield Strength: $F_y := (50) \cdot ksi$
Beam Nominal Depth: NOMINAL_DEPTH := (8)
Beam weight per foot: WEIGHT_PER_FOOT := (21)

Beam Data - Fri Sep 15 09:13:04 2006

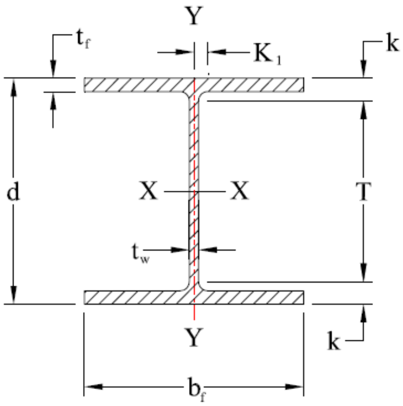
***** **Post Information** *****

Post Data for: Nominal_depth = 8 in

$Wt\_per\_foot = 21\,ft^{-1}\,lb$ $F_y = 50\,ksi$

$Wt\_per\_foot = 21\,ft^{-1} \cdot lb$ Wt. per foot of length (lb/ft)

$d_n = 8$ Nominal Depth of member



POST DETAILS

$Area = 6.16\,in^2$	Area (in^2)
$d = 8.28\,in$	Actual Depth of Member (in.)
$t_w = 0.25\,in$	Thickness of Web (in.)
$b_f = 5.27\,in$	Width of Flange (in.)
$t_f = 0.4\,in$	Thickness of Flange (in.)
$k = 0.81\,in$	Distance to toe of fillet (in.)
$I_x = 75.3\,in^4$	Moment of Inertia (Stg. Axis (in^4))
$S_x = 18.2\,in^3$	Section Modulus (Stg. Axis (in^3))
$Z_x = 20.4\,in^3$	Plastic Modulus (Strong Axis (in^3))
$Z_y = 5.69\,in^3$	Plastic Modulus (Weak Axis (In^3))
$A_f = 2.11\,in^2$	Area Flange (in^2)
$r_x = 3.49\,in$	radius of gyration with respect to X-X Axis (in.)
$I_y = 9.77\,in^4$	Moment of Inertia (Weak Axis (in^4))
$S_y = 3.71\,in^3$	Section Modulus (Weak Axis (in^3))

Texas Transportation Institute

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

***** Steel & Concrete Material properties *****

$F_{ysteel} := 50ksi$ — Yield Strength of Steel Material (ksi)

$F_{yrebar} := 60ksi$ — Yield Strength of rebar (ksi)

$F_u := 65ksi$ — Rupture Strength of Steel Material (ksi)

$f'_c := 4000psi$ — Compressive Strength of Concrete)psi)

****** Anchor Bolt Properties *******

$F_{ubolts} := 125ksi$ — High Strength Super HAS Rod Material, ASTM A193, Grade B7 Material (ksi)

$Dia_{bolt} := \frac{7}{8} in$ — Dia. of anchor bolts (in.) $\quad Area_{bolt} := \pi \, Dia_{bolt}^2 \cdot 0.25 \quad Area_{bolt} = 0.6\,in^2$

$\phi_{bolt} := 1.0$ — Strength Reduction Factor For Bolts

$E_s := 29 \cdot 10^6 \cdot psi$ — Modulus of Elasticity (in.) $\quad N_t := 2$ — 2 bolts on the tension face

$A_s := \frac{\pi \cdot Dia_{bolt}^2}{4} \cdot N_t$ — Area of tension bolts $\quad A_s = 1.203\,in^2$

$E_c := 57000 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi \quad E_c = 3604996.533\,psi \quad n := \frac{E_s}{E_c} \quad n = 8.04$

***** Weld Properties *****

$F_{EXX} := 70ksi$ — Weld Material Strength (ksi)

$t_{weld} := \frac{1}{4} in$ — Weld Size (in.)

$\phi_{weld} := 1.0$ — Reduction Factor for Weld

Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

****** **Baseplate Properties** ******

$D := 14in$ Baseplate Length (in.)

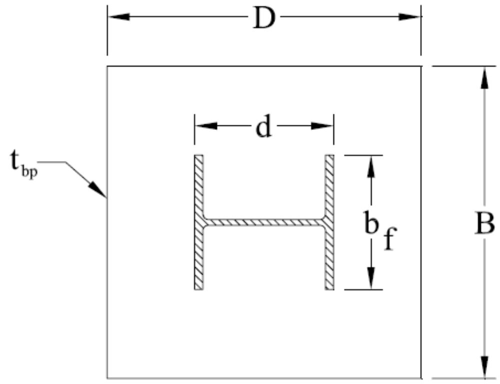
$B := 14in$ Baseplate width (in.)

$t_p := 1.000in$ Baseplate thickness (in.)

$d = 8.28\ in$ Depth of Post (in.)

$b_f = 5.27\ in$ Width of Post (in.)

$Hole_{edgedist} := 1.5in$ Distance to plate edge to hole center (in.)



BASEPLATE DETAILS

***** **Hilti Anchor Properties** *****

1.) As per page 112, 2002 Hilti Product Technical Guide,
HIT RE 500 Epoxy System, Average values for 4000 psi concrete:

$$Tension := \begin{pmatrix} 22670 \\ 63495 \\ 64730 \end{pmatrix} lbf \qquad Shear := \begin{pmatrix} 16365 \\ 48455 \\ 79020 \end{pmatrix} lbf$$

$$Depth_{embed} := \begin{pmatrix} 4 \\ 7.875 \\ 10.5 \end{pmatrix} in$$

Actual Embedment Depth (inches)
, see Hilti guide

$h_{ef} := 10.5000in$

Use Hilti Hight Strength Super HAS, 7/8" Dia. Rod:

$$HIT_{ultimatetensile} := linterp\left(Depth_{embed}, Tension, h_{ef}\right)$$

$$HIT_{ultimateshear} := linterp\left(Depth_{embed}, Shear, h_{ef}\right)$$

Interpolate for Embedment Depth, h_{ef}

$HIT_{ultimatetensile} = 64.73\ kips$ Ultimate Bond Strength (see pg 112 Hilti 2002 Tech. Guide)

$HIT_{ultimateshear} = 79.02\ kips$ Ulitmate shear strength of anchor (see pg 112)

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

$Temperature := 110\,°F$ Max Temperature for Temperature Reduction

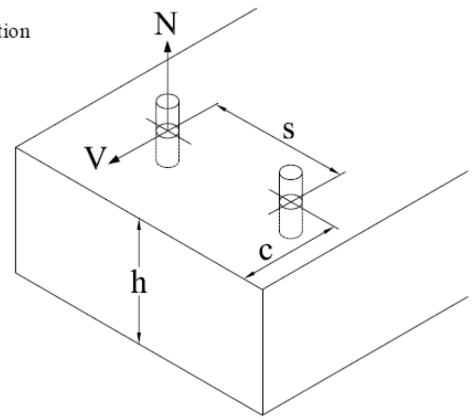
Check Load Adjustment Factors for Anchor Spacings & Clearance:

From page 119, Hilti 2002 Technical Guide

$S_{act} := 11.0in$ Actual anchor spacing (inches)

$C_{act} := 12in$ edge distance (inches) from concrete edge to Centerline of bolts

$h_{nom} := 7.875in$ Standard embedment depth (inches), see page 110



ANCHOR DETAILS

$S_{min} := 0.5 \cdot h_{ef}$ $S_{min} = 5.25\,in$

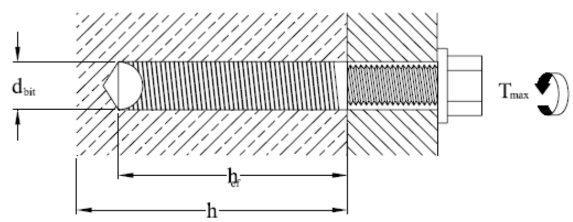
$S_{cr} := 1.5 \cdot h_{ef}$ $S_{cr} = 15.75\,in$

$C_{min} := 0.5 \cdot h_{ef}$ $C_{min} = 5.25\,in$

$C_{cr} := 1.5 \cdot h_{ef}$ $C_{cr} = 15.75\,in$

$h := t_{deck}$ Thickness of slab, (in)

$h = 14\,in$



ANCHOR GEOMETRY

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

$S_{act} = 11\ in$

$h_{ef} = 10.5\ in$

$S_{cr} = 15.75\ in$

**** Calculate Hilti Reduction Factors Spacing Tension & Shear ******

$$f_A := \left| \begin{array}{l} f_A \leftarrow 0.3 \cdot \left(\frac{S_{act}}{h_{ef}} \right) + 0.55 \ \text{ if } S_{cr} \geq S_{act} \geq S_{min} \\ f_A \leftarrow 1.0 \ \text{ if } S_{act} \geq S_{cr} \\ f_A \leftarrow 0 \ \text{ if } S_{act} < S_{min} \end{array} \right.$$

$f_A = 0.864$

***** Calculate Reduction Factors for Edge Distance Tension, "f_{RN}" *******

$$f_{RN} := \left| \begin{array}{l} f_{RN} \leftarrow 0.3 \cdot \left(\frac{C_{act}}{h_{ef}} \right) + 0.55 \ \text{ if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RN} \leftarrow 1.0 \ \text{ if } C_{act} \geq C_{cr} \\ f_{RN} \leftarrow 0 \ \text{ if } C_{act} < C_{min} \end{array} \right.$$

$f_{RN} = 0.89$

5.) Calculate Reduction Factors for Edge Distance Shear, "f_{RVperp}"

$$f_{RVperp} := \left| \begin{array}{l} f_{RVperp} \leftarrow 0.7 \cdot \left(\frac{C_{act}}{h_{ef}} \right) - 0.05 \ \text{ if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RVperp} \leftarrow 1.0 \ \text{ if } C_{act} \geq C_{cr} \\ f_{RVperp} \leftarrow 0 \ \text{ if } C_{act} < C_{min} \end{array} \right.$$

$f_{RVperp} = 0.75$

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

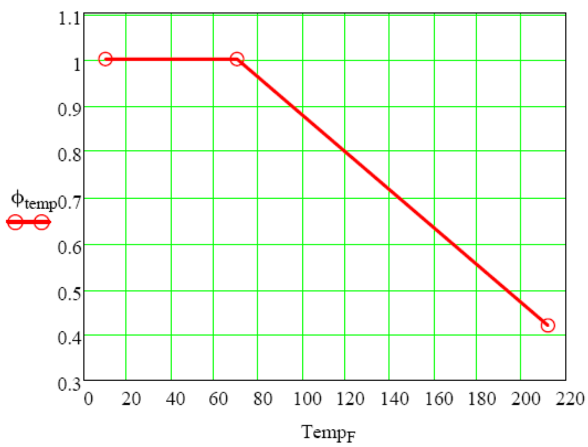
Sponsor: **Washington DOT Pooled Fund**

6.) Calculate total combined Reduction Factors for tension & shear:

$f_{RVperp} = 0.75$ $\quad f_A = 0.86$ $\quad f_{RN} = 0.89$

$$\phi_{temp} := \begin{pmatrix} 1.0 \\ 1.0 \\ 0.42 \end{pmatrix} \qquad Temp := \begin{pmatrix} 10 \\ 70 \\ 212 \end{pmatrix} {}^\circ F \qquad F := Temp \qquad Temp = \begin{pmatrix} 260.93 \\ 294.26 \\ 373.15 \end{pmatrix} K \qquad Temp = \begin{pmatrix} 260.93 \\ 294.26 \\ 373.15 \end{pmatrix} K$$

$$Temp_F := \frac{\left[(Temp - 273.15K)\cdot\frac{9}{5}\right] + 32K}{K}$$ Temperature conversion



$$\phi_{tempreduce} := \text{linterp}(Temp, \phi_{temp}, Temperature)$$

$$\phi_{tempreduce} = 0.84$$

$\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN} \cdot \phi_{tempreduce})}$ $\qquad \phi_{shear} := \overrightarrow{(f_A \cdot f_{RVperp})}$

$\phi_{tension} = 0.65$ $\qquad \phi_{shear} = 0.65$

$\phi R_{tension} := \phi_{tension} \cdot HIT_{ultimatetensile}$ $\qquad \phi R_{shear} := \phi_{shear} \cdot HIT_{ultimateshear}$

$\phi R_{tension} = 41.79 \text{ kips}$ $\qquad \phi R_{shear} = 51.22 \text{ kips}$

Hilti Factored Anchor Strengths for

$h_{ef} = 10.50 \text{ in}$

Project #: 405160-00005

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

7. Calculate the Plastice Strength of the Post:

$F_y = 50\,ksi$ Yield Strength of Steel

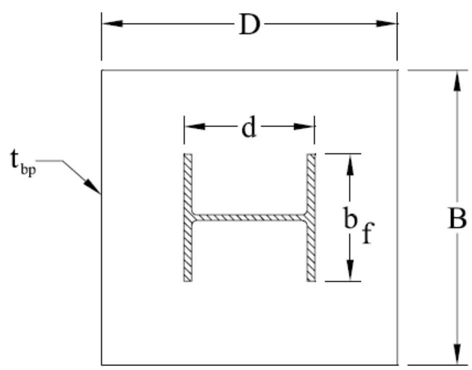
$Z_x = 20.4\,in^3$ Plastic Section Modulus of Post

$M_{xplastic} := F_y \cdot Z_x$

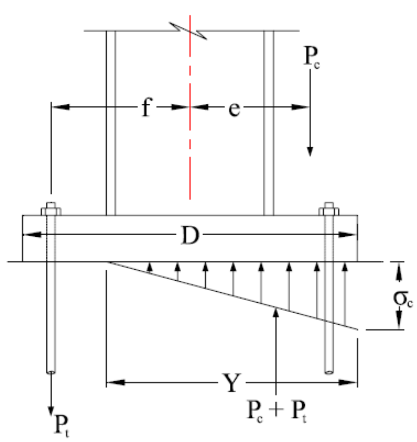
$M_{xplastic} = 85\,kip\cdot ft$ Plastic Moment

$M_{load} = 65\,kip\cdot ft$ Moment from Post Load

8.) Check Baseplate details & calculate anchor bolt forces:



BASEPLATE DETAILS



Given Basic Uplift Procedure as shown in Blodgett, "Design of Welded Structures" pages 3-3-8 through 10. and sketch w/ nomenclature showing Baseplate Geometry and distribution of force.

Find: Maximum Stress (σ_c), "Y", and force in the bolts (P_t) for applied force as shown.

This basic uplift procedure as shown in Blodget's "Design of Welded Structures" pages 3-3-8 through 10. It solves three equations for three unknowns for any combination of vertical & applied moment to the column. You have to combine the vertical load and moment to a single vertical load at some eccentricity "e". (Input Items in Yellow):

4 Bolts are used in he deign with 2 bolts located on the tension face

$P_c := .10 \cdot kips$ Vertical Load on Column (kips)

Select Design Moment from Above:

$M_1 := M_{load}$ Applied Moment (k-ft.)

$e := \frac{M_1}{P_c}$ $e = 7800\,in$ eccentricity (in.)

$D = 14\,in$ BP Length (in.) $B = 14\,in$ BP Width (in.) $f'_c = 4000\,psi$

$d = 8.28\,in$ Post Depth (in.) $D = 14\,in$ BP Length (in.) $N_t = 2$ # Tension Bolts

$b_f = 5.27\,in$ Post Flange Width (in.)

$f := \frac{d}{2} - Hole_{edgedist}$ Distance from Col. Centerline to tension bolts.

From static, there are Three Equations & Three Unknowns, P_t, "Y", & s_c:

Use Mathcad's Solve Block to find solutions. Solve Block requires "Initial guesses and uses these guesses to converge on solutions for the three unknowns, s_c, Y, P_t:

Initial Guesses for unknowns: $\sigma_c := 1000 \cdot psi$ $Y := .3 \cdot ft$ $P_t := 10 \cdot kip$

Given

$$\frac{1}{2} \cdot Y \cdot \sigma_c \cdot B - P_t - P_c = 0$$ **Equation 1**

$$P_t \cdot f + (P_c + P_t) \cdot \left(\frac{D}{2} - \frac{Y}{3}\right) - P_c \cdot e = 0$$ **Equation 2**

$$\sigma_c = \frac{P_t \cdot Y}{A_s \cdot n \cdot \left(\frac{D}{2} - Y + f\right)}$$ **Equation 3**

$$\begin{pmatrix} Y \\ \sigma_c \\ P_t \end{pmatrix} := Find(Y, \sigma_c, P_t)$$

$Y = 3.0253\,in$

$\sigma_c = 4269\,psi$ Compressive stress @ the Edge of the Baseplate on Compression side.

$P_t = 90\,kips$ Tension Force in (N_t) Anchor Bolts

$P_{Bolt} := \frac{P_t}{N_t}$ $P_{Bolt} = 45.15\,kips$ Tension per Bolt (kips)

... o.k. close to Factored Hilti Ultimate for $h_{ef} = 10.5\,in$ $\phi R_{tension} = 41.79\,kips$

9.) Check Baseplate bending/thickness using forces & stress above separately.

Calculate moment in baseplate on bearing side:

$Y = 3.03\,\text{in}$ $\quad d_{edge} := \frac{D}{2} - \frac{b_f}{2}$ $\quad d_{edge} = 4.37\,\text{in}$

$$M_{plate1} := \frac{\sigma_c \cdot Y}{2} \cdot \left[\left(d_{edge} + \frac{t_f}{2}\right) - \frac{Y}{3}\right]$$

$$M_{plate1} = 22.96\,\frac{\text{kip}\cdot\text{in}}{\text{in}}$$

Calculate moment in baseplate on Tension Bolt Side:

$P_{Bolt} = 45.15\,\text{kips}$

$Hole_{edgedist} = 1.5\,\text{in}$

$d_{edge} = 4.37\,\text{in}$ Distance from Baseplate Edge to Post Edge

$$Bolt_{dist} := d_{edge} - Hole_{edgedist} + \frac{t_f}{2}$$

$Bolt_{dist} = 3.07\,\text{in}$ Distance from center of bolt to centerline of post flange

$$M_{plate2} := \frac{P_{Bolt} \cdot Bolt_{dist}}{Bolt_{dist} \cdot 2} \qquad M_{plate2} = 22.57\,\frac{\text{kip}\cdot\text{in}}{\text{in}}$$

$$M_{plate} := \begin{cases} M_{plate1} & \text{if } M_{plate1} > M_{plate2} \\ M_{plate2} & \text{otherwise} \end{cases}$$

Select worst case bending moment in plate bearing or anchor bolt tension

$M_{plate} = 22.96\,\frac{\text{kip}\cdot\text{in}}{\text{in}}$ Design moment in the baseplate for thickness calculations

Substract 1/8" since procedure is little conservative

Therefore: $t_{prequired} := \sqrt{\frac{4 \cdot M_{plate}}{F_y}}$ $\quad t_{prequired} = 1.36\,\text{in}$ $\quad t_{plate} := \left(t_{prequired} - 0.125\,\text{in}\right)$

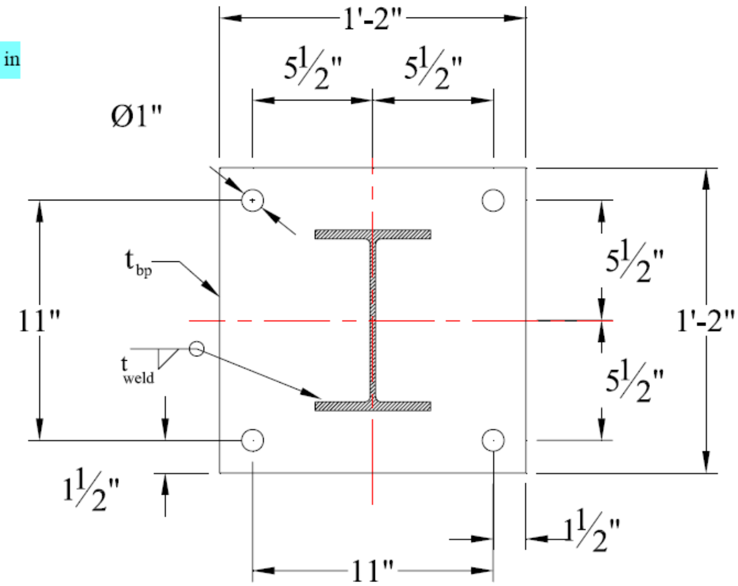
$t_{bp} := \text{Round}\left(t_{plate}, 0.125\,\text{in}\right)$ $\quad t_{bp} = 1.25\,\text{in}$ $\quad$ Final Baseplate Design Thickness (in.)

RCOMMENDED BASEPLATE DETAILS

$t_{bp} = 1.25\ in$

$F_y = 50\ ksi$

$t_{weld} = 0.25\ in$



W8x21
BASEPLATE DETAILS

Anchor Bolts: 7/8" Dia. A193 Threaded Rods, 14 inches Long, embedded 10.0 inches minimum

Anchorage System: Hilti RE 500 Anchoring System

ATTACHMENT E. PHOTOGRAPHS OF TESTING

Figure E1. W6x9 post and deck sample before test P1.

Figure E2. W6x9 post after test P1.

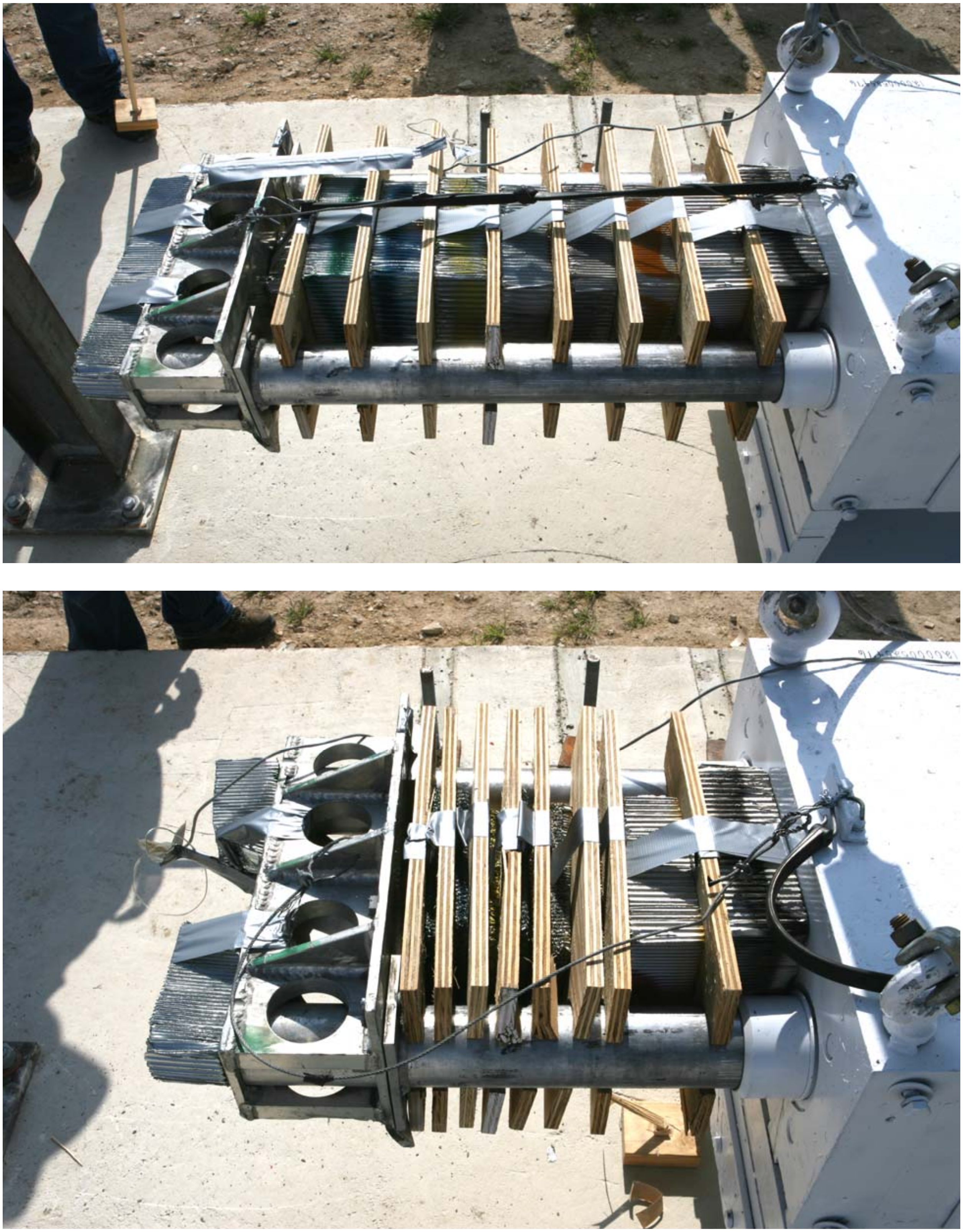
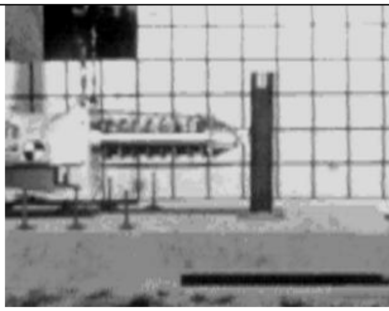
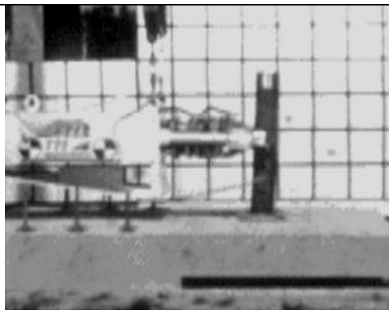


Figure E3. Pendulum bogie nose before and after test P1.

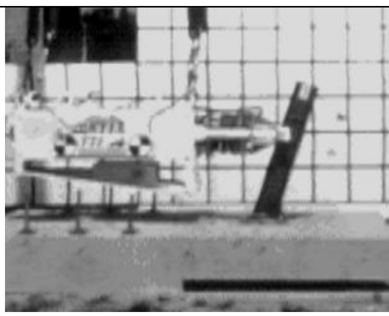
Table E1. Summary of results for pendulum test 405160-5-P1.



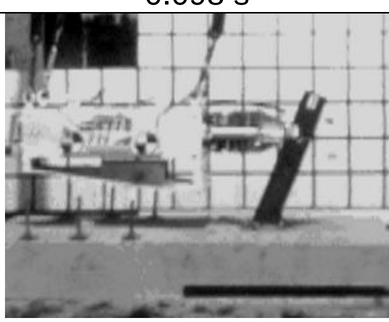
0.000 s



0.049 s



0.098 s



0.147 s

General Information

Test Agency	Texas Transportation Institute
Test No.	405160-5-P1
Date	07-16-2007

Test Article

Type	Guardrail Post
Name	Guardrail Post on Box Culvert
Installation Height (m)	37 inches
Material of Key Element	W6x9

Soil Type	Simulated Box Culvert Deck

Test Vehicle

Type	Bogie
Designation	Pendulum
Test Inertia Mass	839 kg

Impact Conditions

Speed	35.0 km/h
Angle	90 deg

Occupant Risk Values

Impact Velocity

Longitudinal direction	8.9 m/s

Ridedown Accelerations

Longitudinal direction	-3.9 g's

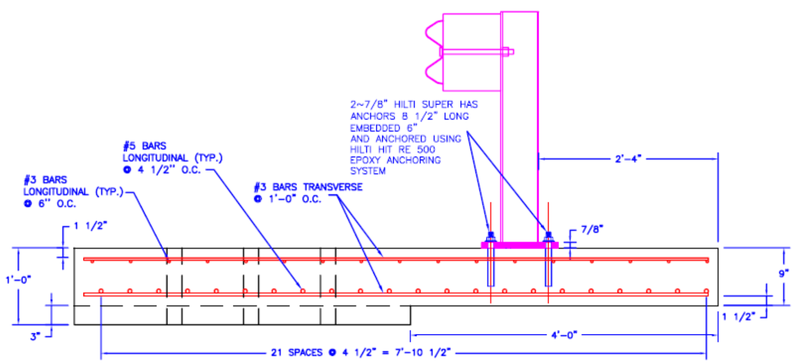
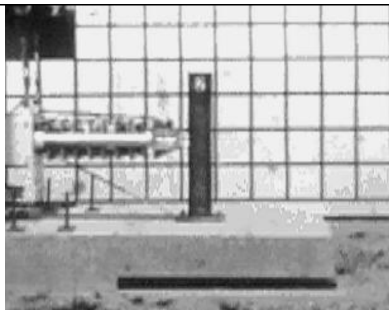


Figure D4. W6x9 post and deck sample before test P2.

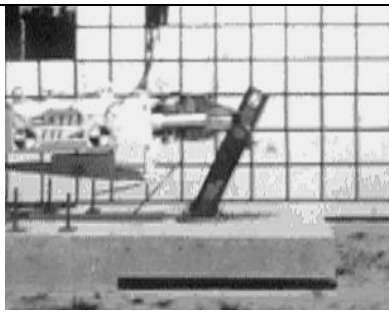
Figure E5. W6x9 post after test P2.

Figure E6. Pendulum bogie nose before and after test P2.

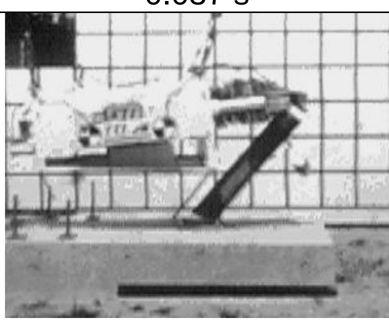
Table E2. Summary of results for pendulum test 405160-5-P2.



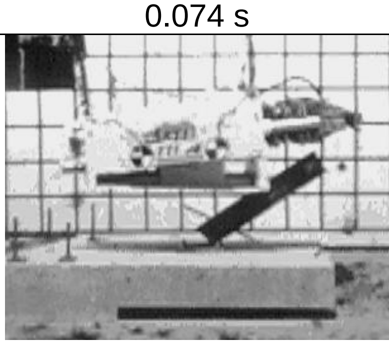
0.000 s



0.037 s



0.074 s



0.123 s

General Information

Test Agency.............................Texas Transportation Institute
Test No. 405160-5-P2
Date 07-16-2007

Test Article

Type.. Guardrail Post
Name ....Guardrail Post on Box Culvert
Installation Height (m)..37 inches
Material of Key Element W6x9

Soil Type.....................................Simulated Box Culvert Deck

Test Vehicle

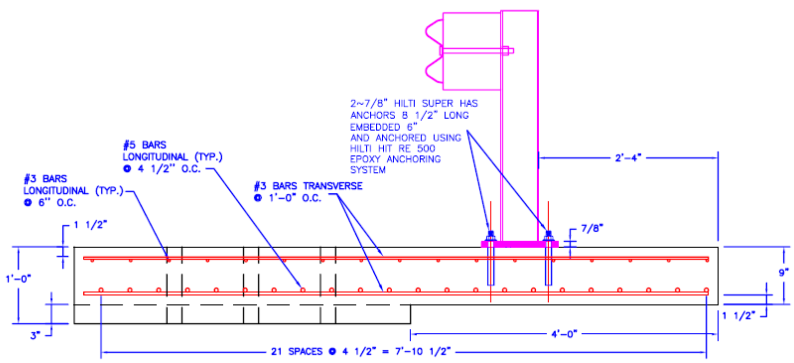
Type.. Bogie
Designation.. Pendulum
Test Inertia Mass ....839 kg

Impact Conditions

Speed ....35.0 km/h
Angle .... 90 deg

Occupant Risk Values

Impact Velocity
Longitudinal direction...6.3 m/s
Ridedown Accelerations
Longitudinal direction...-0.6 g's



ATTACHMENT F. ACCELERATION AND FORCE TRACES

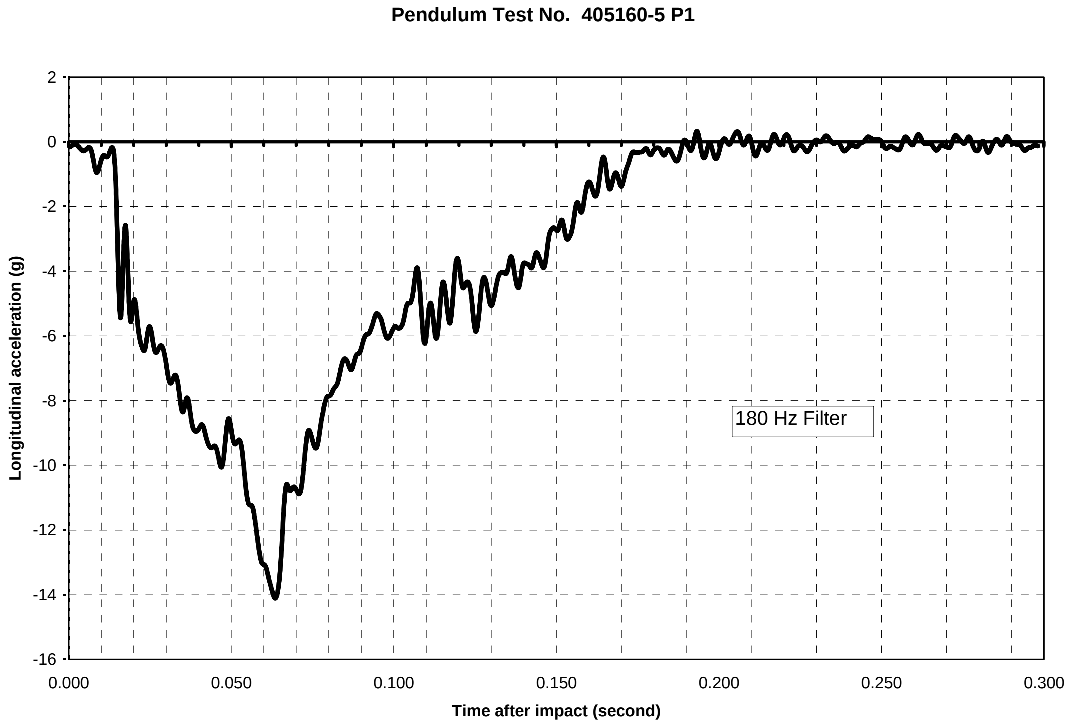


Figure F1. Accelerometer trace for test 405160-5 P1.

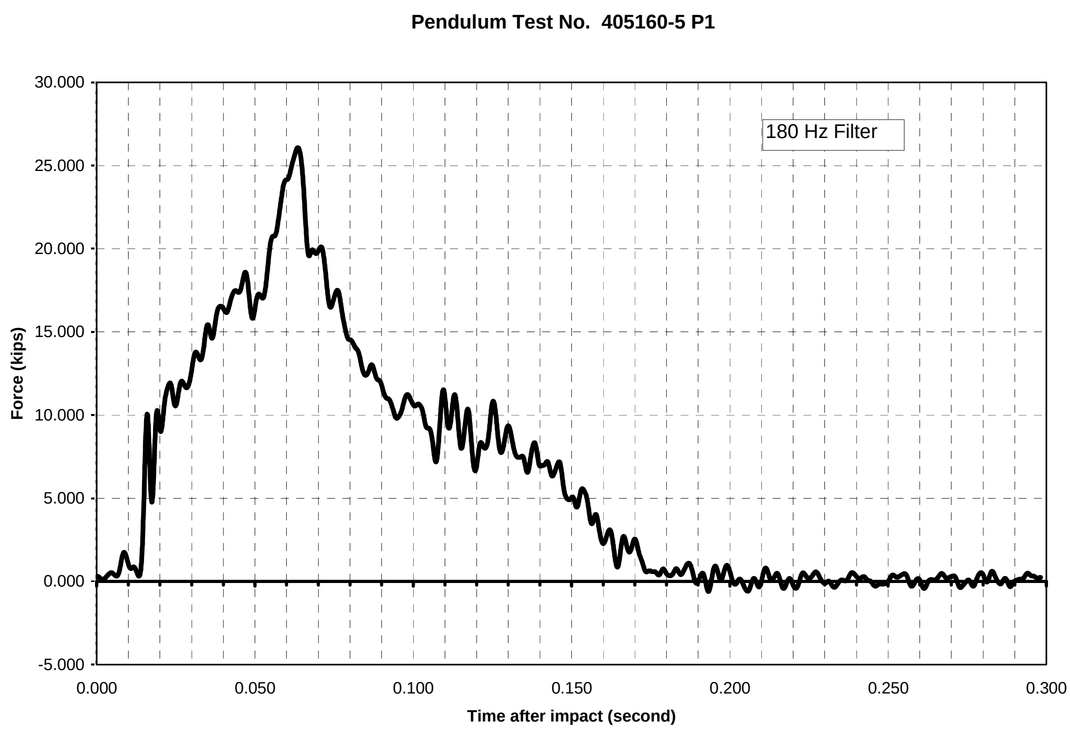


Figure F2. Force trace for test 4005160-5 P1.

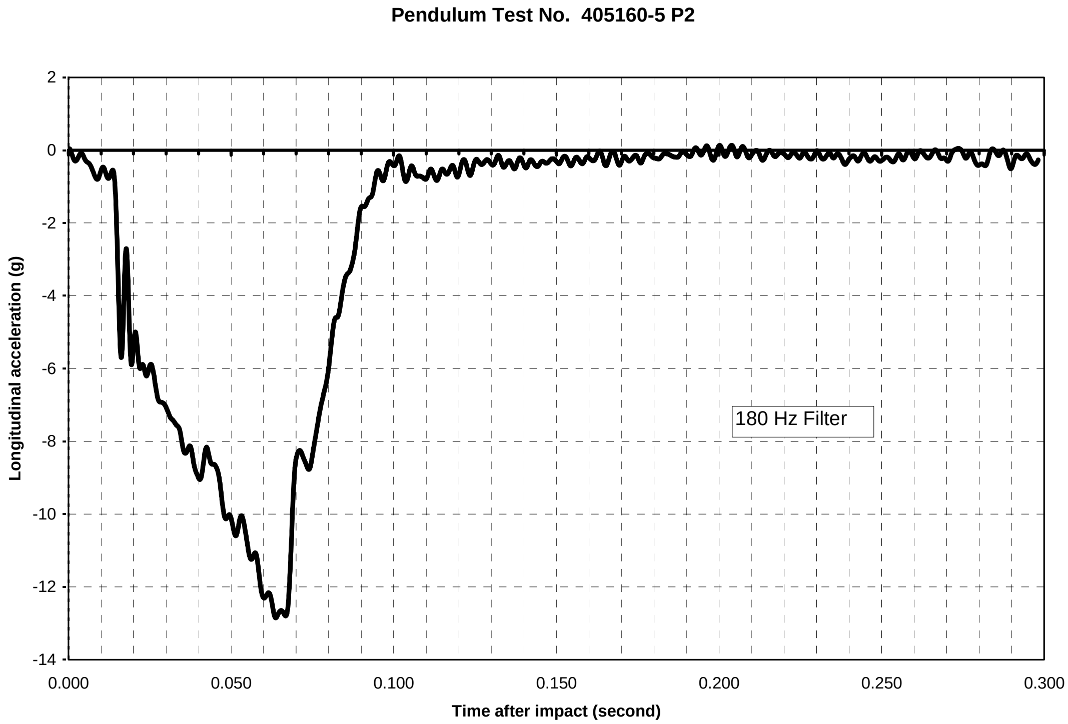


Figure F3. Accelerometer trace for test 405160-5 P2.

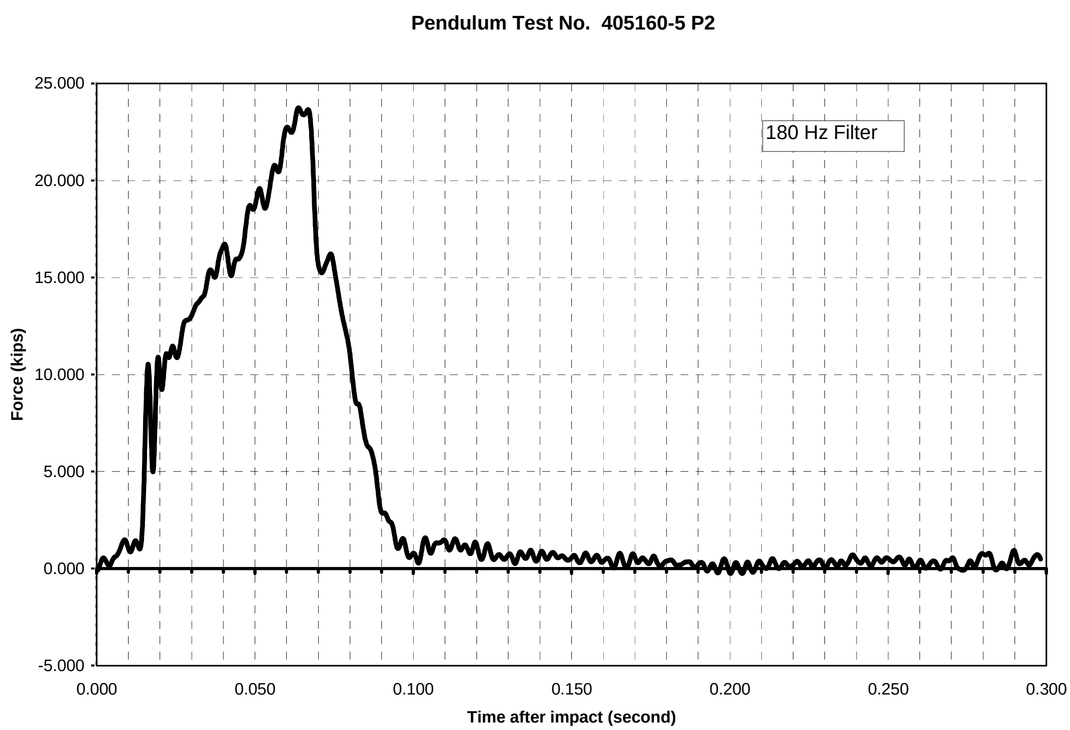


Figure F4. Force trace for test 4005160-5 P2.

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 backup 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 (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® instrumentation data recorder. After the test, the data are played back from the TEAC® 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® 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/compartment impact velocities, time of occupant/compartment 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.

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 video camera and recorder 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 D. TEST VEHICLE PROPERTIES AND INFORMATION

Date: 12-06-2007 Test No.: 405160-5-1 VIN No.: 1GCGC24R6W22686B1

Year: 1998 Make: Chevrolet Model: C2500

Tire Inflation Pressure: 60 psi Odometer: 184843 Tire Size: 245 75R16

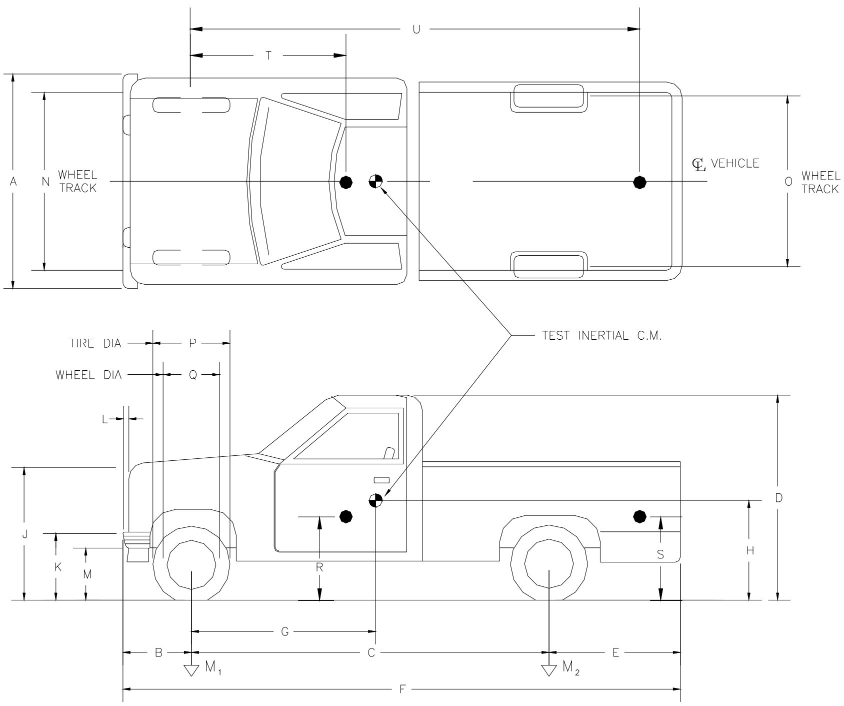
Describe any damage to the vehicle prior to test: ____________

● Denotes accelerometer location.

NOTES: ____________

Engine Type: V8
Engine CID: 5.7 liter
Transmission Type:
x Auto
___ Manual
Optional Equipment:

Dummy Data:
Type: None
Mass:
Seat Position:



Geometry (inch)

A	74	E	51.5	J	41	N	62.5	R	29.5
B	32	F	215.25	K	25	O	63.5	S	35.5
C	132	G	57.5	L	2.75	P	28.5	T	57.5
D	71.75	H		M	16.25	Q	17.25	U	132.25

Mass (lb)	Curb	Test Inertial	Gross Static
M_1	2707	2604	
M_2	2046	2010	
M_{Total}	4753	4614	

Mass Distribution (lb): LF: 1321 RF: 1283 LR: 983 RR: 1030

Figure D1. Vehicle properties for test 405160-5-1.

Table D1. Exterior crush measurements for test 405160-5-1.

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

Note: Measure C_1 to C_6 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 plane		17.75	27.5	0.75	6	8.5	11.75	13.25	17.75	+13.75
2	Side plane		15.75	47.5	1.25	---	---	---	15.25	15.75	+67

[1]Table 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).

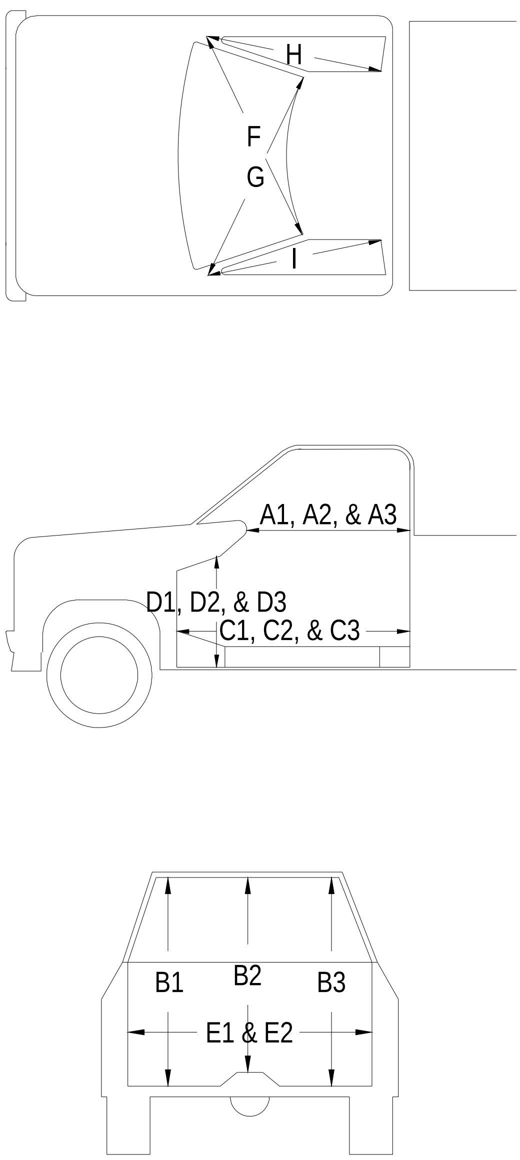
***Measure and document on the vehicle diagram the location of the maximum crush.

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

Table D2. Occupant compartment measurements for test 405160-5-1.

T r u c k

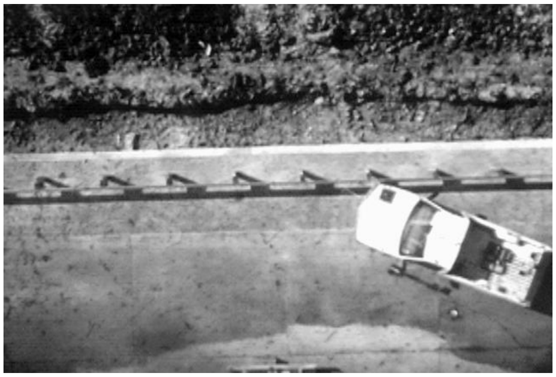
<u>O c c u p a n t   C o m p a r t m e n t   D e f o r m a t i o n</u>



	BEFORE (mm)	AFTER (mm)
A1	870	870
A2	938	940
A3	928	928
B1	1072	1072
B2	950	948
B3	1065	1065
C1	1372	1372
C2	----	----
C3	1370	1356
D1	322	322
D2	158	146
D3	310	310
E1	1588	1588
E2	1588	1588
F	1470	1470
G	1470	1470
H	1060	1060
I	1060	1060
J*	1522	1504

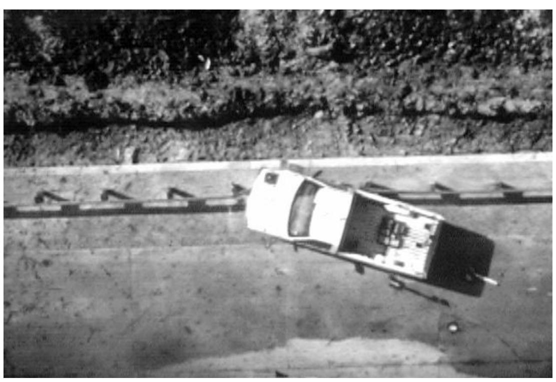
*Lateral area across the cab from
driver's side kickpanel to passenger's side kickpanel.

APPENDIX E. SEQUENTIAL PHOTOGRAPHS



0.000 s

0.061 s



0.122 s

0.183 s

Figure E1. Sequential photographs for test 405160-5-1
(overhead and frontal views).

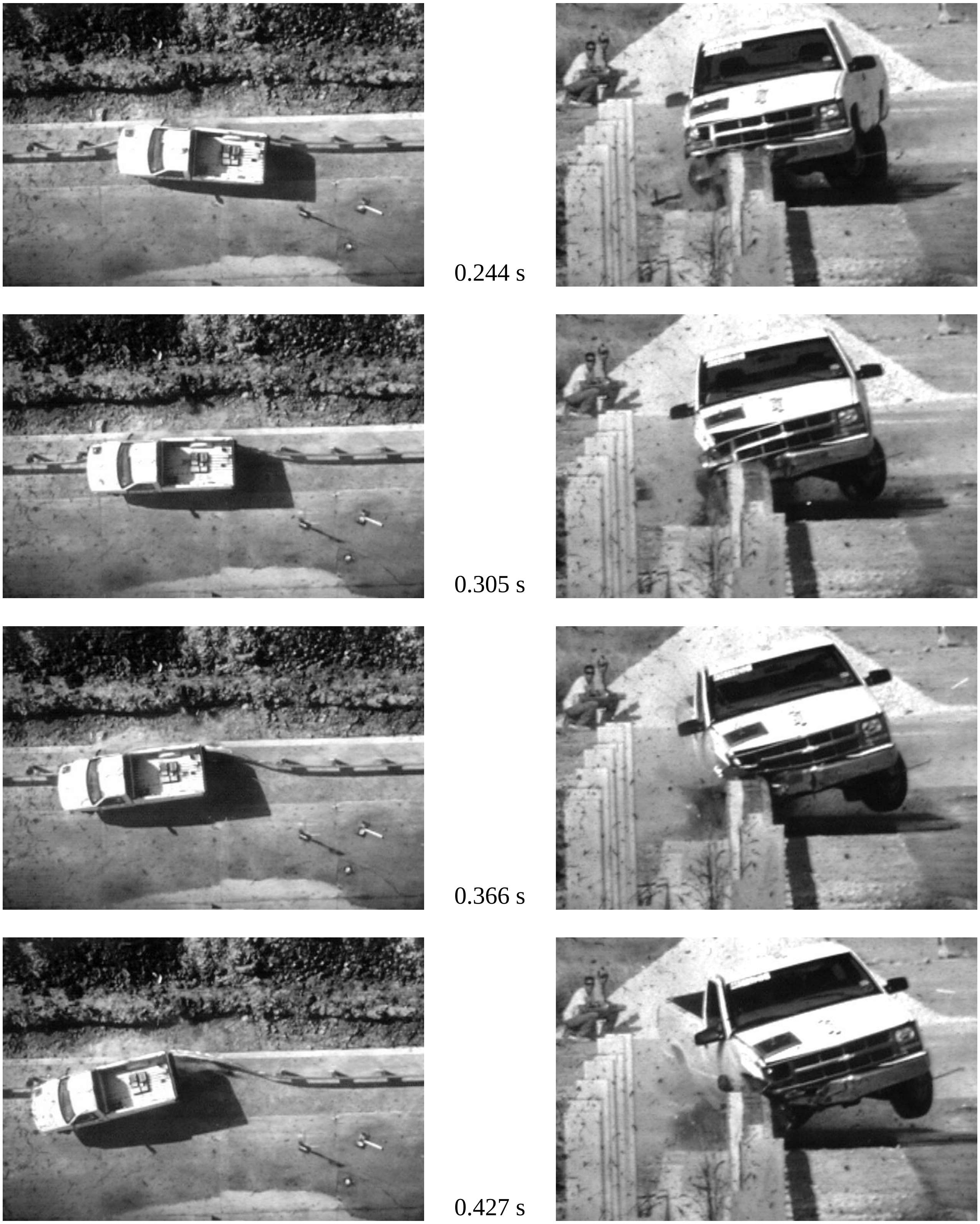
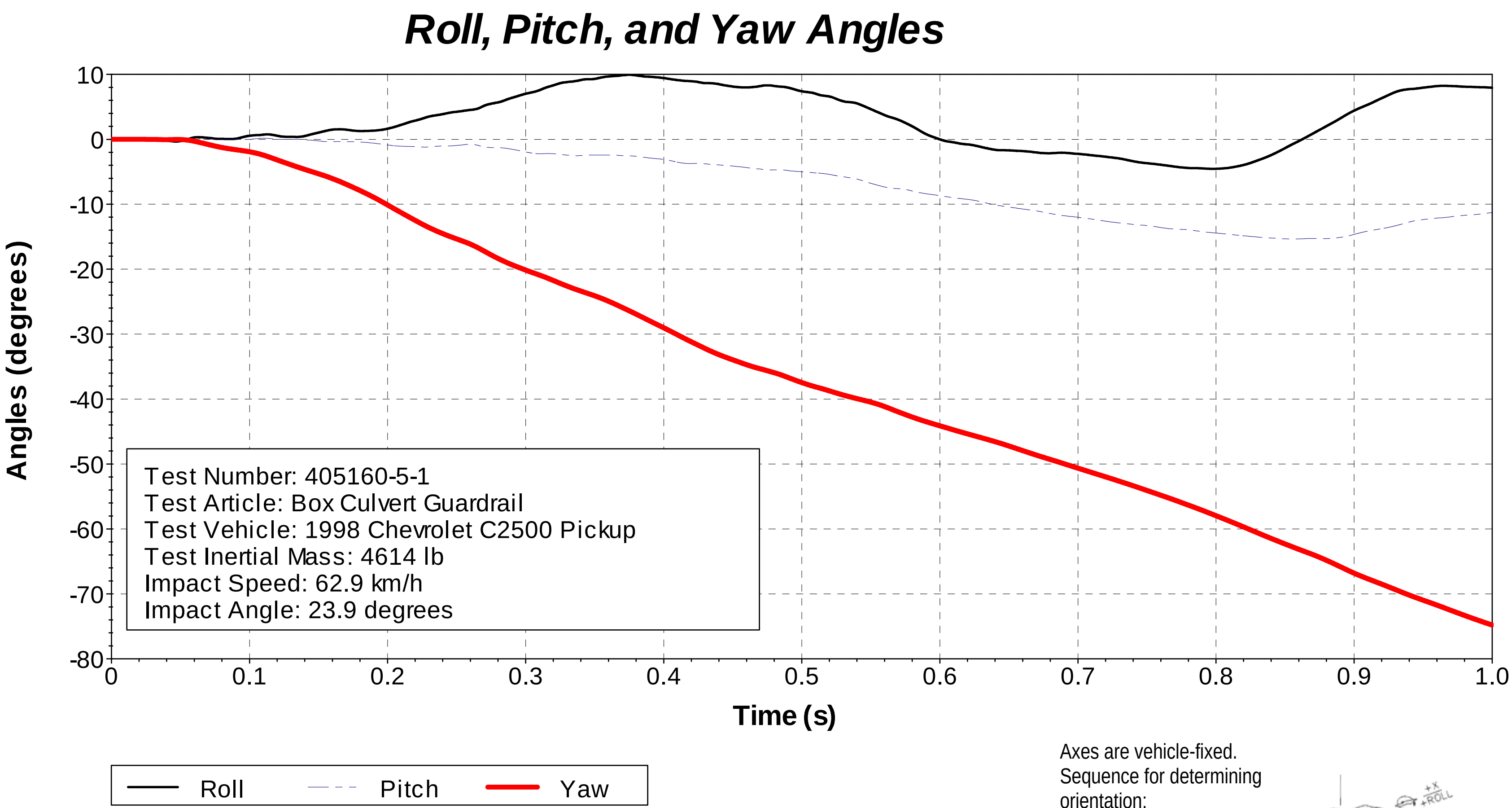


Figure E1. Sequential photographs for test 405160-5-1
(overhead and frontal views) (continued).



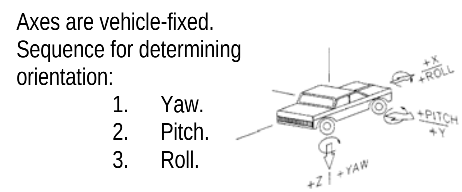


Figure F1. Vehicle angular displacements for test 405160-5-1.

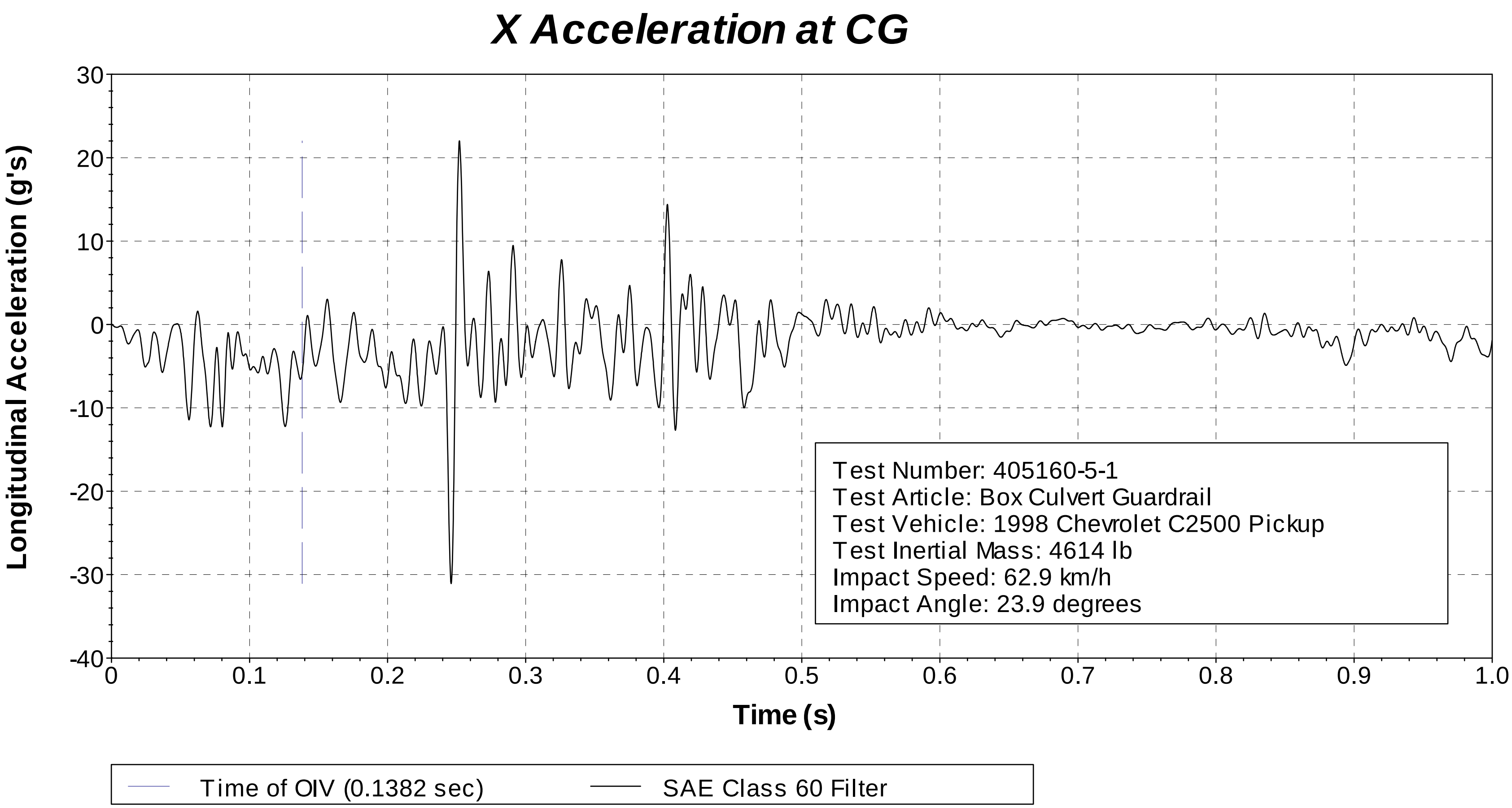


Figure F2. Vehicle longitudinal accelerometer trace for test 405160-5-1 (accelerometer located at center of gravity).

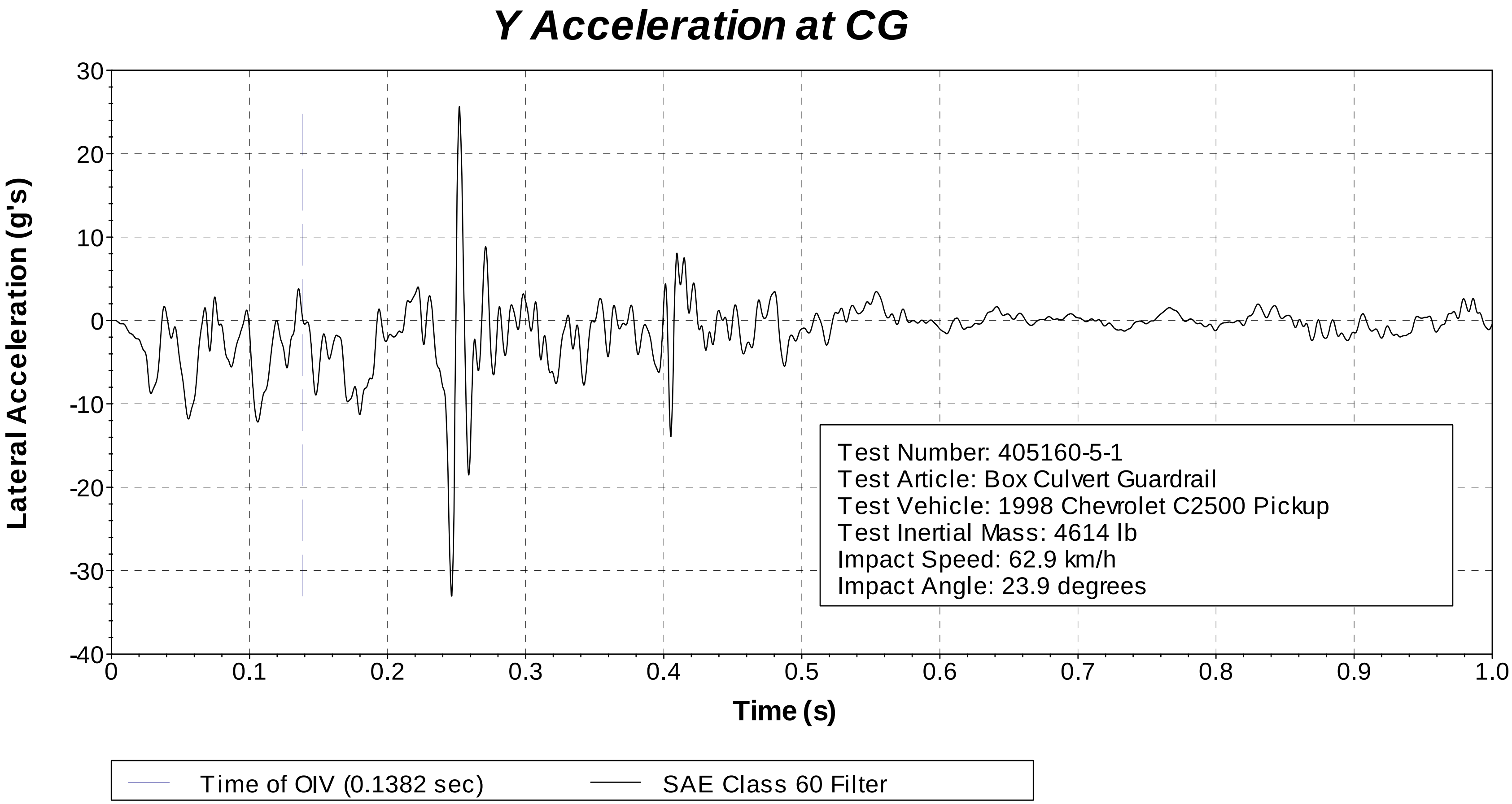


Figure F3. Vehicle lateral accelerometer trace for test 405160-5-1 (accelerometer located at center of gravity).

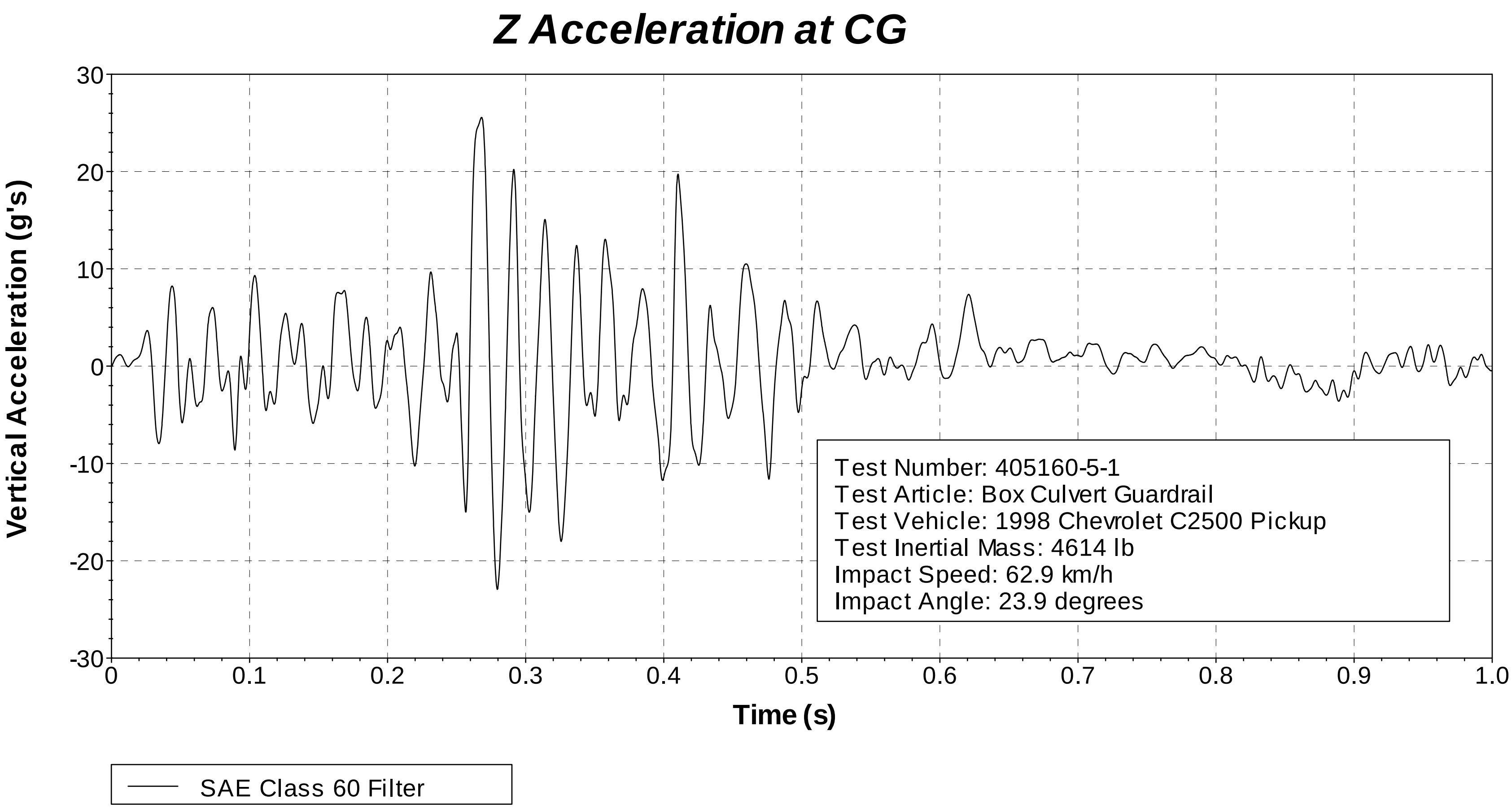


Figure F4. Vehicle vertical accelerometer trace for test 405160-5-1 (accelerometer located at center of gravity).

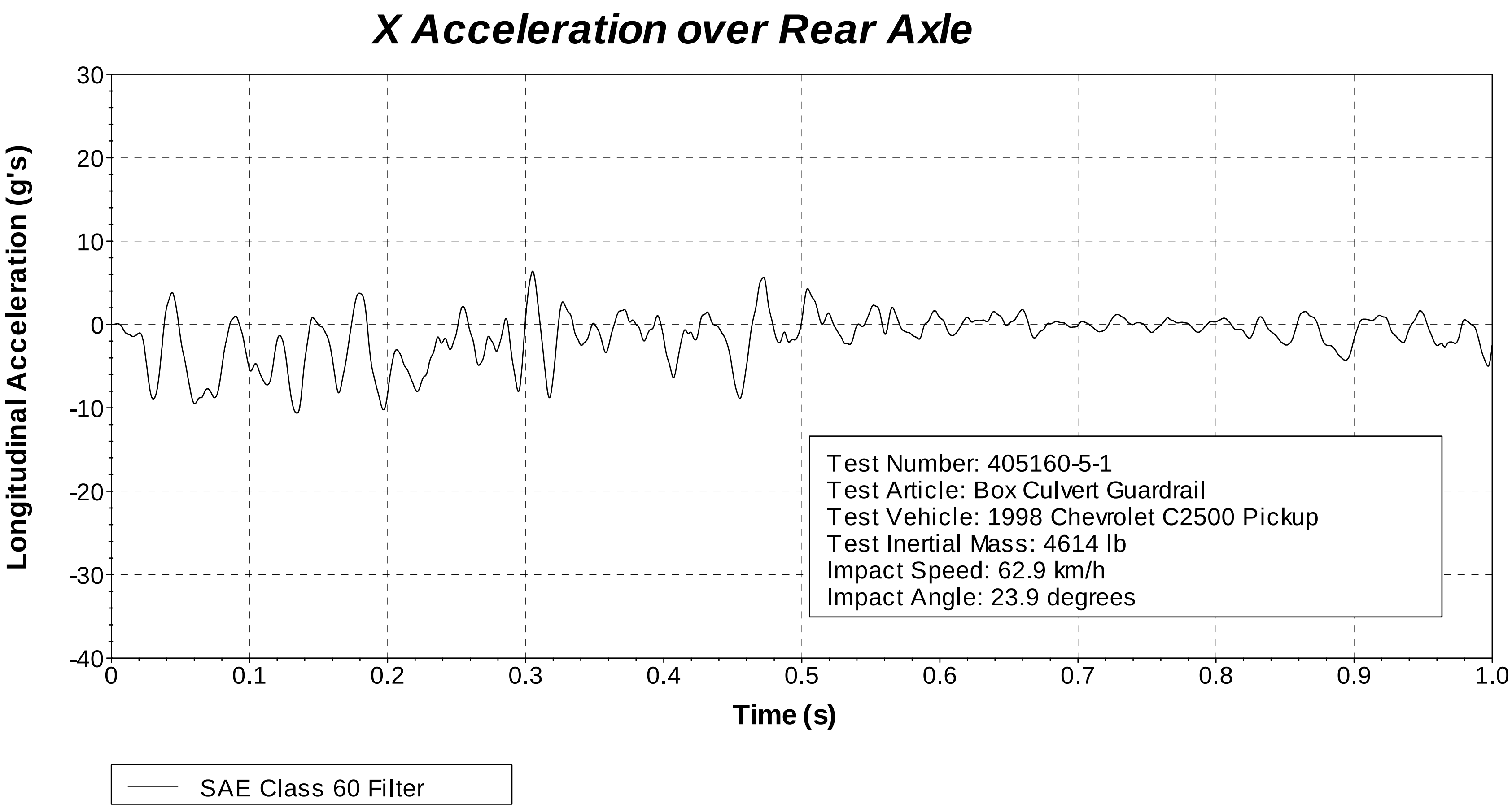


Figure F5. Vehicle longitudinal accelerometer trace for test 405160-5-1
(accelerometer located over rear axle).

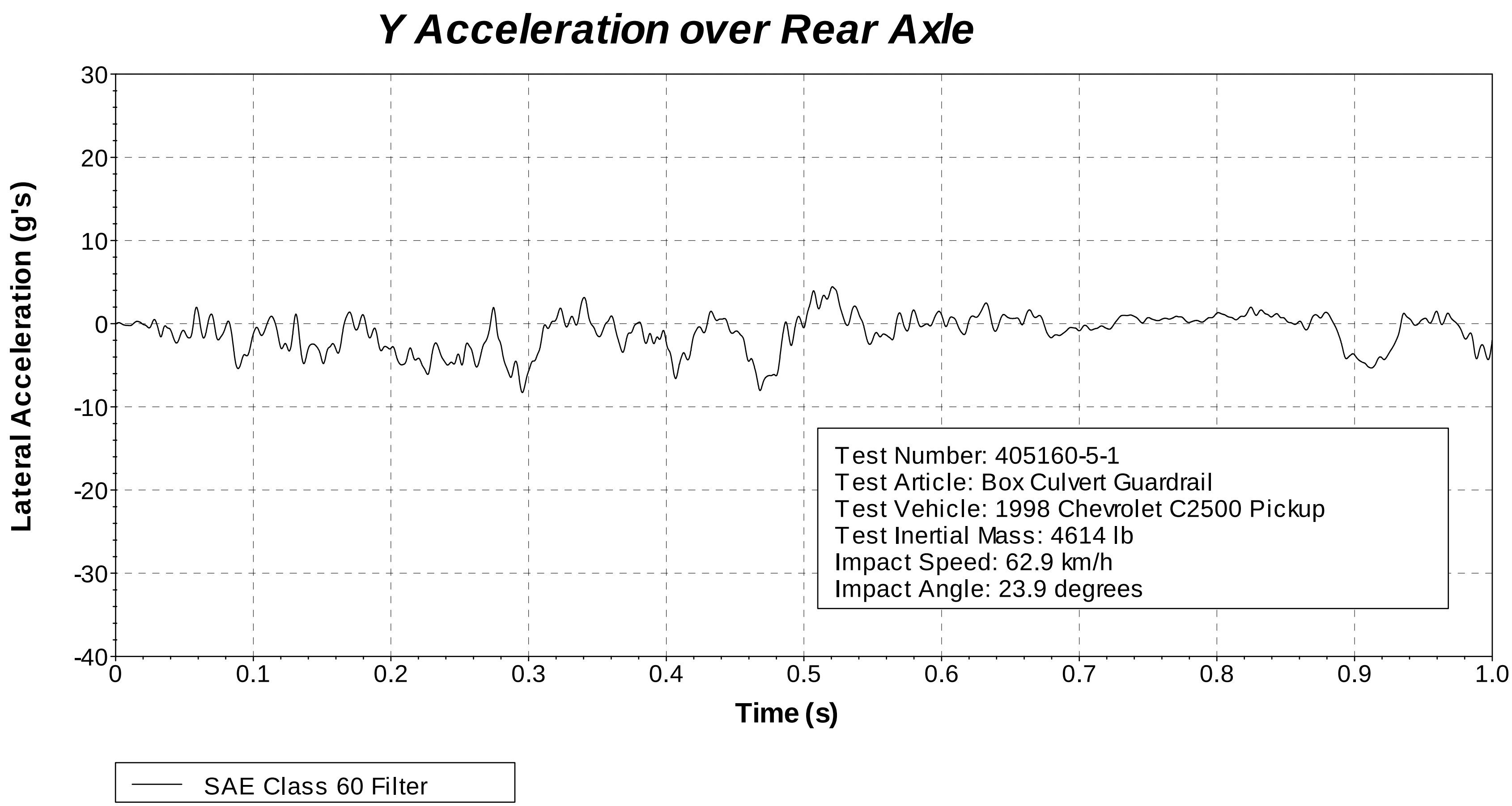


Figure F6. Vehicle lateral accelerometer trace for test 405160-5-1
(accelerometer located over rear axle).

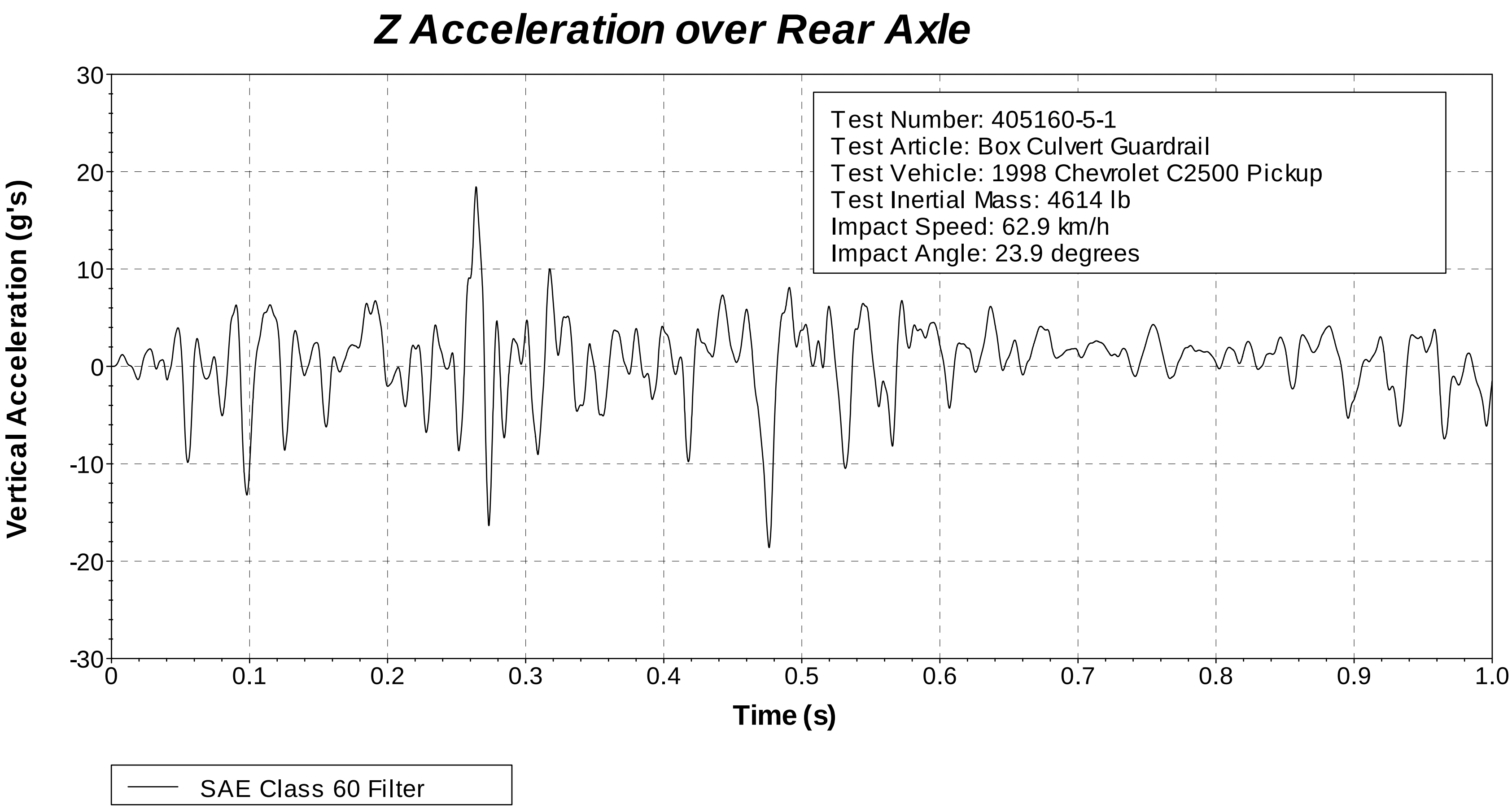


Figure F7. Vehicle vertical accelerometer trace for test 405160-5-1
(accelerometer located over rear axle).